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FOREWORD

Nuclear instruments are used in almost every phase of atomic energy work, from assessing health hazards and prospecting for nuclear materials to plant control and nuclear physics experiments. The demands on nucleonic instrumentation are growing steadily. High-energy particle physics need such instruments for measuring extremely short times; in various research experiments most advanced electronic systems are required; and routine applications of radioisotopes call for more reliable instruments for automated counting facilities.

In order to give designers and users of nuclear instrumentation an opportunity to discuss the research results and to exchange information on recent developments and new designs, the International Atomic Energy Agency, in co-operation with the Federal Nuclear Energy Commission of Yugoslavia, organized a Conference on Nuclear Electronics which was held in Belgrade from 15—20 May 1961. It was attended by more than 300 scientists from nearly 30 countries and five international organizations. Over 150 papers were read and discussed. As the field of nuclear electronics has expanded considerably, it was impossible to discuss all aspects of nuclear electronics in one series of meetings. Included in the main topics were radiation detectors, electronic circuitry in conventional and fast-pulse techniques and advanced electronic systems used in nuclear research.

The Proceedings presented in these volumes contain the full records of the Conference, including discussions. The present state of technique, together with current trends and developments, are outlined. Of particular value should be the world-wide survey on progress recently made in such fields as those connected with semiconductor detectors, spark counters, luminescence chambers and fast electronic facilities for nuclear physics research. Together with the Proceedings of the Symposium on the same subject held in Paris and also published by the International Atomic Energy Agency, these volumes offer reference materials very useful to scientists and engineers directly engaged in the development and design of nuclear electronic instruments, as well as to all those who use these instruments in their research and routine work—in developed as well as developing countries.



Scientific Secretary

Conference on Nuclear Electronics

April 1962

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The units and symbols employed are to the fullest practicable extent those standardized or recommended by the competent international scientific bodies. In the present proceedings, however, the non-standard system of symbols in common use in electronics (e.g. $K = k\Omega$) has been accepted in many Figures (to save redrawing costs) but corrected in the text.

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CONTENTS OF VOLUME I

I. SCINTILLATION AND CERENKOV DETECTORS (Session 1)

Scintillation properties of pure alkali halides at low temperatures	3
<i>H. V. Watts, L. Reiffel and M. D. Oestreich (United States of America)</i>	
Improved organic scintillation detectors	17
<i>J. B. Birks (United Kingdom)</i>	
Жидкостные сцинтилляционные детекторы для регистрации нейтронов	27
<i>И. Визи, Г. П. Жуков, Г. И. Забиякин, Э. Н. Каржавина, Л. Б. Пикельнер, А. Б. Попов, Э. И. Шарапов, Ю. С. Язвицкий (СССР)</i>	
Газовый сцинтилляционный счетчик, наполненный He^3 для спектрометрии потоков нейтронов	37
<i>С. А. Балдин, В. В. Мамвеев (СССР)</i>	
A large Cerenkov detector	47
<i>F. Reines and C. C. Giamati (United States of America)</i>	
Détection de l'effet Cerenkov des particules β dans un liquide par des photomultiplicateurs rapides mis en coïncidence	55
<i>R. et G. Ducros (France)</i>	
A high-resolution differential Cerenkov counter	63
<i>T. F. Kysia and E. W. Jenkins (United States of America)</i>	
Nanosecond decay-time techniques	71
<i>M. Burton and J. Yguerabide (United States of America)</i>	
The non-proportional response of NaI(Tl) to γ -rays and electrons and its effect upon the crystal resolution	87
<i>P. Iredale (United Kingdom)</i>	
Some effects of temperature on the performance of scintillation counters	95
<i>J. F. Cameron, C. G. Clayton and R. A. Spackman (United Kingdom)</i>	
A xenon-helium gas-scintillation counter	111
<i>K. Bergheim and K. Skarsvag (Norway)</i>	
Mise au point d'un scintillateur gazeux de grandes dimensions destiné à l'étude de la section efficace de fission de l'uranium-233 par la méthode du temps de vol	115
<i>H. Nifenecker, A. Michaudon et J. Fagot (France)</i>	
Сцинтилляционные стекла, активированные церием, для детектирования нейтронов	127
<i>В. К. Войтовецкий и Н. С. Толмачева (СССР)</i>	
Пластмассовые сцинтилляторы для регистрации тепловых нейтронов	131
<i>Е. Е. Барони, Д. В. Викторов, И. М. Розман и В. М. Шония (СССР)</i>	
Сцинтилляционный счетчик медленных нейтронов, нечувствительный к γ -излучению	139
<i>И. В. Кирпичников (СССР)</i>	

II. INTENSIFIER SYSTEMS, PHOTOMULTIPLIERS AND LUMINESCENT CHAMBERS (Session 2)

An image-intensifier system for the study of rare decay modes of elementary particles	145
<i>K. Lande, A. K. Mann, K. Reibel and D. H. White (United States of America)</i>	
An image intensifier system	153
<i>H. C. Burrows, Jr., D. O. Caldwell, E. V. Chitnis, J. Dowd, D. A. Hill, K. Li and R. A. Schluter (United States of America)</i>	
Intensifier tube development	159
<i>K. Coleman (United Kingdom)</i>	

The luminescent chamber and its use in high-energy physics experiments	165
<i>L. W. Jones and M. L. Perl (United States of America)</i>	
Recent work on Cerenkov image detectors	183
<i>G. R. Burleson, A. Roberts and T. A. Romanowski (United States of America)</i>	
Photomultiplicateurs sans fenêtre — réalisation — étude des propriétés	189
<i>A. Blanc, C. Jehanno, C. Julliot et J. Vasseur (France)</i>	
Etude des caractéristiques du photomultiplicateur 56 AVP dans le domaine de temps inférieur à la nanoseconde	201
<i>B. Agrinier, Y. Koechlin et A. Raviart (France)</i>	
Experiments on multi-stage light intensification by electroluminescence	213
<i>K. Owaki and T. Nakamura (Japan)</i>	
Development of the photomultiplier FM 50 for standard scintillation counters	223
<i>E. Kansky (Yugoslavia)</i>	
Etude des caractéristiques locales des photomultiplicateurs	229
<i>P. Cachon et A. Sarazin (France)</i>	

III. IONIZATION, GASEOUS AND LIQUID DETECTORS (Session 3)

Expérimentation d'une chambre à étincelles	241
<i>B. Agrinier, B. Mougin et B. Parlier (France)</i>	
A spark-chamber spectrometer	247
<i>G. R. Burleson, A. Roberts and T. A. Romanowski (United States of America)</i>	
A cylindrical spark counter	261
<i>A. Buffington, D. H. Frisch, D. A. Hill and M. Wahlig (United States of America)</i>	
Spark chamber for rare modes of meson decay	263
<i>H. L. Anderson (United States of America)</i>	
Studies on radiation-image detectors	269
<i>L. Reiffel (United States of America)</i>	
Fonctionnement, à la température ambiante, de chambres d'ionisation remplies d'un diélectrique liquide	285
<i>D. Blanc, J. Mathieu et J. Boyer (France)</i>	
Experimental techniques in low-level alpha spectrometry	297
<i>M. Nurmi (Finland)</i>	
A new type of instrument for the study of the angular distribution of fission fragments	303
<i>R. Ramanna, R. Chaudhry, S. S. Kapoor, K. Mikke, S. R. S. Murthy and P. N. Rama Rao (India)</i>	
Система указания координат входа частиц в эмульсионную камеру (СЦУ-1)	313
<i>А. С. Дворецкий, Р. А. Серебряков, И. В. Колесов, В. Ф. Сиколенко, Ю. Оравец, Н. С. Фролов, В. А. Казаков, И. И. Скрыль (СССР)</i>	
Spark counter for neutronographic research	321
<i>D. Bally and E. Tariná (Romania)</i>	
Caractéristiques électriques de compteurs à étincelles du type sphère-plan	327
<i>P. Laborie et D. Blanc (France)</i>	
A proportional counter with reduced wall effect	335
<i>C. Manduchi and G. Zannoni (Italy)</i>	
Construction and operating characteristics of flexible Geiger counters	339
<i>H. G. Richter and L. F. Ballard (United States of America)</i>	
Mise au point de compteurs Geiger-Müller fonctionnant à haute température	345
<i>M. Draghicescu (Romania)</i>	

Управляемая искровая камера — прибор для наблюдения следов заряженных частиц 353
В. А. Михайлов, В. Н. Роинишвили и Г. Е. Чиковани (СССР)

IV. SEMICONDUCTOR DETECTORS AND THEIR APPLICATION IN DETECTION (Session 4)

Кристаллические счетчики из сульфида кадмия	363
<i>М. Борисов и М. Маринов (Болгария)</i>	
Silicon surface-barrier nuclear-particle detectors	379
<i>J. L. Blankenship, C. J. Borkowski and R. J. Fox (United States of America)</i>	
Behaviour of semiconductor nuclear-particle detectors	391
<i>F. J. Walter, J. W. T. Dabbs and L. D. Roberts (United States of America)</i>	
Surface-barrier counters for nuclear reaction studies	403
<i>M. L. Halbert (United States of America)</i>	
A silicon surface-barrier fast-neutron spectrometer	415
<i>T. A. Love, R. B. Murray, J. J. Manning and H. A. Todd (United States of America)</i>	
Semiconductor detector systems (dE/dx and E) for the detection and mass identification of protons, deuterons, tritons, He^3 and alpha particles in the 10- to 30-MeV energy region	427
<i>H. E. Wegner (United States of America)</i>	
Solid-state detectors for measurement of dE/dx and total energy in nuclear reactions at cyclotron energies	447
<i>T. H. Braid and J. T. Heinrich (United States of America)</i>	
Spectromètre à neutrons rapides à lithium-6 et diodes au silicium	451
<i>J. Bok, B. de Cosnac, J.-P. Noël et R. Schuttler (France)</i>	
Propriétés des jonctions nip de silicium-application à la détection des particules relativistes ..	465
<i>L. Koch, J. Messier et J. Valin (France)</i>	
Charge collection in semiconductor radiation detectors	477
<i>G. L. Miller and W. M. Gibson (United States of America)</i>	
Preliminary experiments with a solid-state ionization chamber	497
<i>R. J. Griffiths, C. J. Batty, P. E. Gibbons and D. C. Northrop (United Kingdom)</i>	
Properties of solid-state detectors	501
<i>I. Dunmur, G. George, E. M. Gunnensen and A. Hitchcock (United Kingdom)</i>	
Change of I—V characteristics of SiC diodes upon reactor irradiation	513
<i>M. Heerschap and R. de Coninck (Belgium)</i>	
Semi-conductor counters as charged-particle and neutron spectrometers	523
<i>G. Dearnaley, A. T. G. Ferguson, A. B. Whitehead and J. H. Montague (United Kingdom)</i>	
Recent work on instrumentation for nuclear pulse-height spectroscopy	535
<i>B. Aström (Sweden)</i>	
The use of semi-conductor counters for measuring the distribution of pile-neutron flux	543
<i>B. Lalović and V. Ajdačić (Yugoslavia)</i>	
Semi-conductor counter and its applications for neutron measurement	551
<i>E. Saki (Japan)</i>	
Characteristics of ion-drifted p-i-n-junction particle detectors	567
<i>J. W. Mayer, N. A. Baily and H. L. Dunlap (United States of America)</i>	
Electrical limitations to energy resolution in semi-conductor particle detectors	583
<i>W. L. Hansen and F. S. Goulding (United States of America)</i>	
Полупроводниковые спектрометры заряженных частиц	591
<i>Л. А. Зубрицкий, А. И. Попов, П. В. Сорокин и В. Ф. Самойлов (СССР)</i>	

I.

SCINTILLATION AND CERENKOV DETECTORS

(SESSION 1)

SCINTILLATION PROPERTIES OF PURE ALKALI HALIDES AT LOW TEMPERATURES

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Abstract — Résumé — Аннотация — Resumen

Scintillation properties of pure alkali halides at low temperatures. Fragmentary studies in various laboratories on the scintillation behaviour of several of the alkali halides, both with and without impurity activators, indicate that in general the activated alkali halides scintillate best at room-temperature with pulse-height decreasing at lower temperatures, while the unactivated materials scintillate best at low temperatures and decrease in efficiency as the temperature increases. In our laboratory, a systematic research study on the scintillation properties of the alkali halides is underway and to date we have examined twelve pure (unactivated) alkali halides with both α -particle and γ -ray excitation over the temperature range of 4°K to 300°K. LiI, KI, and CsI exhibit a constant scintillation pulse-height and decay-time at temperatures below 80°K. NaI exhibits a maximum in pulse-height at 60°K similar to that reported previously by VAN SCIVER *et al.* A second CsI sample shows both a low-temperature scintillation-component and a room-temperature component similar to that induced by overheating as in the experiments of KNOEPFEL *et al.* RbI shows two regions of linearly decreasing pulse-height as temperature increases. The scintillation pulse-heights of the iodides are comparable to that observed from thallium-activated sodium iodide and the decay times are about 0.1 to 2 μ s. CsBr, KBr, and NaCl scintillate at low temperatures, but with a much lower intensity than the iodides. LiF, NaF, KCl, and RbBr exhibit no detectable scintillation over the entire temperature range studied. The temperature dependence of pulse-heights and decay-constants is the same for both γ and α -excited emission. Analysis of the scintillation pulse-shape and the temperature-dependence gives an indication of the number of luminescence components and the mode of decay of the excited luminescence centres.

Scintillation des halogénures alcalins purs à basse température. Des études fragmentaires effectuées dans divers laboratoires sur le comportement comme scintillateurs de plusieurs halogénures alcalins activés ou non indiquent que, d'une manière générale, les halogénures alcalins activés scintillent le mieux à la température ambiante, l'amplitude des impulsions étant la plus faible aux basses températures; en revanche, les matières non activées scintillent le mieux aux basses températures, leur propriété diminuant lorsque la température augmente. Le laboratoire où les auteurs exercent leur activité a entrepris l'étude systématique de la scintillation des halogénures alcalins et a examiné jusqu'ici le comportement de douze halogénures alcalins purs (non activés) sous l'action de particules α et de rayons γ dans la gamme des températures comprises entre 4°K et 300°K. Pour LiI, KI et CsI, l'amplitude des impulsions et la durée de vie des scintillations sont constantes au-dessous de 80°K. Pour NaI, l'amplitude des impulsions est maximum à 60°K, résultat très semblable à celui dont Van Sciver et coll. ont déjà rendu compte. Un deuxième échantillon de CsI présente à la fois une composante de scintillation aux basses températures et une composante à la température ambiante semblable à celle produite par surchauffe comme dans les expériences de Knoepfel et coll. Pour le RbI, l'amplitude des impulsions décroît lorsque la température augmente et la courbe correspondante est linéaire en deux régions. Les amplitudes des impulsions de scintillation des iodures sont comparables à celles que l'on observe pour l'iodure de sodium activé au thallium, la durée de vie étant de l'ordre de 0,1 à 2 μ s. CsBr, KBr et NaCl scintillent aux basses températures, mais avec une intensité beaucoup plus faible que les iodures. LiF, NaF, KCl et RbBr n'ont pas de propriété de scintillation décelable dans toute la gamme des températures étudiées. Les amplitudes d'impulsions et les constantes de décroissance varient avec la température de la même façon sous l'effet

de rayons γ et sous l'effet de particules α . L'analyse de la forme de l'impulsion de scintillation et de l'influence de la température donne une idée du nombre des composantes de luminescence et du mode de désexcitation des centres luminescents excités.

Сцинтилляционные свойства чистых щелочных галоидов при низких температурах. Проведенные в различных лабораториях отрывочные исследования особенностей сцинтилляции некоторых из щелочных галоидов как с активаторами взвеси, так и без них показывают, что, как общее правило, активированные щелочные галоиды сцинтиллируют лучше всего при комнатной температуре, причем амплитуда импульсов уменьшается по мере падения температуры, тогда как неактивированные материалы сцинтиллируют лучше всего при низких температурах, причем эффективность сцинтилляции падает по мере возрастания температуры. В нашей лаборатории производится в настоящее время систематическое исследование сцинтилляционных свойств щелочных галоидов, и до сих пор мы изучили двенадцать чистых (неактивированных) щелочных галоидов при возбуждении их как альфа-частицами, так и гамма-излучениями, в интервале температур от 4°K до 300°K . LiI, KI и CsI сохраняют постоянную амплитуду сцинтилляционного импульса и постоянное время распада при температурах ниже 80°K . У NaI максимальная амплитуда импульса наблюдается при температуре в 60°K , подобно тому, что сообщалось ранее Ван Скивером и другими. У второго образца CsI наблюдалась составная часть сцинтилляции при низкой температуре и другая составная часть — при комнатной температуре, аналогично тому, что вызывалось в опытах с перегревом, произведенными Кнопфелем и другими. По мере возрастания температуры у RbI наблюдаются две зоны линейнопадающей амплитуды импульса. Амплитуды сцинтилляционных импульсов йодистых соединений сопоставимы с амплитудами, наблюдавшимися с активированным таллием йодистым натрием, а время распада их лежит в пределах порядка от 0,1 до 2 микросекунд. CsBr, KBr и NaCl сцинтиллируют при низких температурах, но с гораздо меньшей интенсивностью, чем йодистые соединения. У LiF, NaF, KCl и RbBr не наблюдается уловимой сцинтилляции во всех изученных температурных интервалах. Зависимость амплитуды импульсов и констант распада от температуры одинакова как для эмиссии, вызванной гамма-излучениями, так и для эмиссии, вызванной альфа-частицами. Анализ формы сцинтилляционных импульсов и зависимости их от температуры дает указание относительно числа люминесцирующих составных частей и способа распада возбужденных центров люминесценции.

Propiedades de centelleo de los haluros alcalinos puros a baja temperatura. Los estudios parciales realizados en varios laboratorios, sobre las propiedades de centelleo de algunos haluros alcalinos, puros y con impurezas activadoras, demuestran que, en general, el centelleo de los haluros alcalinos activados es óptimo a la temperatura ambiente y que la amplitud de los impulsos disminuye con la temperatura, mientras que el centelleo de las sustancias no activadas es óptimo a baja temperatura y su eficiencia disminuye a medida que ésta aumenta. En nuestro laboratorio se está realizando una investigación sistemática sobre las propiedades de centelleo de los haluros alcalinos y hasta ahora se han examinado doce de éstos en estado puro (no activado) utilizando como excitadores partículas alfa y rayos gamma, en un margen de temperaturas desde 4°K a 300°K . El LiI, KI y CsI presentan una amplitud de impulso de centelleo y un tiempo de caída constantes para temperaturas inferiores a 80°K . La amplitud de los impulsos del NaI presenta un máximo para una temperatura de 60°K análogo al señalado anteriormente por Van Sciver y sus colaboradores. En una segunda muestra de CsI, se han observado dos componentes de centelleo; uno, característico de bajas temperaturas, y otro característico de temperaturas ambiente, análogo al inducido por sobrecalentamiento, como en el caso de los experimentos de Knoopfel y sus colaboradores. El RbI presenta dos regiones en que la amplitud de los impulsos es inversamente proporcional a la temperatura. Las amplitudes de los impulsos de centelleo de los yoduros son comparables a las observadas en el yoduro de sodio activado con talio, y los tiempos de caída son del orden de 0,1 a $2\ \mu\text{s}$. El CsBr, el KBr y el NaCl emiten centelleos a baja temperatura, pero con una intensidad mucho menor que los yoduros. El LiF, NaF, KCl y RbBr no presentan centelleo detectable en toda la gama de temperaturas estudiada.

La variación de las amplitudes de impulso y de las constantes de tiempo de caída en función de la temperatura es la misma cuando los centelleadores se excitan con rayos gamma que cuando se excitan con partículas alfa. El análisis de la forma de los impulsos y de su variación en función de la temperatura da una indicación relativa al número de componentes y la modalidad de caída de los centros luminiscentes excitados.

I. Introduction and background

Studies in various laboratories on the scintillation behaviour of several of the alkali halides, both with and without impurity activators, indicate that, in general, the activated alkali halides scintillate best at room temperature with pulse-height decreasing at lower temperatures, while the unactivated materials scintillate best at low temperatures and decrease in efficiency as the temperature increases. BONANOMI *et al.* [1] have studied the temperature-dependence of the emission of pure and thallium-activated alkali halides down to 77° K. The scintillation intensity versus temperature from 77° K. to 300° K was found to be described fairly well by a function derived under the assumption of two competing temperature-dependent transitions, one radiative, the other non-radiative.

VAN SCIVER [2] [3] has compared the scintillation intensity, decay-time, and spectra of several NaI and NaI(Tl) crystals at low temperatures. He observed a peak in the scintillation intensity of pure NaI at about 80° K. DER MATEOSIAN *et al.* [4] have reported similar results down to 77° K.

KNOEPFEL *et al.* [5] have examined CsI, both pure and activated, down to 77° K. Distinctly different properties were observed for the two types of crystal. The scintillation intensity of thallium-activated CsI remained nearly constant when the temperature was decreased from 300° K. to about 160° K. and then the intensity decreased with a further decrease in temperature. The decay-time increased continuously as the temperature was lowered through this range. With unactivated CsI, the intensity increased continuously as the sample was cooled down to 77° K. and the decay-time remained nearly constant. The intensity of the unactivated samples equalled that of the activated samples at about 160° K. This is similar to the behaviour observed by BONANOMI *et al.* [1] for the pure and unactivated CsI. However, it was found by KNOEPFEL *et al.* [5] that pure CsI would show components of both the activated and unactivated material if it is heated to between 800 and 900°C (MP CsI is 621°C) for about five minutes, and then thermally quenched. The melt must be overheated, not merely heated to the melting point. Because of the fact that iodine was liberated during the overheating, a strong argument is presented in favour of an iodine vacancy rather than a substitutional thallium ion as the luminescence centre. The vacancy is created by the formation of iodine molecules which become incorporated in the crystal lattice in the overheated sample and by a Tl-I-complex, behaving in a similar way chemically to the iodine molecule, in the case of a thallium-activated sample.

MURRAY *et al.* [6] [7] have examined the luminescence emission spectra of pure and europium-activated lithium iodide at temperatures down to 77° K. Measurements on the scintillation intensity and decay-time as a function of temperature were also made.

Although considerable interest has been shown in the low-temperature scintillation-properties of alkali halides, only fragmentary work has actually been done, and most of this work has been done only to 77° K. Therefore, systematic research on pure alkali halides was begun in our laboratory. In the investigations currently underway, the

low-temperature scintillation properties of twelve pure (unactivated) alkali halides have been examined down to 4° K.

II. Apparatus and Techniques

Fig. 1 is a cross-section view through the sample compartment of our double-walled liquid-helium dewar. The samples are mounted within a silver-plated copper cylinder which is the bottom end of the liquid-helium reservoir. Good thermal contact is provided by the crystal holder and the crystal mounting geometry surrounds the samples, as much as possible, with the operating temperature of the copper cylinder. A standard heat-radiation shield attached to the liquid-nitrogen reservoir surrounds the sample mount. The temperature is determined by a copper-constant thermocouple, the junction of which is indium soldered to the sample mount.

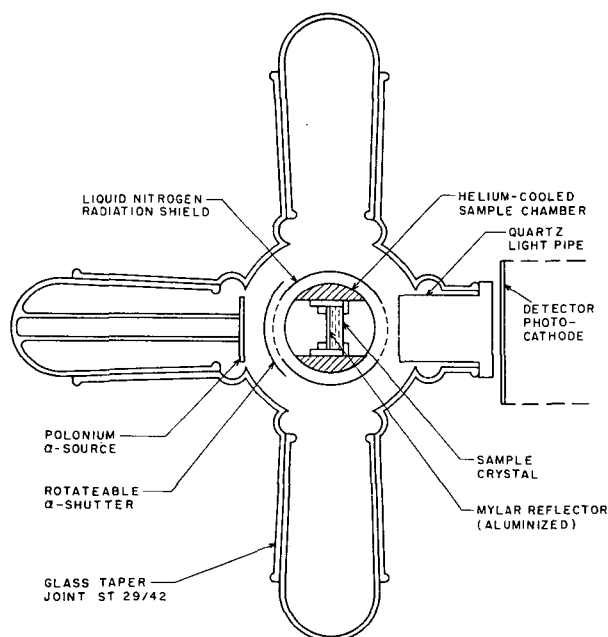


Fig. 1
Cross-section view of sample geometry

Alpha-particle excitation is provided by a polonium-210 source (~ 600 disintegrations/s in forward direction) mounted in the vacuum space of the dewar. A rotatable α -shield is used for stopping the excitation. An external collimated cobalt-60 gamma source was used for γ -excitation.

The source side of the crystal sample is covered by 1/4-mil aluminized mylar as a light reflector for increased scintillation-detection efficiency. The loss in alpha-particle

energy due to this reflector (~ 1 MeV loss) is less than the gain in light-detection which the reflector gives. A cylindrical quartz light-collector is used to further increase the detection geometry or effective aperture.

On the outside of the dewar, optically coupled with silicone fluid (Dow-Corning 600000 silicone fluid) to the quartz light pipe, is the multiplier phototube detector. This tube, DuMont K1306, has a vycor window which extends its spectral response further into the ultraviolet than the standard type 6292 multiplier phototube. The photocathode temperature of this tube remains constant; thus the spectral efficiencies of the detector remain constant throughout the sample temperature region.

The scintillation pulses are viewed and photographed on a Tektronix Model 541 synchroscope with the Tektronix Type L "Hi-gain" pre-amplifier. This system has a combined rise-time of about 10^{-8} s and a sensitivity sufficient to detect the dark noise pulses of the ten-stage multiplier phototube.

If we assume the exponential fluorescence decay, i.e.

$$f(t) = 1/\tau \, e^{-t/\tau}, \quad (1)$$

the voltage pulse as a function of time on the RC anode circuit is

$$V(t) = \frac{A}{C} \left(\frac{RC}{RC - \tau} \right) (e^{-t/RC} - e^{-t/\tau}) \quad (2)$$

where A = constant which includes the total number of scintillation photons produced by the charged particle excitation and the detection efficiency

C = capacity of the anode circuit

R = anode resistance

τ = exponential decay-time.

If the anode circuit is made to integrate ($RC \gg \tau$) the rise of the pulse will be governed by the decay of the fluorescence pulse and Equation (2) can be rewritten as

$$V(t) = A/C (1 - e^{-t/\tau}). \quad (3)$$

Thus the time for the integrated pulse to reach 0.63 of maximum is the decay-constant, τ . In practice RC is set for about 10 to 50 μ s. The peak pulse-height from Equation (3), A/C , is independent of τ and proportional to the scintillation efficiency or total number of scintillation photons produced.

In our apparatus we may conveniently change the value of the anode resistance R so that the conditions of Equation (3) may be tested. All of the peak pulse-heights reported are integrated pulse-heights, independent of τ .

Twelve samples of pure (unactivated) alkali halides were obtained in crystalline form from two commercial suppliers. Ten of these were from one supplier, Harshaw Chemical Company, Cleveland, Ohio, and were selected from the cones of the ingots where maximum purity is obtained. The other materials were obtained from Semi-Elements, Inc., Saxonburg, Pennsylvania. The twelve alkali halides include:

lithium fluoride	(H)
sodium fluoride	(H)
sodium chloride	(H)
potassium chloride	(H)

potassium bromide	(H)
rubidium bromide	(S)
caesium bromide	(H)
lithium iodide	(H)
sodium iodide	(H)
potassium iodide	(H)
rubidium iodide	(S)
caesium iodide	(S) (H)

The symbols (H) and (S) indicate the material source. Note that caesium iodide samples were obtained from both suppliers.

The Harshaw Chemical Company supplied a qualitative spectrographic analysis of their samples. The most significant impurity noted is a "very faint trace" of thallium in one caesium iodide crystal—henceforth to be called CsI'. The other CsI sample from Harshaw did not have a detectable amount of thallium. No analysis was obtained on the samples from Semi-Elements; however, the suppliers claimed that the CsI had no detectable thallium impurity.

The 1/2-in diam., 3/16-in thick crystals were polished and fitted into the dewar sample-holder. Very hygroscopic crystals were protected with a thin film of glycerol which was found to have no detectable influence on the measured intensity at any temperature.

III. Experimental results

TEMPERATURE DEPENDENCE OF SCINTILLATION INTENSITIES AND TIME-CONSTANTS

Before the discussion of the data, a general summary may be made. All of the unactivated alkali iodides scintillated with good efficiencies at the low temperatures. Around 4° K, KBr and NaCl showed detectable scintillation which was 10 to 20 times lower than that of the iodides. CsBr was examined only to 77° K and the scintillation intensity was found to be considerably lower than that of the iodides. No detectable scintillation was observed from LiF, NaF, KCl, or RbBr.

Figs. 2 to 5 show the temperature-dependence from 4° K to 300° K of the alpha-particle, excited luminescence-intensity and decay-constant for those samples which exhibited detectable luminescence. The luminescence-intensity is the integrated peak pulse-height which, as mentioned previously, is independent of the decay-constant and is directly proportional to the total number of luminescent photons produced by the excitation particle (see Equation 2). These peak pulse-heights are readable to about $\pm 5\%$. Decay-times were determined by the method described in the discussion of Equation (3). These values are readable to about $\pm 5\%$.

The pulse-height scale on the Figures is in arbitrary units which are relatively exact from Figure to Figure. The limit of detectability is 0.01 units on this scale. This is the dark-noise pulse-height of the multiplier phototube. A relative value of the detectability of this system can be assessed by noting that the pulse-height of thallium-activated sodium iodide at room temperature is equivalent to 0.25 units on this intensity scale. Since the readability of this detection system is 1/25 of NaI(Tl), this is equivalent to detecting materials which have about 0.5% luminescence efficiency.*

* The absolute luminescence efficiency of NaI(Tl) has been determined by Van Sciver to be 13% for alpha particles.

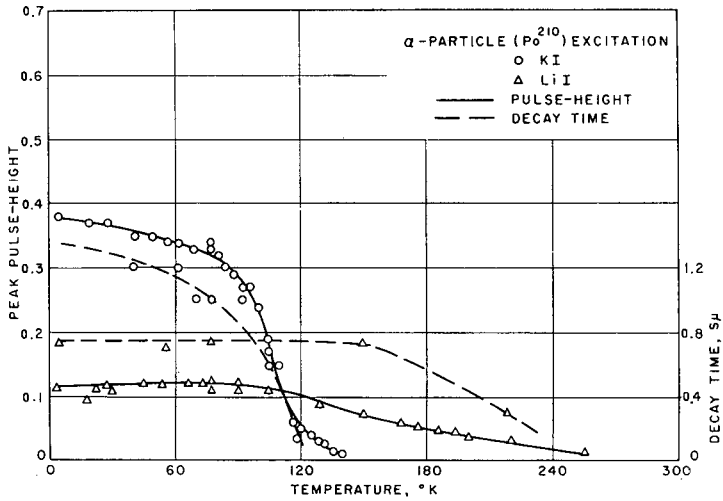


Fig. 2

Scintillation pulse-heights and pulse decay-times as a function of temperature

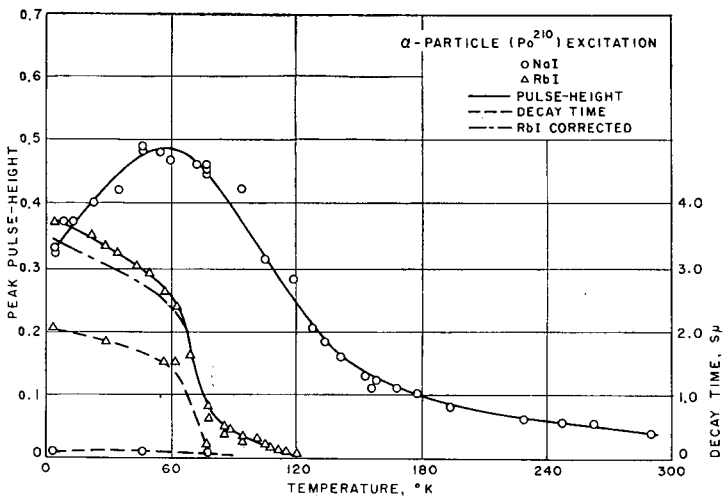


Fig. 3

Scintillation pulse-heights and pulse decay-times as a function of temperature

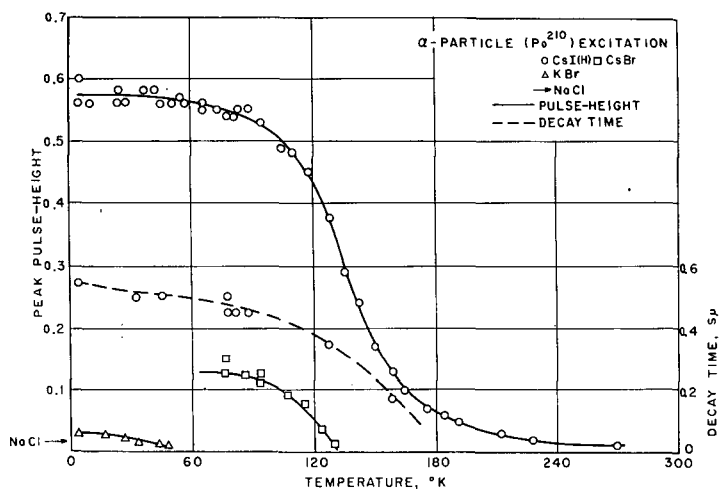


Fig. 4

Scintillation pulse-heights and pulse decay-times as a function of temperature

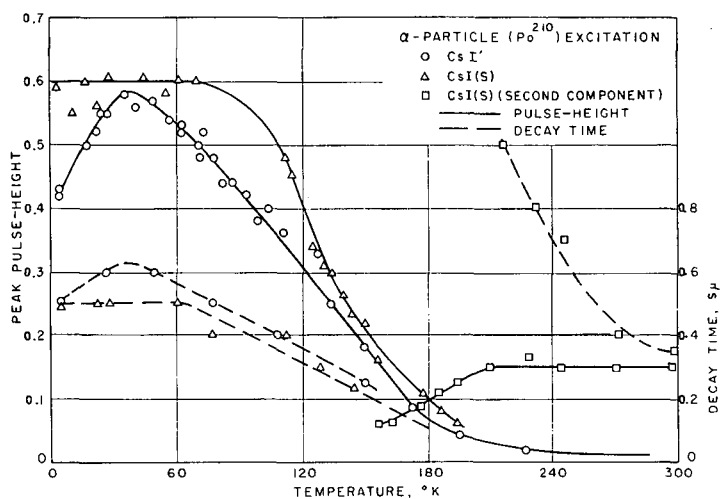


Fig. 5

Scintillation pulse-heights and pulse decay-times as a function of temperature

In Fig. 2 the luminescence behaviours of KI and LiI are shown; in Fig. 3, NaI and RbI data are plotted; and CsI data are given in Fig. 4. The CsI sample shown in Fig. 4 is the Harshaw sample which had no detectable thallium content. All of these iodides scintillate well at low temperatures and all except NaI tend to saturate or slowly increase in intensity as the temperature decreases. Sodium iodide, however, exhibits a maximum in pulse-height at a temperature of about 60° K. The luminescent decay-constants at the lower temperatures are in the range of 0.5 to 2.0 μ s, except for NaI whose pulse decay-time-constant is less than 0.1 μ s. In general, the shape of the decay-constant versus temperature-curve is similar to the intensity-versus-temperature curve.

Also indicated on Fig. 4 are the data of CsBr, KBr, and NaCl. Caesium bromide data were only obtained down to 77° K. Of the non-iodides, this sample exhibited the most efficient scintillation. Potassium bromide's emission was only detectable below 50° K; and at 4° K, the NaCl sample gave a distinguishable scintillation-pulse about twice the noise-pulse height. Because of the low signal-to-noise ratio with KBr and NaCl, pulse decay-times were not accurately determinable, but the decay-times were in the microsecond range. CsBr had a decay-time of 3.5 μ s at 77° K which decreased with the pulse-height as the temperature increased.

On Fig. 5 there are plotted the data from the two other CsI samples which were examined. As mentioned previously, one of these has a very faint trace of thallium in it (CsI') and the other has no detectable thallium, but it was obtained from a different supplier (CsI(S)). The sample with thallium exhibited a much different temperature behaviour. The slope of the intensity-versus-temperature curve in the region of 60° K to 180° K is more gradual than that for "pure" CsI, and there is a maximum in the curve at about 40° K. The decay-constant curve shows a similar shape.

The CsI(S) sample behaves differently from either of the other two samples. At temperatures below 180° K, the luminescent intensity and decay-constant curves are nearly identical to the CsI(H) sample. Below 60° K, however, both the intensity and decay-constant curves are flatter for CsI(S) than for CsI(H) and may actually be decreasing slightly. A more prominent difference between the two non-thallium containing samples occurs in the temperature region above 180° K. There is a distinctly different luminescent component in the CsI(S) sample in this temperature region. The decay-constant of this second luminescent component increases very rapidly below 210° K and finally becomes so large that the measured peak-pulse-height is no longer an integrated pulse-height and thus shows a decrease as the decay-constant increases. When corrections are made for this effect, the integrated intensity does appear to be constant with temperature. As the temperature decreases, the low-temperature component becomes more prominent and completely masks the long decay component.

The above described behaviour of luminescence of caesium iodide is exactly that reported by Knoepfel *et al.* [5] for a temperature-quenched pure CsI sample. Further experiments are being performed on these CsI samples.

SPECTRAL DISTRIBUTION OF EMISSION

Gross spectral distribution was measured with filters to determine whether there are any large changes in emission spectra which would affect the multiplier phototube response and thus the measured pulse-height. The multiplier phototube response extends from 200 m μ to 650 m μ . The first filter used was transparent to all wavelengths greater than 360 m μ , the second to all wavelengths greater than 530 m μ . In all cases, no scintillation emission was observed above 530 m μ . The emission spectra of LiI, KI,

and the CsI samples, as well as they could be defined between the two spectral regions, did not change significantly between 4° K and 77° K. In RbI, however, the spectral emission was observed to shift to the region below 360 m μ as the temperature increased. Since the multiplier phototube relative response is known to be lower in this region than in the 360 m μ < λ < 530 m μ , a "true" intensity at 4° K relative to that at 77° K may be calculated. This correction is indicated on Fig. 3.

The emission of NaI shifted slightly to the region below 360 m μ as the temperature increased. However, the shift is too slight to be shown on Fig. 3. Examination of the spectral emission of NaI also showed a component emitting in the region 360 m μ < λ < 530 m μ which had a decay-time of about 1.5 μ s. This component was undetectable with an unfiltered pulse since the shorter component is about eight times more intense than the longer.

SCINTILLATION EXCITED BY HIGH-ENERGY ELECTRONS

The data presented in the preceding Figures are for α -excited scintillation only. The Compton and photo-electric electrons produced by a cobalt-60 gamma-ray source were also used to excite scintillation. The high-energy electrons produced by this source have a maximum energy of 1.33 MeV. The energy loss of one MeV suffered by the α -particle in passing through the aluminized mylar reflector leaves 4.3 MeV α -particles to excite the crystal. The intensity ratio of α to β -excited scintillation per unit excitation, at 4° K and 77° K, is summarized in Table I.

TABLE I
RATIO OF α -EXCITED TO β -EXCITED SCINTILLATION INTENSITY PER UNIT
EXCITATION ENERGY AT 4° K AND 77° K

Material	4° K	77° K
LiI	0.39 ± 0.04^a	0.39 ± 0.04^a
NaI	0.72 ± 0.07	0.81 ± 0.08
KI	0.74 ± 0.07	0.81 ± 0.08
RbI	0.75 ± 0.07	0.78 ± 0.08
CsI(S)	3.3 ± 0.3	3.5 ± 0.3 $(0.65 \pm 0.06)^b$
CsI(H)	1.0 ± 0.1	1.0 ± 0.1
Cl'	0.91 ± 0.09	0.88 ± 0.09

^a Low ratio due to surface-formation on this hygroscopic crystal.

^b Warm component ratio at 230° K.

If the scintillation efficiency of a given crystal is the same for both α and β -excitation, the intensity ratio per unit excitation would be one. The ratio for lithium iodide is noticeably lower than that for the other materials. This may be due to some surface formation in these extremely hygroscopic materials which inhibits the penetration

of the α -particles. The CsI(S) ratio is much higher than would be expected. There is no obvious explanation for this. In this same material at higher temperatures, the measured values of the room-temperature component are closer to what would be expected.

ANALYSIS OF PULSE SHAPE

According to Equation (2), the observed luminescence pulse should have a time dependence of:

$$V(t) = \frac{A}{C} \left(\frac{RC}{RC - \tau} \right) (e^{-t/RC} - e^{-t/\tau}) \quad (4)$$

Since this equation is derived on the basis of a one-component exponentially decaying pulse, comparison of the calculated pulse-shape to the measured pulse-shape will indicate whether this assumption is valid. A deviation of the measured from the calculated pulse will indicate the presence of either more components and/or a different mode of decay than was assumed.

The pulse shape was calculated for the materials measured here and was then compared to the observed pulse. KI, LiI, and CsI(H) show excellent agreement between the observed and calculated pulse shapes. Both CsI(S) and CsI' exhibit slight deviation from the calculated pulse at the trailing edge.

The pulse from NaI shows considerable deviation from the equation. Undoubtedly this deviation is at least partially due to the long component discussed previously. The fact that there is still some deviation between the observed and calculated pulse after the contribution of the long component has been subtracted from the observed pulse indicates the possible presence of still another component or a different decay mode.

In RbI, there is a considerable deviation between the calculated and observed pulse shapes. Undoubtedly the assumption of an exponentially decaying single-pulse is erroneous. Thus it is apparent that the measured decay-times of both NaI and RbI are only "effective" decay-times resulting from several components or a differing decay mode.

IV. Conclusions

All of the pure alkali iodides scintillate well at low temperatures. The maximum scintillation-efficiency of the iodides range from 10 to 30% as compared to NaI(Tl). CsBr, KBr, and NaCl also have detectable scintillation properties at low temperatures, but with lower efficiencies than the iodides. LiF, NaF, KCl, and RbCl were not observed to scintillate at any temperature. From the known limits of detectability, it is apparent that the efficiency of scintillation of these materials is $\ll 1\%$. There is no apparent correlation between the alkali metal in an alkali halide and the low-temperature scintillation properties.

Table II is a summary of the experimental scintillation measurements for the twelve pure alkali halides.

TABLE II

SUMMARY OF ALKALI HALIDE SCINTILLATION WITH α -PARTICLE EXCITATION

Sample	Inflection Temp. °K	Maximum ^a Scintillation Efficiency (%)	Maximum Decay-Time (μ s)	Number of Pulse Components	Remarks
LiI	100	>8	0.7	1	—
NaI	60*	27	0.1	≥ 2	* emission peak; two components observed directly
KI	90	20	1.3	1	—
RbI	65	20	2.0	>1	—
CsI (H)	115	25	0.55	1	—
CsI (S)	95	30	0.5	1	room temperature component observed
CsI'	40*	27	0.65	≥ 2	* emission peak
KBr	15	1	—	—	—
RbBr	—	—	—	—	^b no detectable scintillation
CsBr	95	5	3.5	—	—
NaCl	35	0.8	—	—	—
KCl	—	—	—	—	^b no detectable scintillation
LiF	—	—	—	—	^b no detectable scintillation
NaF	—	—	—	—	^b no detectable scintillation

^a Calibrated to 13% absolute scintillation efficiency of NaI(Tl) to alpha particles.

^b Minimum detectable luminescences correspond to $\sim 0.4\%$ efficiency.

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DISCUSSION

H. E. Wegner (United States of America): How reproducible is the data for various samples of a given crystal-type in terms of experimental measurements and known purities?

L. Reiffel (United States of America): We have not made a large number of measurements on various crystals, except in the case of caesium iodide, which has the peculiar characteristic observed by Knoepfel of activating upon over-heating. For the caesium iodide case, with Harshaw material, we have found quite good reproducibility as long

as the spectroscopic analysis indicated that the impurity levels were approximately comparable. The over-heated crystals seem to come from Semi-Metals Corporation and spectroscopically they are also quite pure but have apparently passed through some sort of process where over-heating has occurred. For a given family of Harshaw crystals the reproducibility is about 5%, which is also the accuracy of the measurements.

A. Lansiaart (France): Did you see a difference in the amount of light emitted by crystals obtained from the melt and those from the liquid?

L. Reiffel: All the crystals we studied came from the melt—none from the liquid.

A. Lansiaart: Some investigators claim that if the crystalline grid has few dislocations it is possible to obtain more light at low temperature.

L. Reiffel: I have no information on this. The highest absolute efficiency we found was 40%. I think it was a caesium iodide crystal, but I am not sure.

IMPROVED ORGANIC SCINTILLATION DETECTORS

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Abstract — Résumé — Аннотация — Resumen

Improved organic scintillation detectors. Equations have been derived for the practical scintillation efficiency (photo-electrons/MeV) of organic crystals and solutions in terms of molecular parameters and these have been applied to the more important scintillator systems, for photo-multipliers with S11 (glass window) and S13 (quartz window) responses. The results suggest several improvements in current organic scintillation detector practice: the use of binary rather than ternary solutions; the use of quartz rather than glass windows; and the reconsideration of mixed crystal scintillators based on naphthalene. Improvements by factors of 2 or more in the figure of merit (practical efficiency/decay time) for fast-scintillation counting can be obtained.

Possibilités de perfectionnement des détecteurs organiques à scintillations. L'auteur a établi des équations pour déterminer le rendement de scintillation (photoélectrons/MeV) de cristaux et solutions organiques, en faisant intervenir des paramètres moléculaires. Il a appliqué ces équations à des appareils à scintillations plus importantes pour déterminer la réponse des photomultiplicateurs à fenêtre en verre (S11) et à fenêtre en quartz (S13).

Les résultats obtenus ont fait apparaître la possibilité d'améliorer, à plusieurs égards, les détecteurs organiques à scintillations du type courant, par exemple en remplaçant les solutions ternaires par des solutions binaires, les fenêtres en verre par des fenêtres en quartz, ou en réexaminant les possibilités offertes par les scintillateurs à cristaux mixtes à base de naphthalène. L'introduction de ces perfectionnements conduirait à une amélioration, du simple au double ou plus, du facteur de qualité (efficacité/temps de décroissance) des dispositifs de comptage à scintillations.

Усовершенствованные органические сцинтилляционные детекторы. Были выведены уравнения для определения действительной эффективности сцинтилляции (число фотоэлектронов на 1 мэв) органических кристаллов и растворов с точки зрения молекулярных параметров; эти уравнения были применены к более сложным системам сцинтилляторов для фотоумножителей с характеристиками S11 (стеклянное окно) и S13 (кварцевое окно). Результаты указывают на возможность внесения ряда усовершенствований в существующую конструкцию органических сцинтилляционных детекторов, а именно: использование бинарных растворов вместо тройных; использование кварцевого окна вместо стеклянного; пересмотр сцинтилляторов со смешанными кристаллами на основе нафталина. Таким образом можно увеличить вдвое или даже еще больше чувствительность (действительная эффективность, отнесенная ко времени распада) быстро сцинтилляционного счета.

Detectores orgánicos de centelleo perfeccionados. Se han establecido ecuaciones que permiten calcular el rendimiento práctico de centelleo (fotoelectrones/MeV) de los cristales y soluciones orgánicos en función de parámetros moleculares; estas ecuaciones han sido aplicadas a los sistemas de centelleo más importantes, para fotomultiplicadores con respuestas S11 (ventana de vidrio) y S13 (ventana de cuarzo). Los resultados sugieren la posibilidad de perfeccionar de varias maneras los actuales métodos de utilización de detectores orgánicos: empleo de soluciones binarias con preferencia a las ternarias; empleo de ventanas de cuarzo con preferencia a las de vidrio; nueva evaluación de los detectores de cristales mixtos basados en el naftaleno. El índice de calidad (rendimiento práctico/período de caída de la luminiscencia) puede llegar a aumentar al doble para el conteo rápido con detectores de centelleo.

I. Introduction

The design and choice of efficient organic-scintillator systems has to date been largely empirical. An improved understanding of the organic-scintillation process has now made it possible to express scintillation properties in terms of molecular parameters. The present paper summarizes the theory, which is being published in detail elsewhere [1], and applies it to representative organic scintillators.

There are six principal types of organic scintillator:

- (i) Pure crystals;
- (ii) Binary crystal solutions;
- (iii) Binary liquid solutions;
- (iv) Binary plastic solutions;
- (v) Ternary liquid solutions; and
- (vi) Ternary plastic solutions.

Pure liquids and plastics, which like (i) are unitary systems, have a scintillation efficiency which is too low to be of practical interest, while ternary crystal solutions, unlike (v) and (vi), have not yet been considered for scintillation counting.

We shall refer to the solvent (or main constituent), the primary solute and the secondary solute as X, Y and Z respectively. The excitation of scintillations by 1 MeV electrons will be considered. The scintillation response to other ionizing particles of higher dE/dx can be determined therefrom, using the ionization quenching equation [2]. The scintillation process can be divided into two stages:

- (a) The primary process, corresponding to the transfer of energy from the incident radiation to the excitation energy of X; and
- (b) The secondary processes, corresponding to the degradation, migration, transfer, quenching and emission of the molecular excitation energy.

The primary process is similar in all organic-scintillator systems: the secondary processes depend markedly on the molecular properties and relative concentrations of the constituents. Theoretical expressions have been derived for S , the absolute scintillation efficiency, in terms of the molecular properties. The practical scintillation efficiency T , the mean number of photo-electrons ejected from the multiplier photo-cathode due to the incidence of a 1 MeV electron on the scintillator, is determined not only by S but also by m , the degree of match between the scintillator emission spectrum and the photo-cathode spectral response. The figure of merit M of a scintillator for fast counting is given by $M = T/\tau_s$, where τ_s is the scintillation decay-time. Hence S , T and M are all relevant parameters in the comparison of different scintillators.

II. The scintillation process

1. THE PRIMARY PROCESS

The fast-scintillation component arises from the direct excitation of π -electrons of X by the ionizing radiation. Excitation or ionization of π -electrons does not result in fluorescence, while the slow scintillation component associated with the ion recombination following π -electron ionization will not be considered here [3]. The efficiency of the π -excitation process is denoted by P , and the mean π -excitation energy of X by E_{ex} .

It has been proposed on theoretical and experimental grounds [1] that, for an unsubstituted aromatic hydrocarbon molecule,

- (a) the relative probabilities of excitation and ionization are approximately 2:1 [4], and
- (b) each electron has the same total excitation and ionization cross-section for 1 MeV electrons.

Hence

$$P = 2/3 F_x \quad (1)$$

where F_x is the fraction of electrons in the unexcited molecule which are in π -states (2 per double bond, 4 per triple bond). Since $F_x \sim 0.15$ for most polycyclic molecules of interest (e.g. benzene, naphthalene, anthracene, terphenyl, stilbene etc.), we obtain

$$P \sim 0.1 \quad (2)$$

Analysis of data on the alkyl benzene solvents [5] [1] indicates that (2) is also valid for substituted hydrocarbons, i.e. 10% of the incident energy is in general expended in the π -excitation of X.

The mean primary π -excitation energy has been shown, from an analysis of the π -electronic absorption spectra, to be given by

$$E_{ex} \sim 1.5 E_{1x} \quad (3)$$

where E_{1x} is the energy of the 1st π -singlet excitation state of X. The absolute scintillation efficiency

$$S = PQ \quad (4)$$

where Q is the efficiency of the secondary processes.

2. THE SECONDARY PROCESSES

Internal conversion

E_{ex} is internally converted with unit quantum efficiency to E_{1x} , so that the energy efficiency of this process is

$$C = E_{1x}/E_{ex} \sim 2/3. \quad (5)$$

Pure crystals

The molecular fluorescence quantum efficiency of X is

$$q_{0x} = \frac{k_{fx}}{k_{fx} + k_{ix}} \quad (6)$$

where k_{fx} and k_{ix} are the rate parameters of emission and internal quenching respectively.

The technical (thick crystal) fluorescence quantum efficiency of X is reduced by self-absorption [6] to

$$q_{px} = \frac{(1 - a_{xx}) q_{0x}}{1 - a_{xx} q_{0x}} \quad (7)$$

where a_{xx} is the probability of re-absorption of the emission within the crystal. Photons of mean energy E_{px} are emitted, so that

$$Q_x = C \frac{E_{px}}{E_{1x}} q_{px}. \quad (8)$$

Binary solutions

In this case the excitation energy E_{1x} of X is transferred radiatively and/or non-radiatively to Y, with a transfer quantum efficiency f_{xy} , where it is degraded thermally to the 1st π -singlet excitation energy E_{1y} of Y,

$$f_{xy} = \frac{a_{xy} q_{0x} + o_{xy}[Y]}{1 + o_{xy}[Y]} \quad (9)$$

where

$$o_{xy} = \frac{k_{txy}}{k_{fx} + k_{ix}} \quad (10)$$

and a_{xy} is the probability of absorption by Y of the emission by X, $[Y]$ is the mole fraction of Y, and k_{txy} $[Y]$ is the rate parameter of non-radiative transfer.

The fluorescence quantum efficiency q_{0y} of Y is given by an equation similar to (6) (self-absorption being negligible, i.e. $a_{yy} = 0$). Photons of mean energy E_{0y} are emitted, so that

$$Q_y = C \frac{E_{0y}}{E_{1x}} f_{xy} q_{0y} \quad (11)$$

Ternary solutions

In this case E_{1y} is transferred to Z, with a transfer quantum efficiency f_{yz} , where it is degraded thermally to the 1st π -singlet excitation energy E_{1z} of Z. f_{yz} is given by a relation similar to (9). Photons of mean energy E_{0z} are emitted with a fluorescence quantum efficiency q_{0z} , given by an equation similar to (6), so that

$$Q_z = C \frac{E_{0z}}{E_{1x}} f_{xy} f_{yz} q_{0z} \quad (12)$$

III. The scintillation efficiency

Absolute efficiency

The absolute scintillation efficiencies S_x , S_y and S_z of unitary, binary and ternary scintillator systems are given by (4) and (2) in conjunction with (8), (11) and (12) respectively.

The number of fluorescence photons N produced by a 1-MeV electron are hence

$$\text{Pure crystal:} \quad N_x \sim \frac{2}{3} \frac{q_{px}}{E_{1x}} \times 10^5 \quad (13)$$

$$\text{Binary solution:} \quad N_y \sim \frac{2}{3} f_{xy} \frac{q_{0y}}{E_{1x}} \times 10^5 \quad (14)$$

$$\text{Ternary solution:} \quad N_z \sim \frac{2}{3} f_{xy} \frac{f_{yz} q_{0z}}{E_{1x}} \times 10^5 \quad (15)$$

Practical efficiency

The practical efficiency of a scintillator-photomultiplier system is determined by T , the number of photo-electrons liberated by the incidence of N photons.

$$\begin{aligned} T &= NL \frac{\int I(\nu) \eta(\nu) d\nu}{\int I(\nu) d\nu} \\ &= NLm \end{aligned} \quad (16)$$

where L is the maximum photo-electric quantum efficiency of the cathode, $\eta(\nu)$ its relative value at frequency ν , and $I(\nu)$ the relative quantum intensity of the emission at ν . m is a dimensionless spectral matching factor [7] between 0 and 1.

L and $\eta(\nu)$ for commercial photomultipliers of the same nominal type vary within relatively wide limits. For comparison of different scintillators m has been evaluated for two particular spectral responses:

- (i) m_v for the typical S11 response of an Sb-Cs cathode on a glass window, proposed by SWANK *et al.* [7] as a comparison standard; and
- (ii) m_u for a similar cathode deposited on a fused quartz window, where η is independent of wavelength λ from the peak down to 300 m μ [26].

A value of $L = 0.1$ has been taken.

V. Comparison of scintillators

The theoretical values of S and N have been evaluated for a number of the more important scintillators using experimental data for the molecular parameters. The matching factors m_v and m_u have been evaluated from the spectral data, and the corresponding values of the practical efficiencies T_v and T_u have thus been obtained. The results are summarized in Tables I, II and III.

V. Discussion

COMPARISON WITH EXPERIMENTAL DATA

The theoretical value of $S_x = 0.034$ for anthracene agrees reasonably with the experimental values of 0.035 [21] and 0.038 [22]. The relative theoretical values of T_v for different scintillators observed with an S11 photo-cathode agree satisfactorily with the accepted experimental values, allowing for differences in spectral response and considering the approximations made in estimating P and C .

CHOICE OF AN ORGANIC SCINTILLATOR AND PHOTOMULTIPLIER

The results reveal significant features, some of which have not been previously appreciated and which suggest desirable changes in current organic scintillation counter practice.

TABLE I
PURE CRYSTALS

Compound	E_{ix} (eV)	q_{px}	S_x	N_x (10^3)	m_v	m_u	T_{xv} (10^3)	T_{xu} (10^2)	Refs. to mol. data
anthracene	3.15	0.62	0.034	13.0	0.77	0.77	10.0	10.0	[8, 9, 11]
p-terphenyl	3.53	0.40	0.023	7.4	0.81	1.00	6.0	7.4	[8—11]
trans-stilbene	3.43	0.50	0.030	9.5	0.78	1.00	7.4	9.5	[8—11]

TABLE II
BINARY SOLUTIONS

Solvent	Solute	E_{ix} (eV)	f_{xy}	q_{0y}	$f_{xy} q_{0y}$	S_y	N_y (10^3)	m_v	m_u	T_{yv} (10^2)	T_{yu} (10^2)	Refs. to mol. data
toluene	TP (5g/l)	4.57	0.88	0.75	0.66	0.032	9.3	0.59	1.00	5.5	9.3	[12—14] [7]
toluene	PPO (5g/l)	4.57	—	—	0.56	0.025	7.7	0.83	0.96	6.3	7.4	[12] [7]
toluene	BPO (5g/l)	4.57	—	—	0.62	0.025	8.7	0.86	0.90	7.4	7.9	[12] [7]
polystyrene	TPB (20g/l)	4.25	0.54	0.49	0.27	0.011	4.0	0.90	0.91	3.6	3.6	[17—19]
	TP (36g/l)	4.25	0.66	0.73	0.49	0.025	7.2	0.60	1.00	3.0	5.0	[19] [20]
naphthalene	anthracene (1g/l)	3.68	1.0	0.9	0.9	0.047	16.0	0.92	0.96	14.7	15.3	[3] [8] [15] [16]

TABLE III
TERNARY SOLUTIONS

Solvent	Primary solute	Secondary solute	$f_{yz} q_{0z}$	S_z	N_z (10^3)	m_v	m_u	T_{zv} (10^2)	T_{zu} (10^2)	Ref. to mol. data
toluene	TP (5g/l)	POPOP (0.5g/l)	0.73	0.025	9.0	0.87	0.90	7.9	8.1	Table II and [7]
Polystyrene	TP (36g/l)	POPOP (0.5g/l)	0.73	0.020	7.2	0.87	0.90	6.3	6.5	Table II and [7]

(1) The use of photomultiplier tubes with fused quartz windows is to be generally recommended. Except with anthracene and solutes chosen specifically to match the S11 response (POPOP, BPO, TPB) there is always a significant increase in T in changing from a glass to a quartz window. No improvement is to be expected with NaI(Tl), whose emission matches well the S11 response.

(2) The addition of secondary solutes as wavelength-shifters is inefficient, unless one is restricted to glass-windowed photomultipliers, or unless a very large scintillator volume is being used, where it is necessary to eliminate self-absorption effects. Binary liquid and plastic solutions of p-terphenyl used with a quartz-windowed photomultiplier are to be recommended for all normal applications.

(3) When organic scintillators are used in fast-detector systems the figure of merit of the scintillator $M = T/\tau_s$, where τ_s is the scintillation decay-time. M is proportional to the inverse of the mean time required for the ejection of the first n photo-electrons from the cathode by the scintillation. The values of τ_s [23], T_v/τ_s and T_u/τ_s for the more efficient scintillators are compared in Table IV. In view of the improvements in M resulting from the use of a quartz-windowed photomultiplier, it is fortunate that multipliers, combining small electron-transit-time variance with a quartz window, are commercially available.

TABLE IV
FIGURE OF MERIT $M = T/\tau_s$

Scintillator	τ_s (ns)	T_v/τ_s (10^{-9} s $^{-1}$)	T_u/τ_s (10^{-9} s $^{-1}$)
Anthracene	28	0.36	0.36
p-terphenyl	4.5	1.3	1.7
Stilbene	≤ 3.0	≥ 2.5	≥ 3.2
TP (5g/l) in toluene	2.2	2.5	4.2
TP (36g/l) in polystyrene	2.2	1.4	2.3
TP (5g/l) + POPOP (0.5g/l) in toluene	~ 2.2	~ 3.6	~ 3.7
TP (36g/l) + POPOP (0.5 g/l) in polystyrene	3.5	1.8	1.9
Anthracene (1g/l) in naphthalene	~ 6.4	~ 2.3	~ 2.4
Y (1g/l) in naphthalene	2.2	6.0	6.2

IMPROVED ORGANIC SCINTILLATORS

Apart from the utilization of quartz-windowed tubes, the results suggest some promising approaches to improved organic scintillators.

The mixed crystal scintillator, anthracene in naphthalene [24], offers the possibility of a major increase in efficiency over all current organic scintillators, if the required concentration of 1 g/l can be realized and self-absorption is not excessive. The advantages of the crystal solution compared with a liquid or plastic solution are threefold.

- (i) f_{xy} reaches unity at much lower $[Y]$ in crystals, because of the high exciton mobility. Hence the solute self-absorption and self-quenching effects should be reduced, compared with liquid or plastic solutions.
- (ii) Naphthalene has a smaller value of E_{1x} than any of the liquid or plastic solvents in current use, so that N_y (Equation 14) is increased.
- (iii) The self-absorption of anthracene is much less than in the pure crystal so that $q_{px} = 0.62$ is increased towards $q_{oy} = 0.9$.

Should the anthracene self-absorption still prove excessive there is a wide choice of other organic fluors of high q_{oy} and lower self-absorption that can be considered as alternative solutes. The predicted properties of a mixed crystal containing a hypothetical solute Y, with $q_{oy} = 0.8$, $\tau_s = 2.2$ ns, and an emission spectrum similar to that of anthracene, are included in Table IV.

The approach towards improved liquid and plastic solutions is indicated by Equations (14) and (15). The solvent factor is $f_{xy}/E_{1x} \cdot f_{xy}$ can be optimized for both radiative and non-radiative transfer by matching the spectra of the solvent emission and solute absorption and many of the systems arrived at empirically approach this criterion. It is suggested that this method be used directly in "screening" potential solvent-solute combinations. The solute must also possess a high q_{oy} . The other solvent factor is $1/E_{1x}$ and this can be increased by using larger solvent molecules. p-xylene, which has the smallest E_{1x} of the alkyl benzenes, appears the best of the liquid solvents [5]. A major decrease in E_{1x} is produced by the inclusion of a double-ring (naphthalene) group in the molecule. The efficiency of the technique of adding large quantities (~ 50 g/l) of naphthalene to liquid solutions to increase their efficiency [25] is due to the solvent excitation-energy being transferred readily ($f_{xy} = 1$ at these concentrations) to the naphthalene, which then functions as the effective solvent. Similarly polyvinyl-naphthalene has recently been reported as an improved plastic solvent.

A further possibility that is being explored is the use of "triple-bonded" aromatic compounds. A triple bond corresponds to 4 π -electrons compared with the 2 π -electrons associated with a double bond. The values of F_x for acetylene, phenyl acetylene and diphenyl acetylene are 0.286, 0.185 and 0.17 respectively, compared with 0.149 for anthracene. Hence corresponding increases in P are to be expected from Equation (1).

VI. Conclusion

The quantitative theory of the organic-scintillation process indicates some desirable changes in current practice and suggests some promising approaches towards the development of improved organic scintillators.

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DISCUSSION

M. Burton (United States of America): Two points are worthy of note in regard to energy transfer in liquid scintillator systems. First, there are systems (e.g. with cyclohexane as solvent) for which the evidence indicates that it is *not* excitation from the lowest excited state but ionization which is transferred. In such cases excited molecules decompose before energy can be transferred. Ionization appears to be transferred with a decay time (of the ionized solvent) of < 0.3 ns for all solutes studied. Second, a growing body of evidence indicates that collective excitation of the electronic system of the entire solution must be considered; localization of excitation is determined only in part by electron fraction. Thus, we may anticipate that further development of the theory will require consideration of those factors which determine localization of excitation in the scintillator solute, perhaps without intervention by the solvent.

J. B. Birks (United Kingdom): I should say, however, that my paper is intended as a contribution to actual uses of scintillation counters. Professor Burton referred to cyclohexane, which is of interest to radiation chemists but is not normally used as a solvent in liquid scintillation counters. I agree with him that the radiation chemistry of the initial ionization is a matter for detailed study, but what this paper presents is a simplification based on considering only the direct excitation of the solvent by the ionizing particle and we find that this simplification provides numbers which are in reasonably close agreement with those which have been measured directly. We ignore the 90% of the energy that goes into other processes in the belief that it does not contribute to the fluorescence.

M. Birk (Israel): I should like to ask Dr. Birks whether he could say something about the decay times and the different responses to electrons as compared with heavier particles.

J. B. Birks: Could I ask Mr. Birk whether he is referring to the information given in Table IV of my paper where I considered the figure of merit, the ratio of the practical scintillation efficiency to the decay time?

M. Birk: What I had in mind was the different decay times for different ionizing particles—gamma rays compared with alpha particles.

J. B. Birks: I believe the fact that molecules are ionized is what leads to the slow component in organic scintillators. We have some recent data on this but I have no time to report it now. The slow component is associated with the ionization of the molecules and the subsequent re-combination. What I have been considering in this paper is the fast component associated with the direct excitation of the molecules.

M. Burton: Regarding the comment just made by Dr. Birks I should like to say very definitely that, in certain cases I know, the only component that has any significance involves ionization and the only process in which energy is transferred is the ionization process. This occurs in cyclohexane.

J. B. Birks: My remarks are relevant to π -electron systems and cyclohexane has no π -electrons.

ЖИДКОСТНЫЕ СЦИНТИЛЛЯЦИОННЫЕ ДЕТЕКТОРЫ ДЛЯ РЕГИСТРАЦИИ НЕЙТРОНОВ

И. Визи, Г. П. Жуков, Г. И. Забиякин, Э. Н. Каржавина, Л. Б. Пикельнер, А. Б.

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СССР

Abstract — Résumé — Аннотация — Resumen

Liquid scintillation counters for registering neutrons. One of the main methods employed in slow-neutron spectrometry is the time-of-flight method.

The paper describes two detectors intended for time-of-flight work—a neutron detector for measuring total cross-sections, and a capture gamma-ray detector for measuring radiation-capture cross-sections and self-absorption cross-sections.

The paper also indicates how the detectors are used and the results obtained with them.

Détecteurs à scintillateur liquide pour l'enregistrement du comptage des neutrons. Une des méthodes fondamentales employées dans le spectrométrie des neutrons lents est celle du temps de vol.

Le mémoire décrit deux détecteurs destinés aux recherches à l'aide de la méthode du temps de vol: un détecteur à neutrons pour mesurer les sections efficaces totales, un détecteur à rayons gamma de capture pour mesurer les sections efficaces de capture radiative et les sections efficaces d'auto-absorption.

On indique la méthodologie et les résultats des ces mesures.

Жидкостные сцинтилляционные детекторы для регистрации нейтронов. Одним из основных методов спектрометрии медленных нейтронов является метод времени пролета.

В этой работе описываются два детектора, предназначенные для исследований по времени пролета — нейтронный детектор для измерения полных сечений и детектор захватных гамма-лучей для измерения сечений радиационного захвата и сечений самопоглощения.

Приводятся методика и результаты измерений.

Contadores de centelleador líquido para el registro de neutrones. Uno de los principales métodos de la espectrometría de neutrones lentos es el de la determinación de su tiempo de vuelo.

Los autores describen dos detectores destinados a la determinación del tiempo de vuelo: un detector neutrónico para la medición de secciones eficaces totales y un detector de rayos gamma de captura para la medición de secciones eficaces de captura radiactiva y de secciones eficaces de autoabsorción.

En la memoria se indican, además, los métodos de empleo de los detectores y los resultados con ellos obtenidos.

Одним из основных методов спектрометрии медленных нейтронов является метод времени пролета.

В настоящей работе описываются два детектора, предназначенные для исследований по времени пролета — нейтронный детектор для измерения полных сечений и детектор захватных γ -лучей для измерения сечений радиационного захвата и сечений самопоглощения.

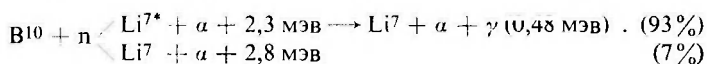
I. Детектор для измерений полных нейтронных сечений

1. Принцип работы и конструкция детектора

К детектору для измерений пропускания предъявляется ряд специфических требований. Детектор должен иметь высокую эффективность к нейтронам,

большую площадь, малое время регистрации и небольшую чувствительность к γ -лучам. При работе на импульсных источниках, имеющих длительность нейтронного импульса $\tau \geq 1$ мсек, в области энергий выше десятков электронвольт наиболее удобным является жидкостной детектор с метилборатом [1]. Ниже излагается устройство и характеристики разработанного нами такого детектора, предназначенного для измерений полных нейтронных сечений.

Нейтроны, попадая в жидкий сцинтиллятор, содержащий метилборат- $B(OCH_3)_3$, замедляются, захватываются ядрами бора, вызывая реакцию



Альфа-частица, образовавшаяся при захвате нейтрона дает световую вспышку в сцинтилляторе, которая улавливается фотоумножителями и преобразуется в электрический импульс, регистрируемый последующими электронными схемами. Трудности разработки такого детектора обусловлены тем, что световые вспышки от α -частиц лежат в области шумовых импульсов ФЭУ. Этот факт приводит к необходимости использовать несколько умножителей и применять схему совпадений для выделения нейтронных импульсов. Вместе с тем приходится принимать ряд мер для повышения светового выхода сцинтиллятора и обеспечения максимального светособирания. (Максимально возможная площадь фотокатодов, высокий коэффициент отражения внутренней поверхности контейнера.)

Для работы на нейтронном пучке нами был изготовлен детектор с четырьмя умножителями ФЭУ-24 (диаметр фотокатодов 80 мм). Общий вид детектора показан на рис. 1. Детектор представляет из себя цилиндр $\varnothing 250$ мм и толщиной 30 мм, на одном из торцов которого укреплены умножители. Внутренние стенки контейнера с помощью краскораспылителя были покрыты отражателем из анатазной формы TiO_2 , смешанной с цапон-лаком (1 ч. — TiO_2 и 1 ч. цапон-лака разводились ацетоном до необходимой вязкости). Для удобства у контейнера сделана съемная крышка, которая после нанесения отражателя приклеивалась особым клеем.



Рис. 1
Общий вид детектора

Способ крепления умножителей показан на рис. 2. Умножители вклеивались в металлический фланец тем же клеем, каким приклеивалась крышка контейнера.

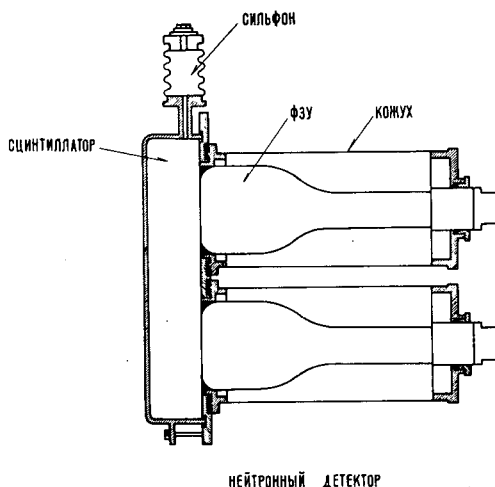


Рис. 2
Схема крепления ФЭУ в контейнере

Состав клея следующий: эпоксидная смола ЭД-6 — 100 частей, дибутилфталат — 20 частей, полиэтиленполиамины — 8 частей. Вместе с фланцем умножитель крепился в светонепроницаемом кожухе и вкручивался в крышку контейнера. Между крышкой контейнера и фланцем помещалась уплотняющая прокладка из фторопласта-4 или резины ФКС-1.

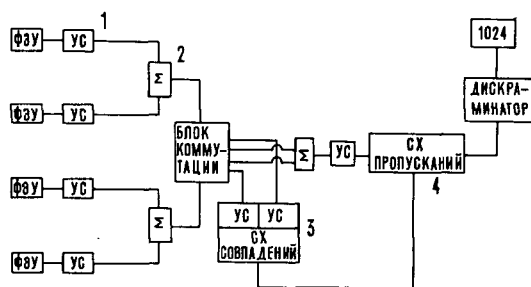
Контейнер и фланцы изготовлены из нержавеющей стали. для компенсации тепловых изменений объема к контейнеру приварены сильфоны.

В работе использовался сцинтиллятор, содержащий 47% метилбората, 31% толуола, 22% нафталина, активированного антраценом, со сцинтиллирующими добавками 4 г/л РРО и 0,5 г/л РОРОР. Такой сцинтиллятор при возбуждении электронами имеет световой выход 50% от стильбена. Чистота метилбората 99,97%. Оптическая однородность детектора проверялась путем засветки различных участков контейнера узким пучком γ -лучей цинка-65. Некоторая неоднородность, не превышающая 35% обнаружена только вблизи цилиндрической стенки контейнера.

2. Блок — схема детектора

На рис. 3 приведена блок-схема установки, которая была собрана из блоков, разработанных в нашей Лаборатории [2]. Предусилители имеют постоянный накал для уменьшения собственного фона, их коэффициент усиления 10. В качестве сумматоров применены анодные повторители. Схема совпадений имеет поканаль-

ную амплитудную формировку на одновибраторах. Разрешающее время схемы совпадений $\tau_p = 0,2$ мксек., мертвое время — 2 мксек. Время нарастания всех усилителей схемы $< 0,1$ мксек. Основной усилитель перед схемой пропускания неперегружающийся с коэффициентом усиления, регулируемым в пределах от 100 до 1000.



БЛОК-СХЕМА НЕЙТРОННОГО ДЕТЕКТОРА

Рис. 3

Блок-схема детектора

1. Усилитель — 2. Сумматор — 3. Схема совпадений
4. Схема пропускания — 5. Дискриминатор

Амплитудный дискриминатор имеет независимо регулируемые нижний и верхний пороги в пределах от 1 до 100 в. каждый. Это дает возможность установить окно дискриминатора любой ширины. Этот же дискриминатор использовался как одноканальный анализатор для снятия амплитудного распределения от нейтронного или γ -источников.

Анодные нагрузки ФЭУ равны 10 ком, что обеспечивает достижение полной амплитуды от быстрой компоненты высвечивания сцинтиллятора ($4 \cdot 10^{-9}$ сек), длительность импульсов при этом около 1 мксек.

Умножители питаются положительным напряжением от высоковольтного выпрямителя ВС-10. Напряжение на каждом ФЭУ подстраивалось так, чтобы коэффициенты умножения всех ФЭУ были одинаковы. Подстройка высокого напряжения производилась по осциллографу с помощью γ -источника. Умножители ФЭУ-24 работали при напряжении 1500—1700 вольт. Это позволило получать на выходе каждого ФЭУ среднюю амплитуду от нейтронов, равную 2 милливольтам.

3. Характеристики детектора

Для оценки эффективности детектора и времени жизни нейтронов были проведены расчеты методом Монте-Карло на машине „Сетунь“ в вычислительном центре МГУ [3]. Расчеты проведены для двух сред сцинтиллятора: с естественным бором и обогащенным. Результаты приведены в таблице I. Эффективность детектора с естественным бором можно выразить формулами:

для детектора толщиной 3 см $\epsilon = 0,90 - 0,19 \lg E_{э6} / \leq E \leq 1000$ эв

для детектора толщиной 4 см $\epsilon = 0,94 - 0,13 \lg E_{э6} / \leq E \leq 100000$ эв

Таблица I

РАСЧЕТНЫЕ ХАРАКТЕРИСТИКИ ДЕТЕКТОРА

Состав А — бор необогащенный, состав Б — обогащенный (80%), ε — эффективность,
 τ — время жизни в мсек.

Е	Состав Характеристика	Толщина слоя детектора см												
		1	2	3	4	5	6	7	8	9	11	13	∞	
100 КэВ	А	ε	0,0108	0,041	0,163	0,264	0,355	0,425	0,505	0,525	0,585	0,625	0,677	
		τ	0,04	2,14	1,03	2,18	2,26	2,20	2,16	2,10	2,10	2,05	2,12	
	Б	ε	0,0077	0,098	0,191	0,315	0,45	0,53	0,61	0,66	0,70	0,723	0,730	0,74
		τ	0,058	0,308	0,30	0,405	0,42	0,423	0,420	0,424	0,425	0,434	0,435	0,433
50 КэВ	А	ε	0,0006	0,066	0,212	0,328	0,43	0,478	0,546	0,574	0,594	0,63	0,66	
		τ	0,8	1,50	1,80	2,02	1,97	1,89	1,93	1,97	1,93	1,90	1,99	
	Б	ε	0,015	0,154	0,286	0,472	0,533	0,66	0,666	0,674	0,695	0,71	0,733	0,74
		τ	0,05	0,35	0,414	0,434	0,432	0,473	0,473	0,475	0,480	0,485	0,485	0,480
10 КэВ	А	ε	0,0175	0,12	0,272	0,420	0,528	0,584	0,635	0,667	0,702	0,718	0,730	
		τ	0,78	1,24	1,81	2,65	2,50	2,34	2,24	2,18	2,14	2,16	2,16	
	Б	ε	0,050	0,215	0,340	0,485	0,586	0,636	0,662	0,686	0,710	0,730		
		τ	0,05	0,287	0,338	0,434	0,447	0,460	0,48	0,48	0,475	0,47		
5 КэВ	А	ε	0,0087	0,178	0,339	0,485	0,574	0,646	0,686	0,695	0,704	0,712	0,726	
		τ	0,81	1,06	1,02	1,59	1,84	1,85	1,88	1,90	1,92	1,93	1,90	
	Б	ε	0,0686	0,216	0,40	0,546	0,635	0,693	0,72	0,734	0,751	0,756	0,764	
		τ	0,156	0,256	0,327	0,404	0,416	0,416	0,431	0,435	0,462	0,460	0,462	
1 КэВ	А	ε	0,0352	0,194	0,367	0,555	0,65	0,706	0,734	0,755	0,77	0,78		
		τ	0,38	1,36	1,57	1,73	1,86	1,92	1,96	2,02	2,03	2,01		
	Б	ε	0,158	0,365	0,523	0,675	0,74	0,775	0,808	0,812	0,82	0,826		
		τ	0,204	0,284	0,384	0,495	0,523	0,523	0,540	0,541	0,542	0,542		
100 эВ	А	ε	0,139	0,362	0,516	0,643	0,740	0,755	0,793	0,806	0,815	0,82		
		τ	0,93	1,39	1,60	1,84	2,33	2,34	2,40	2,39	2,39	2,38		
	Б	ε	0,315	0,61	0,722	0,854	0,902	0,921	0,933	0,935	0,938	0,942		
		τ	0,214	0,361	0,428	0,447	0,523	0,506	0,513	0,514	0,516	0,519		
10 эВ	А	ε	0,285	0,582	0,721	0,827	0,864	0,878	0,887	0,90	0,904			
		τ	0,87	1,58	1,75	1,86	1,99	2,07	2,14	2,20	2,26			
	Б	ε	0,578	0,854	0,94	0,971	0,984	0,984	0,986					
		τ	0,29	0,405	0,456	0,488	0,502	0,502	0,510					
1 эВ	А	ε	0,505	0,777	0,90	0,942	0,956	0,962						
		τ	1,38	2,06	2,38	2,54	2,60	2,62						
	Б	ε	0,836	0,977	0,982	0,989	0,99							
		τ	0,398	0,52	0,541	0,541	0,547							

Работа детектора проверялась на тепловых нейтронах. Источником тепловых нейтронов служил Ро-Ве источник, помещенный в парафиновый куб. Снималось амплитудное распределение импульсов и бралась кадмиевая разность (рис. 4). детектор защищался 5 см свинца от γ -лучей источника и захватного излучения кадмия. Амплитудное распределение от нейтронов имеет форму пика, обуслов-

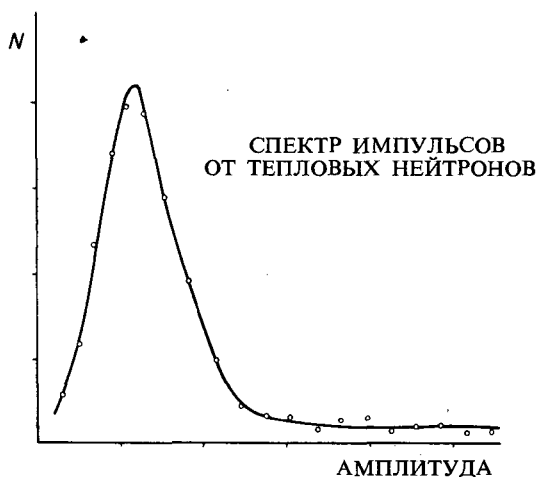


Рис. 4

Спектр импульсов от тепловых нейтронов

ленного импульсами от α -частиц, с „хвостом“ в области больших амплитуд, который вызван регистрацией 480 Кэв γ -квантов, сопровождающих в 93 % случаев реакцию $\text{B}^{10}(\text{n}, \alpha)\text{Li}^7$. Пик от α -частиц имеет полуширину 90 %. Форма пика следует распределению Пуассона, поскольку число первичных фотоэлектронов, вылетающих из фотокатодов ФЭУ, мало. Сравнение пика от α -частиц с распределением Пуассона показывает, что среднее число фотоэлектронов, образующихся на всех ФЭУ, равно 8*. Это не позволяет использовать схему совпадений с числом каналов больше 2, так как в этом случае были бы существенны просчеты импульсов от α -частиц.

Для уменьшения эффективности к γ -лучам окно дискриминатора устанавливалось так, чтобы регистрировались только импульсы, соответствующие пику от α -частиц. При этом не регистрировалась та часть нейтронов, поглощение которых в детекторе сопровождалось комптоновским рассеянием 480 Кэв гамма-лучей, возникающих в реакции $\text{B}^{10}(\text{n}, \alpha)\text{Li}^7$. Возможная доля несчитанных нейтронов определена экспериментально. Были сняты амплитудные спектры от нейтронного источника для разных толщин контейнеров (от 2 до 6 см) и оценена относительная площадь, обусловленная регистрацией 480 Кэв γ -квантов. Было найдено, что она линейно растет с толщиной и определяется формулой

$$\eta = 0,11 + 0,024 d, \text{ где } d$$

* Поскольку число световых квантов от α -частиц достаточно велико, то флуктуации числа квантов малы. В случае хорошей оптической однородности контейнера можно считать потоки световых квантов на каждую пару ФЭУ равными. Тогда число фотоэлектронов на каждой паре ФЭУ будет определяться в основном только флуктуациями квантового выхода фотокатодов и будет распределено по закону Пуассона, по этому же закону будет распределено и полное число фотоэлектронов на всех ФЭУ при регистрации α -частиц. Следовательно амплитудное распределение должно быть пуассоновским.

толщина контейнера в см. Таким образом для оценки можно принять, что эффективность детектора к нейтронам равна

$$\varepsilon = E \text{ расчетное } (1 - \eta)$$

Эффективность детектора к γ -лучам была определена экспериментально и для случая, когда окно дискриминатора установлено на пик от α -частиц, $\varepsilon\gamma = 0,012$ d для γ -квантов с энергией 1 Мэв, (d-толщина контейнера в см.) Поканальная загрузка схемы совпадений от шумов ФЭУ равна $3 \div 5 \cdot 10^3$ имп/сек, что дает $3 \div 10$ имп/сек. случайных совпадений. Благодаря амплитудному отбору на выходе детектора число случайных совпадений в несколько раз меньше.

Было установлено, что собственный фон детектора в основном создает естественное радиоактивное загрязнение помещения. Экранировка детектора с четырех сторон свинцом толщиной 5 см снижает фон детектора в $3 \div 4$ раза. Детектор, помещенный в свинцовую защиту, открытую только вдоль нейтронного пучка имеет фон 22 имп/сек. Такое значение собственного фона вполне приемлемо, поскольку оно составляет 10% от фона при работе с детектором на пучке. В работе детектор показал себя надежным и стабильным. Нестабильность эффективности детектора, за 15 дней не превышает 3%.

Детектор установлен на 1000-метровой пролетной базе нейтронного спектрометра по времени пролета, использующего в качестве источника нейтронов импульсный реактор на быстрых нейтронах ОИЯИ [4]. На рис. 5 приведена полученная с этим детектором кривая пропускания для образца серебра толщиной 1 мм. Статистическая ошибка пропускания меньше 4%.

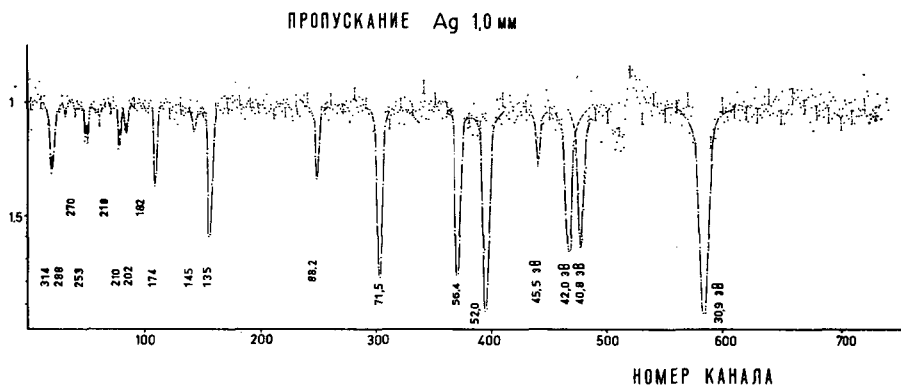


Рис. 5
Пропускание серебра толщиной 1 мм

II. Сцинтилляционный (n, γ) детектор

Сцинтилляционный (n, γ) детектор предназначен для регистрации гамма-лучей, возникающих при радиационном захвате нейтронов, в исследованиях по спектроскопии медленных нейтронов методом времени пролета.

Детектор состоит из двух дюралевых баков диаметром 800 мм и длиной 400 мм каждый с внутренним каналом диаметром 220 мм. Баки заполнены сцин-

тиллятором следующего состава: толуол, пара — терфенил (3 г/л, РОРОР/0,1 г/л). Общее количество сцинтиллятора в обоих баках — около 400 л. На внутреннюю поверхность баков нанесен отражатель на основе двуокиси титана TiO_2 .

Каждый бак просматривается с торца четырьмя фотоумножителями ФЭУ-49, находящимися в непосредственном контакте со сцинтиллятором. Герметичность обеспечивается клеей ФЭУ в дюралевые кожухи на эпоксидной смоле и применением в качестве прокладок специальной резины марки ФКС-1, стойкой к органическим растворителям.

Фотоумножители ФЭУ-49 имеют диаметр фотокатода 150 мм и амплитудное разрешение с кристаллом NaI (Tl) диаметром 35 мм 10—14% для гамма-линии Cs^{137} .

Схема экспериментальной установки приведена на рис. 6. Импульсы с четырех ФЭУ, просматривающих каждый бак, суммируются, усиливаются и через дискриминатор подаются на медленную схему совпадений с разрешающим временем 0,3 мксек. Одновременно импульсы после сумматоров поступают на быструю схему совпадений с разрешающим временем 0,1 мксек, которая подает открывающий импульс на схему пропускания. Проходящий импульс с медленной схемы совпадений подается на временной анализатор. Вся использованная электронная аппаратура разработана и изготовлена в Лаборатории нейтронной физики [2].

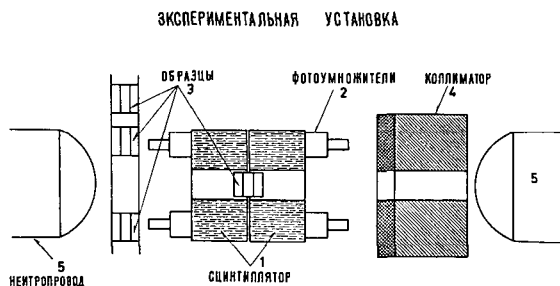


Рис. 6

Схема экспериментальной установки

1. Сцинтиллятор — 2. Фотоумножители — 3. Образцы
4. Коллиматор — 5. Нейтропровод

Применение двух баков в детекторе и схемы совпадений связано с наличием значительного фона установки, обусловленного главным образом космическим излучением и естественной радиоактивностью. Суммарный фоновый счет двух баков при пороге дискриминации около 0,5 Мэв составлял 5000 имп/сек. Введение схемы совпадений существенно снизило фон, который составлял при том же пороге около 50 имп/сек. Одновременно использование схемы совпадений позволяет значительно уменьшить чувствительность детектора к рассеянным нейтронам, которые при захвате на водороде в сцинтилляторе дают гамма-кванты с энергией 2,2 Мэв. Для устранения совпадений за счет комптоновского рассеяния из одного бака в другой, между баками был поставлен свинцовый экран толщиной 2 см.

Для оценки эффективности детектора были проделаны измерения с источником Co^{60} известной активности. Эффективность регистрации двухквантового распада

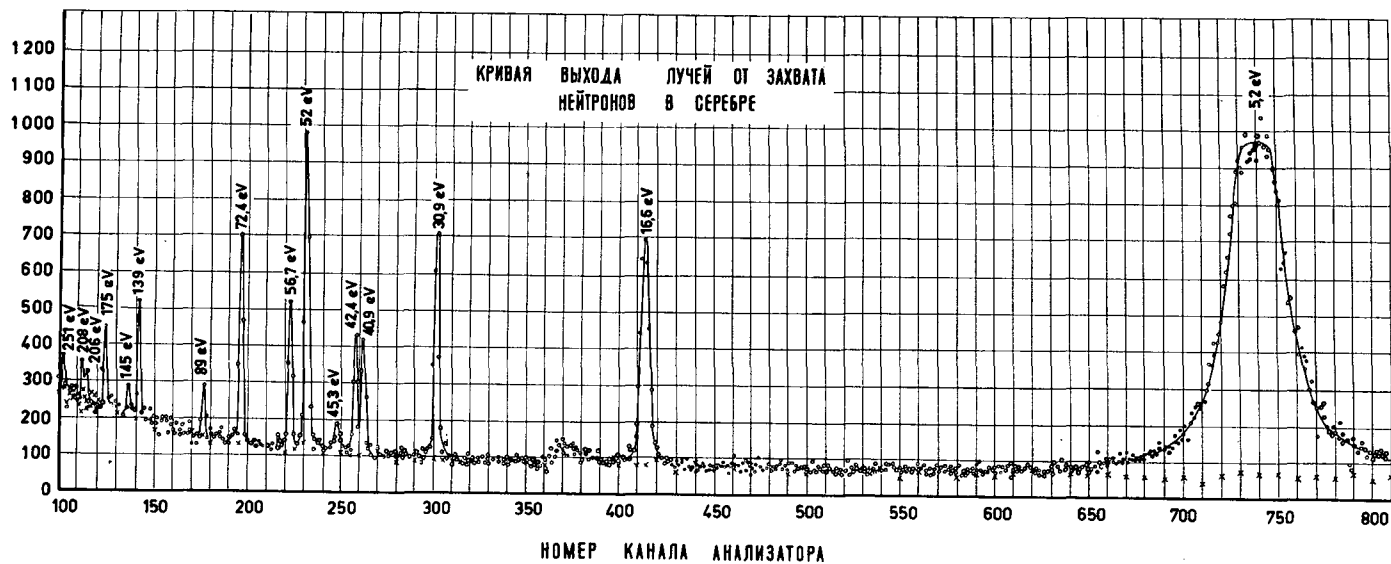


Рис. 7

Кривая выхода гамма-лучей от захвата нейтронов в серебре

Co^{60} (энергия гамма-квантов 1,17 и 1,33 Мэв) при использовании схемы совпадений оказалась равной 20% при пороге дискриминации 200 Кэв и помещении источника между баками в центре канала. При радиационном захвате нейтрона испускается несколько квантов с общей энергией 5—8 Мэв, поэтому эффективность детектора будет больше указанной и, вообще говоря, будет зависеть от характера гамма-переходов составного ядра.

Описанный выше детектор был использован в установке Объединенного института ядерных исследований для спектроскопии нейтронов методом времени пролета [4]. На рис. 7. для примера приведена резонансная кривая, полученная с 1024-канальным временным анализатором [5] при пролетном расстоянии 750 м. В качестве образца использовалась серебряная фольга толщиной $5 \cdot 10^{20}$ яд/см и площадью 240 см², расположенная в канале детектора перпендикулярно пучку нейтронов. Крестиками отмечен уровень фона в отсутствии образца.

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ГАЗОВЫЙ СЦИНТИЛЛЯЦИОННЫЙ СЧЕТЧИК, НАПОЛНЕННЫЙ He^3 ДЛЯ СПЕКТРОМЕТРИИ ПОТОКОВ НЕЙТРОНОВ

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СССР

Abstract — Résumé — Аннотация — Resumen

A gaseous scintillation counter filled with He^3 for neutron spectrometry. The paper describes a gas plant and gaseous scintillation counter, and gives the results of experiments on the recording and spectrometry of neutron beams using a gaseous scintillation counter filled with a mixture of 10% xenene and 90% helium-3 at an overall pressure of 20 ata. Data are given on the design of the gas plant, which makes it possible to operate the counter continuously over long periods of time, as well as providing the required gas mixtures at overall pressures of up to 60 atm and ensuring constant freedom of the gas from contamination. In addition, the paper presents the results of research on the counter's energy resolution and linearity at different energy levels and indicates its efficiency in gamma fields of intensity up to 3 r/h; the possibility of extending the working energy-range of gaseous scintillation counters filled with helium-3 is also considered.

Compteur à scintillateur gazeux rempli de ^3He pour la spectrométrie des flux de neutrons. Les auteurs décrivent un compteur à scintillateur gazeux ainsi que les résultats des expériences d'enregistrement et de spectrométrie des flux de neutrons qui ont été faites au moyen d'un compteur à scintillateur gazeux rempli d'un mélange de 10% de xénon et de 90% d'hélium-3 sous une pression de 20 atmosphères. Ils exposent les données relatives à la construction d'un appareillage qui assure le fonctionnement ininterrompu du compteur durant un laps de temps prolongé, l'obtention des mélanges de gaz indispensables sous une pression totale de 60 atmosphères et l'épuration continue du gaz. En outre, ils examinent les résultats de l'étude du pouvoir de résolution en énergie et de la linéarité du compteur en fonction de l'énergie, le fonctionnement du compteur dans les champs de rayonnement gamma d'une intensité allant jusqu'à 3 r/h, ainsi que la possibilité d'élargir la gamme d'énergie dans laquelle on peut employer des compteurs à scintillateurs gazeux de ^3He .

Газовый сцинтилляционный счетчик наполненный He^3 для спектрометрии потоков нейтронов. В докладе описывается газовый агрегат, газовый сцинтилляционный счетчик, а также результаты экспериментов по регистрации и спектрометрии потоков нейтронов при помощи газового сцинтилляционного счетчика, наполненного смесью 10% ксенона и 90% гелия-3, при общем давлении 20 ата. Приводятся данные об устройстве газового агрегата, обеспечивающего непрерывную работу счетчика в течение длительного времени, получение необходимых смесей газов с общим давлением до 60 атм, и постоянную очистку газа от загрязнений. Кроме того в докладе обсуждаются результаты исследования энергетического разрешения и линейности счетчика по энергии, его работоспособность в гамма-полях мощностью до 3 р/час, а также вопросы, связанные с возможностью расширения энергетического диапазона работы газовых сцинтилляционных счетчиков, наполненных гелием-3.

Contador de centelleador gaseoso cargado con helio-3 para la espectrometría neutrónica. En esta memoria se describe un aparato de suministro de gas y un contador de centelleador gaseoso, y se exponen los resultados de experimentos sobre el registro y la espectrometría de flujos neutrónicos realizados mediante ese contador cargado con una mezcla de 10 por ciento de xenón y 9 por ciento de helio-3 a una presión de 20 atm. abs. Se proporcionan datos sobre la construcción del aparato de suministro que asegura el funcionamiento ininterrumpido del

contador durante largo tiempo, proporciona las mezclas de gases necesarias a una presión de 60 atmósferas y permite proceder a una purificación continua del gas. Se examinan, además, los resultados del estudio del poder de resolución energética y la linealidad del contador en función de la energía, su rendimiento con intensidades en campos gamma de hasta 3 roentgens/h, y algunas cuestiones relacionadas con la posibilidad de ampliar el intervalo energético en el que pueden aplicarse los contadores de centelleador gaseoso cargados con helio-3.

Вопрос регистрации и спектрометрирования потоков нейтронов, особенно в условиях мощных гамма-полей, продолжает оставаться одной из сложнейших проблем исследования ядерных излучений. Хотя потребность в приборах, позволяющих не только регистрировать, но и определять энергетический спектр нейтронного излучения, постоянно растет и к решению этой задачи направлены усилия многих исследователей, тем не менее она до сих пор не имеет окончательного решения.

Одним из перспективных направлений в этой области, до последнего времени не нашедшего достаточного развития, являются газовые сцинтилляционные счетчики.

Прогресс в области газовых сцинтилляционных счетчиков стал возможен благодаря многочисленным работам, посвященным исследованию сцинтилляции в чистых газах и газовых смесях (напр. [1—7]). В этих работах были выяснены основные условия необходимые для работы газовых сцинтилляционных счетчиков. Исходя из этих требований, были построены газовые сцинтилляционные камеры, при помощи которых были проведены исследования по применению счетчиков для регистрации α -частиц и осколков деления.

В настоящее время можно считать решенными вопросы регистрации осколков деления и спектрометрии α -частиц газовыми сцинтилляционными счетчиками в лабораторных условиях с разрешением 5—7%.

Однако использование газового сцинтилляционного счетчика наполненного легким изотопом He^3 , который должен позволить определять энергетический спектр нейтронов, до сих пор является малоисследованным вопросом.

Настоящая статья посвящена описанию экспериментов по регистрации нейтронов с помощью установки наполненной изотопом He^3 , результатом исследования ее работоспособности в мощных γ -полях, а также рассмотрению некоторых вопросов, связанных с возможным расширением энергетического диапазона подобных спектрометров.

Установка состоит из двух основных частей: газового агрегата для обеспечения работы сцинтилляционной камеры и собственного газового сцинтилляционного счетчика. Блок-схема газового агрегата вместе с сцинтилляционным счетчиком приведена на рис. 1. В отличие от ранее описанной установки [6] в блок-схему данного агрегата не входит диффузионный насос и улучшена система коммутации. Это, заметно не отражаясь на эксплуатационных параметрах счетчика, упрощает установку и делает ее более удобной в работе.

Не останавливаясь подробно на рассмотрении отдельных узлов газового агрегата, которые уже были описаны в [6], рассмотрим лишь циркуляционный насос, конструкция которого была полностью переработана.

Ранее применявшийся циркуляционный насос, обеспечивая нормальную работу счетчика при малых давлениях, которые используются при спектрометрии потоков

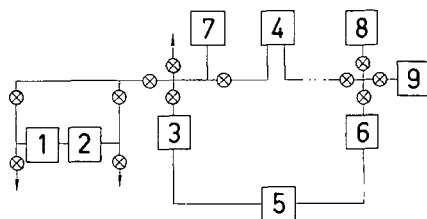


Рис. 1

Блок-схема газового агрегата со сцинтилляционной камерой

1. Компрессор
2. Азотная ловушка
3. Циркуляционный насос
4. Сцинтилляционная камера
5. Азотная ловушка
6. Кальциевая печь
7. Манометр
8. Манометрическая лампа
9. Форвакуумный насос

α -частиц, оказался недостаточно производительным при повышении давления до 50—60 атм. Поэтому был разработан новый циркуляционный насос, работающий по типу пластинчато-роторного насоса. В качестве двигателя насоса был использован стандартный электромотор типа ДТ-75., который был переделан в электродвигатель с экранированным и герметизированным якорем. Пластины ротора насоса были изготовлены из фторопласта-4. Опыт работы показал, что такой насос, изготовленный из неагящих материалов, обеспечивает требуемую циркуляцию при давлениях до 100 атмосфер. При нормальном давлении насос обеспечивает перепад давлений не менее 40 мм рт. ст. Питание электродвигателя осуществлялось через автотрансформатор, при помощи которого скорость циркуляции в установке может изменяться в широких пределах.

Газовый сцинтилляционный счетчик состоит из сцинтилляционной камеры и фотоэлектронного умножителя типа ФЭУ-24, импульс с которого через катодный повторитель подается непосредственно на стокальный анализатор импульсов типа АИ-100, или одноканальный анализатор типа АСС-1.

Сцинтилляционная камера представляет собой цилиндр $\varnothing$ 80 мм, на одном торце которого крепится стекло, а другой выполнен в виде конуса с углом 90° при вершине. Внутренние стенки камеры покрывались окисью магния, на которую напылялся слой кватерфенила толщиной 150—200 мкг/см². Внутренняя поверхность стекла, толщиной 10 мм, также была покрыта слоем кватерфенила. В камере имеется два отверстия для ввода и вывода газа, расположенные в одной плоскости под углом 90° друг к другу, а также отверстие для ввода альфа-источника. Устройство для ввода источника (без нарушения герметичности) представляет из себя цилиндр из нержавеющей стали, закрытый с одной стороны и имеющий резьбу для ввинчивания в камеру с другой. Внутри цилиндра помещен цилиндр из мягкого железа, к которому крепится точечный альфа-источник. Перемещая плунжер при помощи наружной электромагнитной катушки, можно вводить источник внутрь камеры и возвращать его в исходное положение.

Альфа-источник служит для контроля стабильности работы установки и как реперная точка для установления энергетической шкалы спектрометра.

Как известно, требования предъявляемые к веществу, вводимому в счетчик для спектрометрирования потоков нейтронов по энергии заряженных продуктов ядерной реакции, весьма жестки. Это относится, как к чисто ядерным характеристикам (достаточно большое сечение реакции и плавный ход сечения с энергией, отсутствие низколежащих, возбужденных уровней продуктов реакции, оптимальная величина энергии реакции и т. п.), так и к его атомным свойствам. Вещество вводимое в объем газового сцинтилляционного счетчика кроме этого должно еще находиться в газообразном состоянии во избежание потерь энергии в самом слое вещества. Газ не должен быть электроотрицательным, ибо электроотрицательные газы активно гасят сцинтилляцию [4, 8]. Наиболее полно этим требованиям, как известно, отвечает легкий изотоп гелия — He^3 , который благодаря реакции He^3 (пр) T, ($Q = 770$ кэв) позволяет осуществлять спектрометрию нейтронных потоков. Недостатком указанного вещества является малая масса ядра He^3 , в результате чего максимальная энергия передаваемая ядру отдачи при упругом рассеянии нейтрона становится сравнимой с энергией реакции Q при энергии нейтронов порядка 1 мэв.

Как было показано в [4] чистый гелий обладает слабым сцинтилляционным и тормозной слабостью. Поэтому для повышения как светового выхода, так и тормозной способности гелий желательно использовать в виде смеси с каким-либо тяжелым благородным газом. Исследования [4, 5, 9] различных смесей благородных газов показали, что наиболее высокой сцинтилляционной эффективностью обладает смесь гелия с ксеноном. Чтобы обеспечить достаточно высокую эффективность счетчика при регистрации нейтронов, необходимо чтобы смесь содержала возможно большее количество гелия, что накладывает определенные требования как на полное, так и парциальные давления газов.

Исследования сцинтилляций в смесях газов показали, что смесь состоящая из 90% гелия и 10% ксенона дает световой выход даже несколько более высокий, чем чистый ксенон. Для исследования сцинтилляций смеси гелия с ксеноном при высоких давлениях были сняты кривые зависимости амплитуды импульса и энергетического разрешения счетчика для α -частиц от относительной концентрации и общего давления смеси.

Из полученных кривых, приведенных на рис. 2, видно, что при изменении общего давления от 2,5 до 50 атмосфер и относительной концентрации гелия от 0 до 20 разрешающая способность счетчика изменяется не существенно.

В то же время световой выход смеси изменяется в этих условиях весьма заметно.

Примененный в работе изотоп гелия предварительно очищался от примесей на криогенной установке.

Исследовались параметры газового сцинтилляционного счетчика, наполненного смесью 90% He^3 и 10% Xe при общем давлении 20 атмосфер. При этом давлении эффективность регистрации нейтронов с энергией 1 мэв составляет несколько десятых процента.

Линейность энергетической шкалы спектрометра проверялась при помощи тепловых нейтронов, фотонейтронов Na^{24} (30 мкюри) + D_2O ($E_n = 0,22$ мэв), Na^{24} + Be ($E_n = 0,83$ мэв) и α -частиц Po^{210} ($E_\alpha = 5,29$ мэв). Полученные результаты показали, что зависимость светового выхода от энергии, теряемой в газе тяжелыми заряженными частицами, носит линейный характер.

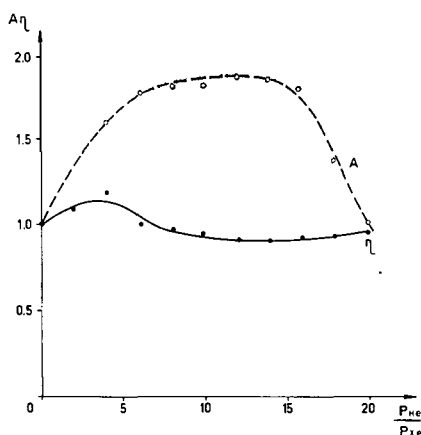


Рис. 2

Зависимость амплитуды импульса и энергетического разрешения (Источник Po^{210} $E_\alpha = 5,29$ мэв) от относительной концентрации и общего давления смеси $\text{He} + \text{Xe}$.

Пунктирная кривая — зависимость амплитуды импульса

Сплошная кривая — зависимость энергетического разрешения

Вопрос получения высокого энергетического разрешения газового сцинтиляционного счетчика, в случае его использования в качестве нейтронного спектрометра, отличается от случая его использования как альфа-спектрометра. Различие заключается, главным образом в условиях светосбора: при спектрометрировании потоков α -частиц свет регистрируется либо из малого сферического объема вокруг точечного источника, либо с небольшого же объема, прилегающего к поверхности плоского источника. В случае использования счетчика для спектрометрии потока нейтронов свет может испускаться из любой точки сцинтилляционной камеры счетчика и поэтому неоднородность сбора света по объему камеры весьма заметно ухудшает разрешающую способность счетчика. В связи с этим выбор формы и размеров камеры, тип фотоумножителя и однородность чувствительности его фотокатода, толщина нанесения преобразователя света, геометрия световода и т. п. играет существенную роль.

Исследование с этой точки зрения примененной сцинтилляционной камеры проводилось при помощи точечного источника альфа-частиц, помещаемого в различные точки камеры. Опыты показали, что изменение амплитуды импульсов при перемещении источника по радиусу камеры не превосходит 3—4%, практически независимо от расстояния источника до фотокатода умножителя. С другой стороны при перемещении источника по вертикали эти изменения гораздо резче и вблизи фотокатода их относительная величина возрастает до 20 + 25%. При этом разрешающая способность счетчика меняется подобным же образом в зависимости от расположения источника, но величина относительных изменений проявляется более резко.

Указанные опыты проводились при давлении ксенона равном 3 ата и толщине окна равном 8 мм. При изменении толщины окна (световода) неоднородность сбора также изменяется и может быть заметно понижена.

Исходя из этого видно, что полученное энергетическое разрешение порядка 14% для тепловых нейтронов, является не наилучшим и может быть повышено путем более рациональной конструкции камеры и выбора соответствующего световода.

На рис. 3 в качестве иллюстрации приведен спектр тепловых нейтронов Ро-Ве источника, помещенного в парафиновый шар диаметром 18 см, снятый на сто-канальном анализаторе типа АИ-100.

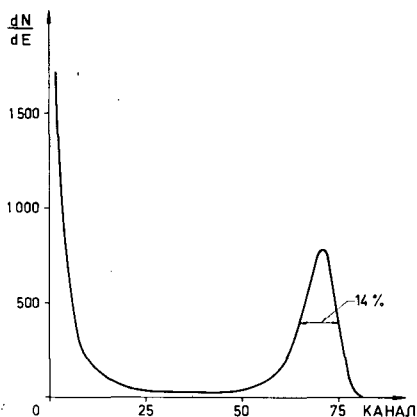


Рис. 3

Спектр тепловых нейтронов

Одним из достоинств газового сцинтилляционного счетчика является его слабая чувствительность к гамма-излучению, позволяющая использовать его для регистрации и спектрометрирования потоков нейтронов в условиях мощных гамма-полей. С этой точки зрения была проверена работоспособность описываемого спектрометра в гамма-полях до 3 р/час, создаваемых точечным препаратом Na^{24} ($E_\gamma = 1,38$ и $2,76$ мэв). На рис. 4 приведены дифференциальные спектры импульсов, получаемые со счетчика, наполненного смесью 90% He^3 + 10% Xe при общем давлении 20 атм, при мощности гамма-поля 3; 1,5; 0,33 р/час. Максимум распределения импульсов со счетчика от тепловых нейтронов при условиях, в которых проводился эксперимент, находился в 59 канале анализатора. Таким образом, даже при таких относительно мощных потоках гамма-излучения, при помощи спектрометра можно определять спектры нейтронов, начиная с тепловых энергий. Необходимо отметить, что исследование работоспособности различных типов фотоумножителей в таких условиях является самостоятельной задачей и изменения параметров ФЭУ, происходящие при этом, необходимо учитывать при интерпретации получающихся результатов (10).

Одним из существенных недостатков, который часто указывается для спектрометров, наполненных He^3 является ограниченность энергетического диапазона, возникающего вследствие упругого рассеяния нейтронов на ядрах He^3 . Полный спектр нейтронов может быть получен лишь до энергий нейтронов порядка 1 мэва.

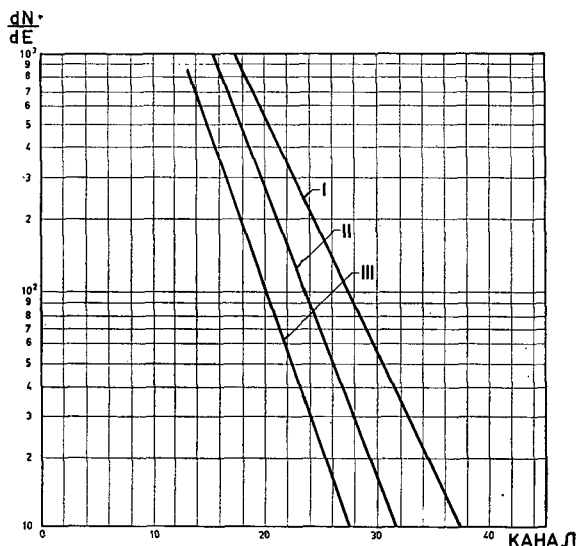


Рис. 4

Дифференциальные спектры импульсов. Смесь 90% He^3 + 10% Xe , общее давление 20 ата. Источник препарат Na^{24} ($E_\gamma = 1,38$ и $2,76$ мэв)

При энергиях нейтронов больше 1 мэв могут быть сняты лишь частичные спектры, лежащие между прямыми, показывающие изменение полной энергии и энергий ядер отдачи в зависимости от энергии нейтрона. Однако указанный недостаток является скорее субъективным, чем органическим недостатком сцинтилляционного спектрометра с He^3 . Действительно, если применить для интерпретации получающихся амплитудных распределений методику, аналогичную применяемой для расшифровки энергетических спектров гамма-излучения, то вклад ядер отдачи может быть исключен. Например, если исследуется спектр состоящий из нескольких моноэнергетических линий нейтронов, то последовательно вычитая (начиная с максимальной энергии) из экспериментально полученного распределения импульсов, теоретически рассчитанные спектры импульсов ядер отдачи с учетом сечений рассеяния и ядерной реакции, можно получить исходный спектр нейтронов. Если же исследуемый спектр нейтронов является непрерывным, то можно применять аналогичный метод последовательных вычитаний, принимая за отдельные монохроматические линии отдельные участки распределения. Такая методика вполне допустима благодаря тому, что высокоэнергетическая часть нейтронного спектра не искажена наличием ядер отдачи.

На практике проведение подобного относительно сложного анализа занимает, однако, много времени, но если учесть прогресс в области автоматизации процессов обработки сложных спектров с помощью счетно-решающих машин, то повидимому в ближайшее время подобная операция не будет представлять особых трудностей.

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DISCUSSION

V. Urošević (Yugoslavia): (a) How many times bigger than the background were the pulses due to alpha particles, and (b) what was the energy resolution for alpha particles of Po²¹⁰?

V. V. Matveev (USSR): As I said, (a) the relation between the light yield of the counter and the energy of heavy charged particles is linear, so the peak due to thermal neutrons is determined by the reaction energy. When the scintillation counter is irradiated by a gamma source at a dose rate of 3 r/hour, the maximum pulse amplitude is at Channel 37 of the analyser. The maximum amplitude in the pulse distribution due to thermal neutrons is at Channel 59. The pulse amplitude for alpha particles is thus

$\frac{E_{\alpha}}{Q_n \text{ He}^3}$ times greater. (b) The resolution of the spectrometer for Po²¹⁰ alpha particles, using this chamber, was approximately 6%. With other special chambers we have obtained an energy resolution of approximately 4—5%.

H. E. Wegner (United States of America): Do you have any data on resolution for mono-energetic fast neutrons in the 1 to 5 MeV region?

V. V. Matveev: We have checked the resolution of the spectrometer for fast neutrons obtained from a Van de Graaff electrostatic generator. The resolution of the spectrometer remains practically constant, even for higher energies up to about 2 or 3 MeV; it is approximately 13—14%.

N. Vylkov (Romania): With your gaseous detector, how does the efficiency for gamma-quanta compare with the efficiency for neutrons?

V. V. Matveev: It is difficult to speak of the efficiency of this spectrometer for gamma-quanta because the frequency and amplitude of pulses at the output when the counter is irradiated by a powerful gamma source does not depend solely on the sensitivity of the scintillator itself to gamma radiation, but also, for example, on the effect of gamma rays on the photomultiplier and the light-pipe. We have carried out experiments on a gaseous scintillation counter with a glass light-pipe and with a plexiglass light-pipe; the efficiency for gamma radiation was higher with the plexiglass. Similarly, gamma rays are quite likely sensed by the photomultiplier more quickly than by the scintillator itself. We irradiated a counter filled with gas and without gas, and the change in the distribution of the pulse amplitudes was not appreciable. As I have said, in this design the photomultiplier is rather sensitive to gammas; if the counter is irradiated by an Na²⁴ source at a dose rate of about 3 r/hour, the maximum amplitude, if we extrapolate the pulse distribution-curve to zero, is to be found in Channel 37 of the analyser and the peak from the thermal neutrons is to be found in Channel 59.

A LARGE CERENKOV DETECTOR

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Abstract — Résumé — Аннотация — Resumen

A large Cerenkov detector. Several problems, e.g. a test of nucleon conservation and high-energy neutrino detection of interest to us at Case Institute, have led to the construction of a large Cerenkov detector. This device consists of a tank 2.4 m in diameter and 2.1 m high which is painted with a white reflecting coat. The 7400-l water-volume used as the filling at present is viewed from above by 52 type-6364 Dumont multiplier phototubes. Internal to the detector as it is being currently used is a 200-l liquid scintillation-counter enclosed in an 8000-kg Fe shield. In this paper we describe constructional details and the response of the detector using cosmic-ray muons as a probe. We also present results on the effectiveness of the detector as an anti-coincidence blanket and will discuss the relevance of these numbers to the question of detecting high-energy neutrinos—both cosmic and man-made.

Un détecteur Cerenkov de grandes dimensions. Plusieurs travaux — parmi lesquels une expérience prouvant la conservation de particules nucléaires et de détection de neutrinos de haute énergie, qui intéressaient les chercheurs du Case Institute — ont amené les auteurs à construire un détecteur Cerenkov de grandes dimensions. Ce dispositif se compose d'un réservoir ayant un diamètre de 2,4 m et une hauteur de 2,1 m revêtu d'une couche de peinture blanche réfléchissante. Au-dessus du volume d'eau de 7400 litres utilisé à l'heure actuelle comme remplissage ont été disposés 52 tubes photomultiplicateurs du type Dumont 6364. A l'intérieur du détecteur, tel qu'il est normalement employé, se trouve un compteur à scintillation à liquides de 200 litres entouré d'une protection en fer de 8 tonnes. Les auteurs du mémoire décrivent certains détails de montage et indiquent quelle est la réponse du détecteur lorsqu'ils l'essaient avec des muons d'origine cosmique. Ils exposent également les résultats concernant l'efficacité du détecteur en tant que dispositif d'anticoïncidence; ils examinent l'intérêt que ces données numériques présentent pour la détection des neutrinos de haute énergie d'origine cosmique ou produits artificiellement.

Большой детектор Черенкова. Некоторые представляющие для нас (в Институте им. Кейса) интерес проблемы, как, например, испытания по сохранению нуклонов и обнаружение нейтрино большой энергии, привели к необходимости разработки детектора Черенкова больших размеров. Это устройство состоит из бака диаметром в 2,4 метра и высотой в 2,1 метра, покрытого изнутри белой отражающей краской. Наблюдение за объемом в 7400 литров, служащим для наполнения водой, ведется в настоящее время посредством находящихся над ним 52 умножительных фотоэлементов Дюмонта типа 6364. Согласно обычной практике внутри детектора помещается 200-литровый жидкий сцинтилляционный счетчик, защищенный железным экраном весом в 8000 кг. В настоящем докладе мы опишем конструкционные детали и характеристику детектора при использовании в качестве пробы мюезонов космических лучей. Мы представим также результаты относительно эффективности детектора при использовании его в качестве схемы антивосовпадения и обсудим пригодность полученных цифровых данных для решения вопроса об обнаружении нейтрино большой энергии как среди космических, так и среди искусственных лучей.

Detector de Cerenkov de grandes dimensiones. Diversos problemas de interés para el Case Institute, por ejemplo, los ensayos de conservación de nucleones y la detección de neutrinos de alta energía, han llevado a la construcción de un detector de Cerenkov de grandes dimensiones. El instrumento consiste en un tanque de 240 cm de diámetro por 210 cm de alto, al que se ha aplicado pintura blanca reflectora. Actualmente se emplean para llenarlo 7400 l de agua, y encima del tanque están dispuestos 52 tubos fotomultiplicadores Dumont tipo 6364. En el

interior se encuentra un contador de centelleo líquido de 200 l encerrado en un blindaje de Fe de 8000 kg. La memoria da detalles de la construcción y expone la respuesta obtenida con el detector utilizando como sonda muones de origen cósmico. También presenta los resultados obtenidos respecto a la eficacia del detector cuando se emplea como pantalla de anticoincidencia, y discute la importancia que tienen estas cifras para el problema de la detección de neutrinos de energía elevada, tanto de origen cósmico como obtenidos artificialmente.

Introduction

A large Cerenkov detector with a liquid capacity of 7400 l, an overall diameter of 2.67 m and 2.16 m high, has been constructed for use as a cosmic ray detector, an anti-coincidence blanket and as a model for possible giant neutrino detectors. In this paper we describe the construction and operating characteristics of the detector and then discuss briefly some of the experiments currently in progress and planned for the future.

DETECTOR CONSTRUCTION AND CIRCUITRY

The detector, shown schematically in Fig. 1, is a circular cylinder of sheet-iron 2.4 m inside diam. and 2.1 m high. In the centre of the cylinder and mounted on the floor is an approximately cubical iron house 1.13 m on edge. The experiments which will be described made use of a second detector of the liquid-scintillation type which was enclosed in this internal house. The walls of the large tank were made of four semi-circular pieces which were bolted together against rubber gaskets on to a circular floor-plate. White paint was applied to the interior walls of the tank to enhance reflectivity for the Cerenkov light. The tank was capped by a cover through which fifty-two 5-in Dumont photomultiplier tubes were able to view the liquid. The tank and the tube-assembly are shown in Figs. 2 and 3. Provision was made to reduce tube noise by dividing the tubes into two inter-leaved banks of 26 and requiring coincidences between them. The tube gains were individually balanced by selecting an appropriate high-voltage dropping-resistor for each tube. Although many clear liquids could have been used, we chose city drinking-water which we passed through demineralizing resin-exchange filters. An iron cover was placed over the top of the assembly to keep out the earth's magnetic field and stray electrical fields due to transients.

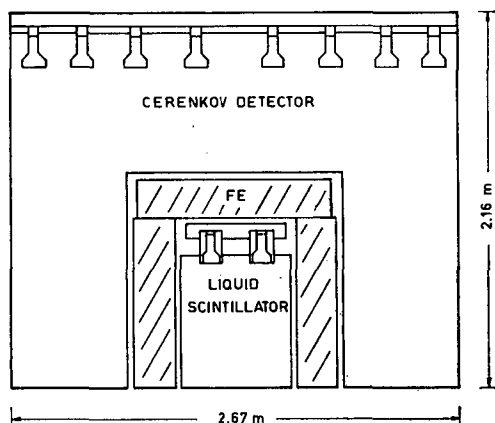


Fig. 1
Schematic of large Cerenkov detector

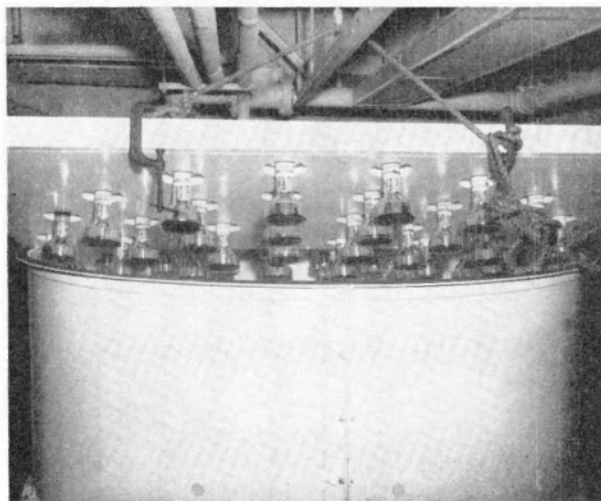


Fig. 2
Tube assembly in Cerenkov detector

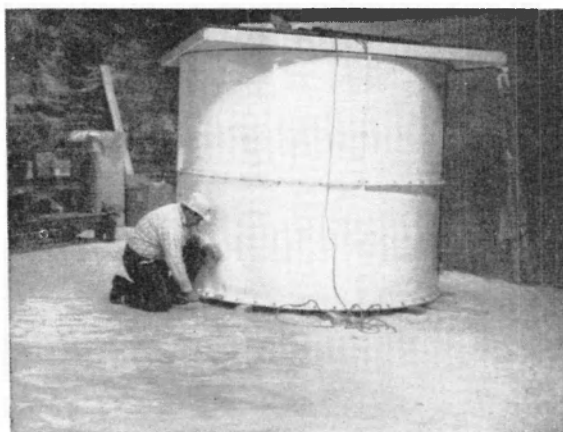


Fig. 3
Assembled Cerenkov detector located in salt mine

The electronic circuitry used with the detector is a conventional array: high-voltage supply for the photomultiplier tubes, pre-amplifiers, amplifiers, scalars, coincidence circuits, pulser with oscilloscopic presentation and photographic recording of detector pulses.* Pulse-height spectra were measured during study of the detector characteristics

* Block diagrams and other experimental details will be described in a forthcoming Ph. D. Thesis by Mr. Giamati.

by means of a 256-channel, Technical Measurements Corporation, type CN-110, transistorized pulse-height analyser with a model-213 plug-in logic.

OPERATING CHARACTERISTICS

The operating characteristics of the detector were measured in the basement of the Case Institute Physics Building using cosmic rays which penetrated at a rate of about $10^3/\text{s}$. Several kinds of spectra were measured: the total spectrum of cosmic rays as seen by the detector, the spectrum produced in the Cerenkov detector by those cosmic rays which passed in coincidence through two liquid scintillators, one in various positions outside the big detector and the other one inside it. The external scintillation-detector was a cylindrical container 0.6 m in diam., 0.25 m deep, painted white and filled with 50 l of toluene activated with terphenyl (3 g/l) and POPOP (0.3 g/l). The scintillation liquid was viewed by one 5-in photomultiplier tube. Sample curves are shown in Fig. 4

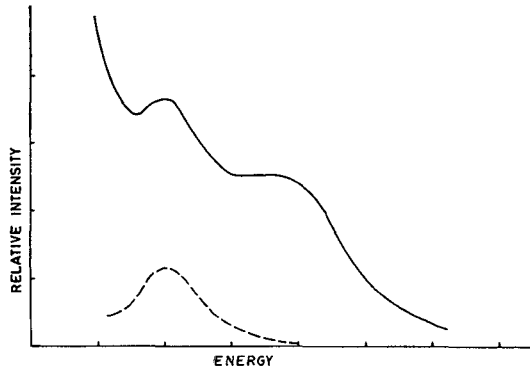


Fig. 4

Cosmic-ray spectra as seen by large Cerenkov detector alone, and as seen in coincidence with internal scintillation detector

for the large Cerenkov detector alone and the spectrum seen by it when a coincidence is required only with the internal scintillation-detector. It is seen that the unbiased total response to cosmic rays has two peaks. The lower one presumably arises from the collection of shorter paths associated with particles passing from the water surface through the inner house. The higher peak is reasonably associated with the particles which do not intersect the inner house but pass through the greater depth of the detector. The coincidence-spectrum has one peak which is consistent with the path determined by the liquid-air surface and the top of the inner house. Assuming an energy loss for a minimum ionizing particle in water of 1.8 MeV/cm, the coincidence peak which corresponds to an average path-length of 66 cm is at approximately 120 MeV. These curves were taken after a wavelength-shifter β -methyl umbelliferone* [1] was added

* In small detectors ($15 \times 30 \times 15$ cm) N. A. Porter reports a maximum pulse-height enhancement of 2 in the range of 5 to 100 mg/l. The additional enhancement noted by us may be due to the larger number of reflections required before light reaches the photo-cathodes and the increase in reflectivity with increased wavelength.

to the water. It was noted that the coincidence peak was raised by a factor of 3.8 by the addition of 5 mg/l of the shifter and that the increase did not yet appear to have been saturated.

A question can be raised concerning the best manner in which to add a wavelength-shifter to very large detectors which have surface-reflectivities dependent on wavelength. The point is that the addition of a shifter increases the scattering in the medium and, hence, the path-length and probability of light absorption. It might be better, as detector sizes are increased, to coat the reflecting surface with a shifter rather than distribute it throughout the volume. Because of the large scattering and absorption mean-free paths involved (10–40 m in clear water) and the complicated geometry, it is difficult to make appropriate measurements in the laboratory short of using a full-scale device. It may be that a semi-empirical approach is most economical in designing such large detectors.

The response of the Cerenkov detector for energy deposited in various parts of it was deduced from the location of the coincidence peaks. Allowing for the different path-lengths in the water associated with each configuration of path selectors, it appears that the detector response to a given energy deposition varies by a factor of 4 throughout its volume. The response measured with pure H₂O only drops monotonically with distance from the photomultipliers. The addition of the shifter reduced the variation by a factor roughly estimated to be at least two.

The stability of the system was checked by observing the location of the peaks as a function of time. They remained constant within 5% over a period of one month. This measurement was made with pure water. There has not yet been time to check long-term stability using the umbelliferone wavelength-shifter. A test was made of the dependence of the spectral response on the number of tubes employed. These spectra, shown in Fig. 5, held up surprisingly well as the number was diminished. However, the variation of effectiveness as an anti-coincidence shield versus the number of tubes has not yet been directly measured.

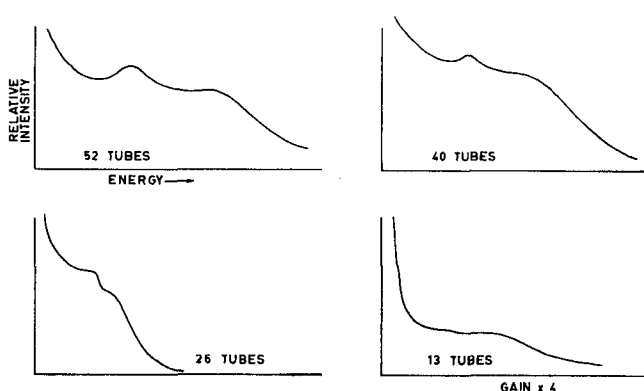


Fig. 5

Dependence of spectral response on the number of photomultiplier tubes employed

Experimental applications*

BARYON CONSERVATION

One investigation for which the detector system is being currently employed is to check, even more stringently than in the past, the law of conservation of baryons [2]. The idea behind this experiment is to so reduce the background, seen in a large-volume detector because of the action of cosmic rays, that exceedingly rare events associated with proton or nucleon decay will be visible. The kind of events which are sought are those which would be expected if all the conservation laws except those of baryon and lepton are obeyed. Since the rest-energy of a nucleon is available, it should be expected to appear as energetic products. This, coupled with the conservation of electric charge, implies the appearance of an energetic charged particle.

Accordingly, a liquid scintillation-detector containing 200 l of scintillator (decalin, with 0.8 g/l terphenyl, and 1.5 g/l α NPO) and viewed by four 5-in photomultiplier tubes has been placed inside the house internal to the large Cerenkov detector which serves as a cosmic-ray anti-coincidence blanket. In order to prevent proton decays in the scintillation detector from triggering the anti-coincidence, an 8-t iron shield was placed around the internal scintillation-detector, isolating it from the Cerenkov detector. Tests made at sea-level indicate an anti-coincidence factor of 300 for a lower energy bias-setting of 20 MeV in the scintillation detector. The background is reduced by an additional factor of 5×10^4 by placing the entire assembly in a salt mine 585 m deep. It is expected that, because the neutral radiations associated with sea-level cosmic rays are absent in the mine, anti-coincidence factors, considerably in excess of the sea-level value, will result. This experiment, now in progress in a salt mine near Cleveland has yielded preliminary values for the lower limit on the stability of free protons of 5×10^{25} yr, an improvement by a factor of ten over previous values. The limit for bound nucleons is now in excess of 2×10^{26} yr.

MEASUREMENT OF COSMIC-RAY FLUX UNDERGROUND

Because of the large area presented to cosmic rays by the detector, a rate of approximately 200 penetrating events per hour is observed in the mine referred to above. This rate is sufficiently great for it to become possible, not only to establish the underground intensity with great precision, but also to look further for diurnal variations in the intensity of high-energy muons (above ~ 500 GeV) and, hence, primaries responsible for the underground signal. A word of explanation is necessary concerning interest in the diurnal effect. As the earth rotates on its axis and moves through the solar system, the cosmic rays seen by the underground detector come from different parts of the heavens because of the shielding provided by the earth so that if there are sufficient

* Large Cerenkov detectors of the type described here are particularly useful when the particle energy of interest is high and the flux under observation is low. Liquid scintillation detectors are also useful in such circumstances and the decision concerning which approach is best depends on the mean-free paths of the emitted light and the relative costs of photomultiplier tubes and scintillation liquids. In this connection, it should be remembered that liquid scintillators convert 30 to 40 times as much of the energy lost by a relativistic ionizing particle to light as does a Cerenkov medium. Of course, in applications which require directional discrimination, a Cerenkov detector can be designed to have decided advantages.

concentrations of high-energy sources, they can be looked for in this fashion. It is recognized that, to date, there is no convincing evidence for any anisotropy in the high-energy cosmic radiation.

COSMIC-RAY NEUTRINOS

If we view the system as a detector for neutrino-like particles produced by the interaction of the primary cosmic-rays with the earth's atmosphere, we can estimate the expected counting-rate from the known properties of the primary cosmic-ray flux and its interactions which produce neutrinos through such reactions as π , μ -decay and μ , e -decay. The iron shield in the internal detecting house is a neutrino target and if a neutrino interacts with it, it produces charged particles which can be detected by the internal scintillation-counter. An estimate of the expected rate [3] [4] [5], made by extrapolating the Fermi theory to high energy, indicates that we might see one event in approximately two years. If intermediate bosons exist, the rate could be increased.

Estimates by GREISEN [3] on the neutrino signal rate from cosmic neutrinos, i.e., produced outside the earth's atmosphere, say by collision in intergalactic space, would indicate a very much lower level at probably a very much higher energy.

It appears from our experience with the present large Cerenkov detector that a detector of a size sufficient, say ~ 1000 tons, to allow a count-rate of one a day, due to neutrinos from cosmic-ray interactions in our atmosphere, can be built, and our experience with the sea-level anti-coincidence factor makes it likely that an acceptable signal-to-background ratio can be achieved.

MACHINE-MADE NEUTRINOS

Apart from the possible use of a Cerenkov detector for the investigation of neutrinos made by electro-nuclear machines, we have determined through the anti-coincidence factor, previously mentioned, that it is possible to keep out unwanted cosmic-rays in such experiments with machines having relatively large, inexpensive and simple anti-coincidence systems. So, for example, a rough estimate would indicate a neutrino-induced count-rate of 1 h^{-1} under certain assumptions [4] for a one-ton detector. Allowing for a machine-pulse duration of 1 ms^* and 10^3 pulses/h, the cosmic-ray background is a few hundred times the expected signal. The necessary discrimination against cosmic-ray background can be supplied with the anti-coincidence factor of a few hundred which we have shown to be obtainable.

ACKNOWLEDGEMENTS

The authors wish to thank W. R. Kropp for his help in operating the system, A. A. Hruschka for his part in the design and construction of the detectors and Dr. T. L. Jenkins for helpful discussions. The Morton Salt Co. has been most generous in allowing the use of their facilities.

* It is obviously important to reduce the pulse duration for neutrino experiments.

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DETECTION DE L'EFFET CERENKOV DES PARTICULES BÊTA DANS UN LIQUIDE PAR DES PHOTOMULTIPLICATEURS RAPIDES MIS EN COÏNCIDENCE

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Abstract — Résumé — Аннотация — Resumen

Detection of the Cerenkov effect of β particles in a liquid by rapid photomultipliers in coincidence.

An electronic assembly in the nanosecond region was studied for the detection of weak light pulses due to the Cerenkov effect, which an ordinary photomultiplier represents by pulses of a level comparable to that of the thermal noise at ambient temperature. The elimination of these extraneous counts was effected by rapid coincidence between two photomultipliers viewing the same source of light. This arrangement, eliminating the cooling normally used in this type of detection, permits a significant reduction of the volume and weight of the apparatus used with the Cerenkov detector proper.

The apparatus described has been applied to the detection of β -emitters in solution; it has permitted the measurement of Sr-Y activity in water, in concentrations at the MCP level.

Détection de l'effet Cerenkov des particules β dans un liquide par des photomultiplicateurs rapides mis en coïncidence. Un montage électronique du domaine de la nanoseconde a été étudié pour détecter de faibles impulsions lumineuses dues à l'effet Cerenkov, qu'un photomultiplicateur traduit normalement par des impulsions d'un niveau comparable à celui de son bruit à température ambiante. L'élimination des coups parasites de bruit se fait par coïncidences rapides entre deux photomultiplicateurs regardant la même source lumineuse; cette disposition, dispensant du refroidissement utilisé normalement dans ce genre de détection, permet une réduction notable de volume et de poids de l'appareillage accompagnant le détecteur Cerenkov proprement dit.

Le montage décrit a été appliqué à la détection d'émetteurs β en solution; il a permis la mesure d'activité de Sr-Y dans l'eau, en concentration au niveau de la CMA.

Обнаружение эффектом Черенкова бета-частиц в жидкости при помощи быстродействующих фотоумножителей, смонтированных по принципу совпадения. Авторы изучали электронную схему в области наносекунды для обнаружения слабых световых импульсов, вызываемых эффектом Черенкова, которые фотоумножитель обычно передает при помощи импульсов уровня, сравнимого с уровнем своего фона при окружающей температуре. Гашение ненужного фона производится быстрыми совпадениями между двумя фотоумножителями, направленными на один и тот же световой источник; это расположение избавляет от охлаждения, которое обычно применяется в такого рода обнаружении и позволяет значительно уменьшить объем и вес приборов, присоединяемых к самому детектору Черенкова.

Описанная схема применялась к обнаружению излучателей бета-частиц в растворе; она позволила измерить активность в воде в максимально допустимой концентрации.

Detección del efecto Cerenkov de las partículas β en un líquido mediante fotomultiplicadores rápidos puestos en coincidencia. Los autores han estudiado un circuito electrónico que trabaja en el campo de los nanosegundos y sirve para detectar impulsos luminosos débiles causados por el efecto Cerenkov, que normalmente se manifiestan en un fotomultiplicador en forma de impulsos de amplitud comparable a la de su ruido de fondo a temperatura ambiente. La eliminación de los impulsos parásitos se hace por coincidencias rápidas entre dos fotomultiplicadores enfocados hacia la misma fuente luminosa; gracias a esta disposición, que evita

la necesidad del enfriamiento utilizado corrientemente en este tipo de detección, se logra reducir notablemente el volumen y el peso del instrumental auxiliar del detector Cerenkov propiamente dicho.

Se aplicó la instalación descrita a la detección de emisores β en solución; se pudo medir así la actividad de Sr-Y en el agua, en una concentración de orden de la máxima admisible.

Introduction

Il est nécessaire, pour le contrôle des eaux, de détecter aussi simplement que possible les éléments radioactifs tels que ^{90}Sr et son descendant ^{90}Y , au niveau de la concentration maximale admisible qui, pour ces éléments, est $8 \cdot 10^{-7} \mu\text{C}/\text{cm}^3$.

Le but de cette étude est de préciser les possibilités d'effectuer cette détection par l'émission de lumière Cerenkov des particules en mouvement dans l'eau, sans concentration ou traitement préalable, et sans addition à l'eau, de corps scintillateur ou de substance fluorescente.

Quantité de lumière associée à une émission

Le strontium et l'yttrium émettent respectivement des β de 0,536 et 2,24 MeV d'énergie maximale; mais, le spectre d'émission en énergie étant un spectre continu, et le phénomène Cerenkov ayant un seuil — pour l'eau: 260 keV [3] (fig. 2) —, bon nombre d'électrons émis sont trop peu énergiques pour que leur passage dans l'eau s'accompagne de création de lumière. Pour le strontium-90, notamment, la courbe «spectre permis» que donne la théorie de Fermi [2] (fig. 1) ne laisse prévoir pratiquement aucune émission

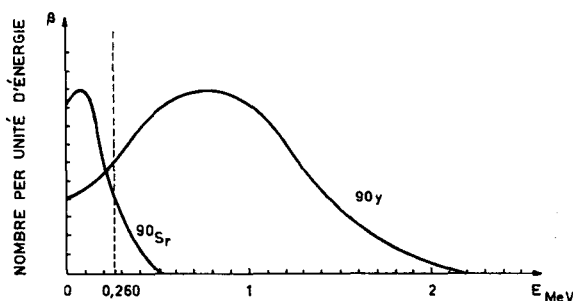


Figure 1
Spectre en énergie «permis» du ^{90}Sr et ^{90}Y .

lumineuse. L'yttrium reste détectable, mais avec un rendement lié à la quantité de lumière que produit un électron tout au long de sa trajectoire dans l'eau; elle dépend de l'énergie du β , mais elle est en général très faible, surtout lorsqu'on approche de la limite 260 keV, car le nombre de photons en fonction de l'énergie de la particule, linéaire au-dessus de 0,9 MeV, tend rapidement vers zéro au-dessous (fig. 2).

Remarquons enfin que cette lumière, couvrant une gamme de longueurs d'onde allant de 3000 à 7000 Å dans l'eau, laisse prévoir de nouvelles pertes de la part du photomultiplicateur chargé de l'observer à cause des sensibilités spectrales des photocathodes courantes.

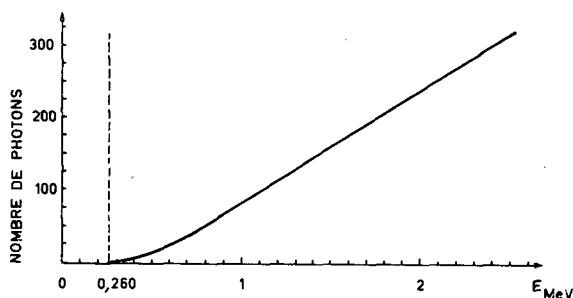


Figure 2

Photons émis entre 3000 et 7000 Å par passage d'un β dans l'eau.

Autant de raisons donc qui nous imposent, pour avoir un rendement acceptable, de donner au détecteur lumineux et à son électronique associée la plus grande sensibilité possible.

Mouvement propre de l'ensemble détecteur, lié au problème des faibles activités

Dans le même sens aussi, intervient le problème des faibles activités. La raison de simplicité nous impose de n'effectuer aucune concentration de l'eau à étudier, mais nous amène alors, pour l'analyse d'une eau peu active, à garantir malgré une grande sensibilité un niveau de parasites faible. Ces coups parasites sont dus en majeure partie au bruit des photomultiplicateurs. La méthode de refroidissement permet de les éliminer; elle a d'ailleurs été appliquée et a donné de bons résultats.

Mais, jouant sur le fait que l'effet Cerenkov est un phénomène rapide, nous avons essayé, en utilisant la technique des coïncidences rapides, de nous dispenser du refroidissement, ce qui permet une réduction notable de volume et de poids de l'appareillage accompagnant le détecteur Cerenkov proprement dit.

L'appareillage de détection dans son ensemble

Un ensemble de ce type est décrit ci-après. Une cuve transparente, remplie d'eau à analyser, où le passage d'un β fait naître une émission Cerenkov, est vue par deux photomultiplicateurs disposés symétriquement; à leur suite, deux mises en forme délivrent des signaux indépendants de l'amplitude et de la forme des impulsions fournies par les photomultiplicateurs, mais synchrones; les deux voies attaquent un circuit à coïncidence, qu'un ensemble de comptage ordinaire totalise finalement.

RÉCIPIENT D'ANALYSE

La cuve contenant l'eau à analyser est une cuve de verre cylindrique de 20 cm³; ses dimensions, diamètre 3,5 cm, hauteur 1,8 cm, sont suffisantes pour que la majorité des β naissant au sein de l'eau y effectuent leur parcours total — un β de 2,2 MeV a un trajet, dans ces conditions de 10,7 mm.

Nous assurons une collection lumineuse correcte en utilisant une feuille d'aluminium brillant comme réflecteur [3]. Le contact optique entre la cuve et l'aluminium n'est pas assuré, afin de ne pas perdre les avantages de la réflexion totale.

PHOTOMULTIPLICATEURS ET LEURS PERFORMANCES

Nous avons employé des photomultiplicateurs à haut gain et faible temps de résolution du type 56 AVP Radiotechnique. Leur diamètre de photocathode est de 2 pouces (5 cm). Ce phototube permet, avec ses quatorze étages de multiplication, d'atteindre des coefficients d'amplification élevés, de l'ordre de 10^8 . Son optique d'entrée assure une bonne collection de photoélectrons, en même temps qu'une réduction de l'étalement de leur temps de transit lorsqu'ils proviennent des divers points de la photocathode; on conserve ainsi la rapidité du phénomène Cerenkov, qui nous est nécessaire pour assurer l'élimination du bruit par coïncidence. On peut estimer à quelque 10^5 cps le mouvement propre à température ordinaire de ces photomultiplicateurs, pour le gain choisi.

Afin de conserver malgré tout un rapport signal/bruit aussi élevé que possible, nous avons divisé l'alimentation des dynodes du phototube en deux.

Une première alimentation stabilisée et réglable débite dans une chaîne alimentant les douze premières dynodes; les derniers étages sont séparés et polarisés par un diviseur potentiométrique dans lequel passe un assez fort courant 6 mA. De cette façon, on évite les variations de tensions instantanées des dynodes. Cette condition est importante dans ce cas de taux de comptage élevé (bruit) qui ne doit pas nuire à l'amplification correcte des impulsions Cerenkov.

On règle le gain de l'ensemble en agissant sur la première chaîne. Il existe un optimum, obtenu avec des tensions de l'ordre de 1200 V pour la première et 500 V pour la deuxième chaîne. Pour ces tensions, les microclaquages produits dans les phototubes et vus par les deux photocathodes à la fois sont à un niveau assez bas — 200 par minute environ. Ces microclaquages sont très gênants, car ils engendrent des coïncidences vraies.

Cependant, l'amplification est assez forte pour que les signaux recueillis à l'anode sur une charge de $100\ \Omega$ aient une amplitude relativement élevée — jusqu'à 6 V. Leur largeur est de $3 \cdot 10^{-9}$ s.

Ces signaux, dont la majorité est à très bas niveau, sont issus à la fois des événements Cerenkov et de tous les autres événements parasites que l'on a englobés sous le nom général de «bruit». Ils sont directement envoyés, sous basse impédance, aux deux circuits parallèles de mise en forme.

DISPOSITIF ÉLECTRONIQUE

Avec un circuit à coïncidence du type additif, tel que celui que nous avons employé, les mises en forme ont une importance primordiale, car d'elles dépendent une bonne résolution en temps et une bonne définition du temps de coïncidence, deux qualités directement liées au taux de coïncidences fortuites. Malgré les différents niveaux d'entrée, l'impulsion de sortie doit avoir une amplitude constante et un temps de montée fixe et rapide.

Par ailleurs, pour recueillir le maximum d'événements Cerenkov et obtenir un bon rendement de détection, le seuil de ces mises en forme doit être aussi bas qu'il est possible.

Enfin, recevant des taux de comptage élevés, ces circuits demandent à avoir un faible temps de restitution.

La description de l'ensemble électronique où nous nous sommes attachés à réunir ces performances est donnée ci-après.

Mises en forme. Les tubes V_1 V_2 V_3 V_4 composent l'une des mises en forme. Les impulsions sont négatives à l'entrée, et, pour des largeurs de 2,5 à 3 ns, le seuil inférieur est 0,15 V. Le circuit est plus spécialement conçu pour des impulsions brèves, mais il s'accommode sans inconvénients de signaux larges ou de grandes amplitudes (cosmiques-claquages). A cet effet, V_1 et V_3 agissent comme limiteurs; de faibles capacités de découplage des tubes V_1 V_2 introduisent une contre-réaction sélective, qui limite la largeur des signaux dès V_2 , en même temps qu'elle favorise les hautes fréquences. De plus, pour augmenter la pente du tube près du cut-off et la bande passante de l'étage, les tensions d'anode et d'écran sont plus élevées qu'en utilisation normale. Dans l'ensemble, cependant, les signaux brefs sont légèrement intégrés par chaque tube, si bien qu'ils s'élargissent en conservant un temps de montée court. La charge modique de V_3 est un câble court-circuité d'impédance 100 Ω ; sa largeur est telle que la coupure s'effectue à 5 ns; le câble est adapté par la résistance de fuite de grille V_4 fortement polarisé; on élimine ainsi la partie négative du signal provenant de V_3 . La largeur de 5 ns a été choisie pour obtenir un temps de coïncidence compatible avec le taux de coïncidences fortuites permis par notre manipulation. L'amplification totale assure une amplitude de 3,5 V, négative, en sortie, même pour les plus faibles signaux d'entrée 0,15 V. Le temps de restitution des circuits de mise en forme est inférieur à $0,5 \cdot 10^{-6}$ s.

Circuit de coïncidence. Chaque voie parallèle attaque ensuite l'une des branches d'un circuit classique de coïncidences, à diodes du type GARWIN [4], dont le contraste est voisin de 6 avec les éléments portés sur la figure 3. Puis le signal résultant est discriminé par une diode polarisée. La suite du dispositif électronique est tout à fait courante et lente; après amplification et intégration, les impulsions Cerenkov, séparées du bruit, sont totalisées par un ensemble de comptage ordinaire.

Résultats expérimentaux

Avec l'appareillage que nous venons de décrire, nous avons effectué quelques mesures et obtenu les résultats suivants:

- Comptage, les 2 PM isolés du point de vue lumière l'un de l'autre: 36 cp/mm
 - Comptage, les 2 PM non isolés du point de vue lumière l'un de l'autre, sans cuve entre eux: 248 cp/mm
 - Comptage, les 2 PM face à face, avec la cuve de 20 cm³ remplie d'eau distillée: 271 cp/mm
 - Comptage, les 2 PM face à face, avec la cuve de 20 cm³ remplie de la solution test Sr, Y à $5 \cdot 10^{-3}$ $\mu\text{C}/\text{cm}^3$: 31 800 cp/mm
- soit un rendement de 14,2%.

Conclusions

Ces résultats indiquent, abstraction faite des interactions lumineuses constatées pour les deux détecteurs 56 AVP utilisés sans précautions spéciales, la possibilité de détecter, en prenant comme comptage caractéristique le quart du mouvement propre, une activité de $2,4 \cdot 10^{-7}$ $\mu\text{C}/\text{cm}^3$, soit trois fois la dose maximale admissible Sr, Y.

Diverses améliorations peuvent être envisagées pour les photomultiplicateurs, la collection de lumière ou le temps de coïncidence. Des photomultiplicateurs à fenêtre de quartz, joints à une cuve en quartz à parois rendues bien réfléchissantes par un dépôt de magnésie, devraient augmenter d'un facteur de l'ordre de 2 la quantité de lumière reçue effectivement sur la photocathode.

On espère ainsi obtenir des résultats meilleurs que ceux cités ici. Cette méthode de détection par effet Cerenkov pourrait alors servir à résoudre certains problèmes difficiles, tels que celui du contrôle continu des eaux.

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A HIGH-RESOLUTION DIFFERENTIAL CERENKOV COUNTER

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Abstract — Résumé — Аннотация — Resumen

A high-resolution differential Cerenkov counter. A large, differential gas Cerenkov counter has been constructed for use at the Brookhaven National Laboratory Alternating Gradient Synchrotron. This counter is used to identify fast charged particles produced at the target by 30 GeV protons. Particles after momentum separation and collimation pass through the counter and give off Cerenkov radiation at angles depending upon their velocity. This light is focussed by a spherical mirror into ring-images of differing radii. An annular slit set in a reflecting diaphragm, allows the Cerenkov ring-image to pass through at 4.5° and to be focussed upon a 5-in diam. photomultiplier. Light produced at other Cerenkov angles falls upon the reflecting portion of the diaphragm and is refocussed by its ellipsoidal surface onto a second photomultiplier. The signal-to-noise ratio is improved by requiring (using tunnel-diode transistorized discriminators) that a large light pulse falls into the 4.5° coincidence channel and that a small or negligible light pulse appears in the anti-coincidence channel. The anti-coincidence feature of this counter reduces the background by at least two orders of magnitude. The counter is designed to resolve particles having a difference in velocity, $\Delta\beta$, as small as 1.8×10^{-4} ; the narrowest ring image produced should correspond to a $\Delta\beta$ half-width of 7×10^{-5} . The velocity range of from $\beta = 0.98$ to $\beta = 1.0$ is covered by varying the pressure. The counter was designed to use as a radiator methane, due to its low dispersion and multiple scattering, but other gases such as CO_2 may be used where high resolution is not a necessity. The gas radiator is 2.5 m in length providing at least 25 photoelectrons in the coincidence channel. The counter can accept a beam with a diameter of 18 cm. Measured results on the counter performance at high momenta and details on the transistorized electronics are presented.

Un compteur différentiel de Cerenkov à grand pouvoir de résolution. On a construit un grand compteur différentiel de Cerenkov à gaz pour le synchrotron à gradient alterne du Brookhaven National Laboratory. Le compteur est utilisé pour l'identification de particules chargées rapides produites sur la cible par des protons de 30 GeV. Après séparation des particules d'après leur quantité de mouvement et collimation, celles-ci passent à travers le compteur et produisent une émission Cerenkov faisant un angle qui varie selon leur vitesse. Un miroir sphérique fait converger cette lumière et il se forme au foyer des images circulaires de rayons divers. Une fente annulaire percée dans un diaphragme réfléchissant laisse passer l'image circulaire Cerenkov produite sous l'angle $4,5^\circ$ et permet de la diriger sur un photomultiplicateur de 5 pouces de diamètre. La lumière produite sous d'autres angles Cerenkov est réfléchiée par le diaphragme et converge au foyer de sa surface ellipsoïdale sur un deuxième photomultiplicateur. On a, au moyen de discriminateurs transistorisés, amélioré le rapport signal-bruit en faisant en sorte qu'une forte impulsion lumineuse apparaisse dans le canal de coïncidence de $4,5^\circ$ et qu'une impulsion lumineuse faible ou négligeable apparaisse dans le canal d'anticoïncidence. La caractéristique d'anticoïncidence de ce compteur réduit le bruit de fond de moitié environ. Le compteur est conçu pour distinguer des particules ayant entre elles une différence de vitesse $\Delta\beta$ de $1,8 \cdot 10^{-4}$; l'image circulaire la plus étroite produite devrait correspondre à une demi largeur $\Delta\beta$ de $7 \cdot 10^{-5}$. On parcourt la gamme des vitesses allant de $\beta = 0,98$ à $\beta = 1,0$ en faisant varier la pression. A l'origine, le compteur devait être utilisé avec du méthane comme milieu radiatif en raison des dispersion et diffusion multiple faibles de ce gaz, mais on peut utiliser d'autres gaz, comme par exemple le CO_2 , s'il n'est pas nécessaire que le pouvoir de résolution soit grand. Le milieu radiatif gazeux se trouve dans un récipient long de 2,5 m,

ce qui permet d'obtenir au moins 25 photoélectrons dans le canal de coïncidence. Le compteur peut recevoir un faisceau de 18 cm de diamètre. On présente les résultats de mesures sur le fonctionnement du compteur pour les quantités de mouvement élevées ainsi que des renseignements détaillés sur le montage transistorisé.

Дифференциальный счетчик Черенкова с высокой разрешающей способностью. Был сконструирован большой дифференциальный газовый счетчик Черенкова для применения в синхротроне Брукхейвенской национальной лаборатории со знакопеременным градиентом магнитного поля. Этот счетчик применяется для опознания быстрых заряженных частиц, производимых протонами в 30 бэв в мишени. Частицы после моментального разделения и коллимации проходят через счетчик и испускают радиацию Черенкова под углами в зависимости от их скорости. Этот свет фокусируется специальным зеркалом в круговые изображения различных радиусов. Кольцевой разрез, установленный в отражающей диафрагме, позволяет круговому изображению Черенкова под углом $4,5^\circ$ проходить и фокусироваться на фотоумножителе диаметром в 5 дюймов. Свет, производимый под другими углами Черенкова, падает на отражающую часть диафрагмы и вновь фокусируется ее эллипсоидной поверхностью на второй фотоумножитель. Отношение сигнала к шуму улучшается тем, что при использовании туннельно-диодных дискриминаторов на транзисторах, большой импульс света падает в $4,5$ -градусный канал совпадения и что малый или пренебрежимо малый импульс света появляется в канале антисовпадения. Схема антисовпадения счетчика уменьшает фон, по крайней мере, на два порядка величины. Счетчик предназначен для разрешения частиц, имеющих различие в скорости $\Delta\beta$, равное $1,8 \times 10^{-4}$; самое узкое круговое изображение должно соответствовать половине ширины $\Delta\beta$ равное 7×10^{-5} . Диапазон скорости от $\beta = 0,98$ до $\beta = 1,0$ покрывается варьированием давления. Счетчик предназначен для использования метана в качестве излучающей среды из-за его низкой дисперсии и многократного рассеяния, а другие газы, такие как CO_2 , могут быть использованы, когда не требуется высокое разрешение. Газовый излучатель имеет 2,5 метров в длину, что обеспечивает регистрацию по крайней мере 25 фотоэлектронов в канале совпадения. Счетчик может принимать пучок диаметром 18 см. Будут представлены данные по работе счетчика количества движения и детали об электронике на транзисторах.

Contador Cerenkov diferencial de elevado poder de resolución. Se ha construido un contador Cerenkov diferencial de gas de grandes dimensiones para su utilización en el sincrotrón de gradiente alterno del Laboratorio Nacional de Brookhaven. Este contador sirve para identificar partículas cargadas rápidas producidas en el blanco por protones de 30 GeV. Una vez separadas según su cantidad de movimiento y colimadas, las partículas atraviesan el contador emitiendo radiación Cerenkov según ángulos que dependen de su velocidad. Esta luz es focalizada por un espejo esférico en imágenes anulares de diferentes radios. Una rendija anular, situada en un diafragma reflector, deja pasar la imagen anular Cerenkov a $4,5^\circ$ para ser focalizada en un fotomultiplicador de 5 pulgadas de diámetro. La luz producida a otros ángulos de Cerenkov incide en la parte reflectora del diafragma, siendo focalizada de nuevo por su superficie elipsoidal en un segundo fotomultiplicador. Si se utilizan discriminadores transistorizados con diodos túnel, puede mejorarse la relación señal-ruido, haciendo que un gran impulso luminoso incida en un canal de coincidencia de $4,5^\circ$ y que un impulso luminoso pequeño o despreciable aparezca en el canal de anticoincidencia. Gracias a sus características de anticoincidencia, este contador reduce el fondo en dos órdenes de magnitud como mínimo. Este contador tiene por objeto distinguir partículas cuya diferencia de velocidad $\Delta\beta$, puede llegar a ser de $1,8 \times 10^{-4}$; la imagen anular más estrecha obtenida debería corresponder a una semianchura $\Delta\beta$ de 7×10^{-5} . Modificando la presión, pueden abarcarse velocidades comprendidas entre $\beta = 0,98$ y $\beta = 1,0$. El contador se destina a su empleo con metano como radiador debido a su baja dispersión y difusión múltiple, pero pueden utilizarse otros gases, por ejemplo el CO_2 cuando no se precisa un elevado poder de resolución. El radiador gaseoso tiene 2,5 metros de longitud y suministra como mínimo 25 fotoelectrones al canal de coincidencia. El contador admite un haz de 18 cm

de diámetro. Los autores presentarán los resultados obtenidos acerca del rendimiento del contador al trabajar con elevadas cantidades de movimiento, así como detalles de los circuitos electrónicos transistorizados.

I. Introduction

At the Brookhaven National Laboratory Alternating Gradient Synchrotron many types of particles are produced for the purpose of studying their properties and interactions. It becomes increasingly more difficult to identify these particles as they become more energetic and such conventional methods as time-of-flight and electromagnetic separators become impractical. The only method that is feasible at present is to simultaneously set a requirement on the momentum and velocity (Cerenkov effect) of the particle which could thus be only satisfied by one mass or one type of particle. The momentum is determined from the deflection in a bending magnet and the velocity measured by a High-Resolution Differential Cerenkov Counter which is to be described.

The limits on the range of velocity selection for this counter have been set at $0.98 < \beta < 1$ since particles with $\beta < 0.98$ can be identified with existing Cerenkov counters. The specification on the resolution is that the counter be able to distinguish K mesons from π mesons at momenta as high as 20 GeV/c where the velocity difference $\Delta\beta$ between K mesons and π mesons is 2.8×10^{-4} . Furthermore, the counter should have at least a 90% counting efficiency for a beam with a reasonable angular divergence and momentum spread. These requirements have been met and the counter is now operational. With this counter, experiments may now be performed at very high energies using the Cerenkov counter to trigger a spark chamber, a scintillation chamber, or to label particles entering a bubble chamber.

II. Principle

When a particle with velocity β passes through an optical medium of refractive index n , Cerenkov light is emitted at an angle θ where $\cos \theta = \frac{1}{\beta n}$. This light can be brought to a ring image of radius $f \tan \theta$ at the focal plane of the spherical mirror. Velocity selection is made at the focal plane by means of an annular slit set in a diaphragm which accepts only the Cerenkov light that was originally given off within some angular interval $\Delta\theta$ about θ . A photomultiplier tube looking at this light gives a pulse (C) whenever a particle with the correct velocity passes through the optical medium with its direction parallel to the axis of the spherical mirror. Particles with different velocities can be detected by varying the refractive index of the optical medium. A marked reduction in false counts can be accomplished by refocussing the light which strikes the diaphragm at points other than the slit opening on to another photomultiplier ($\bar{C}$). The output of this photomultiplier is connected in anti-coincidence with C.

III. Details of the counter

The counter design and optical details are shown in Fig. 1. A near-parallel beam of particles is incident on the counter from the left. The pressure vessel is filled with carbon dioxide whose pressure is varied to give the desired index of refraction. Light given off by particles with different velocities is focussed by a spherical mirror, which has a focal length of 170 cm, into ring images of differing radii. The spherical mirror

images the light to a focus at the diaphragm mirror after deflection by the 45° mirror. To bring the light accepted by the annular slit of the diaphragm to a photomultiplier tube, a large light-collecting mirror is used. It is a hand-blown piece of glass with its inside surface aluminized. Its shape in the plane of the figure is elliptical with one focus at the quartz window and the other at the diaphragm slit. Almost all the light passing through the slit reaches the photocathode of the RCA 7046 photomultiplier tube.

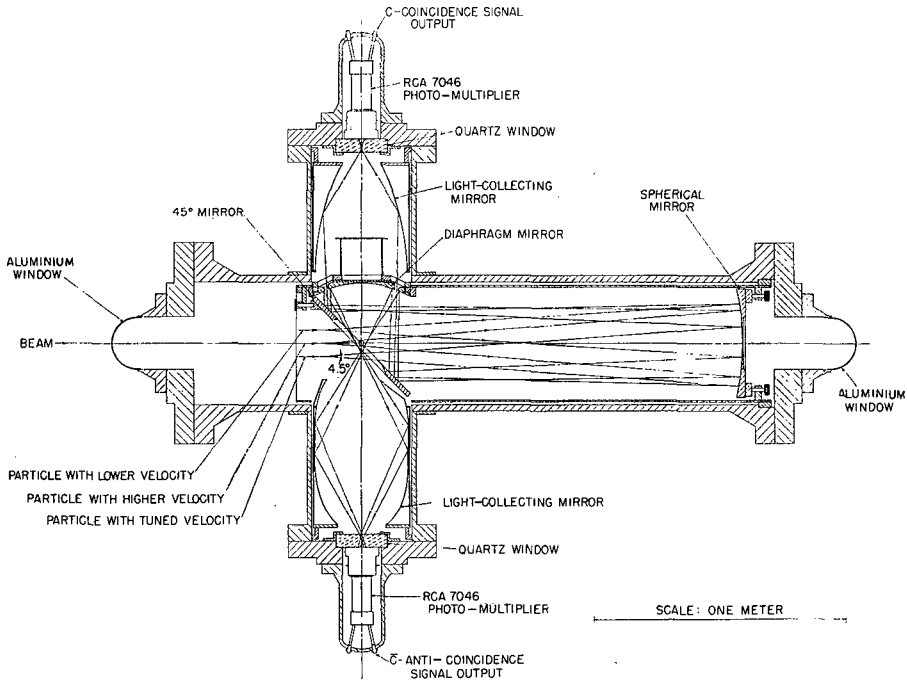


Fig. 1

The high-resolution differential Cerenkov counter

Light emitted by faster or slower particles falls upon the reflecting portion of the diaphragm and is refocussed by its ellipsoidal surface through the opening in the 45° mirror. The ellipsoidal diaphragm mirror has foci which are the centre of the front spherical mirror and a point 2 cm below the centre of the 45° mirror axis. Its function is similar to that of a field lens in that it directs almost all the light striking it through the hole of the 45° mirror. This light is then brought to a focus at the second RCA 7046 photomultiplier by the lower light-collecting mirror.

IV. Anti-coincidence feature

A false count can be obtained in the coincidence channel by a particle which does not have the correct velocity but whose ring image partially overlaps the ring slit of the diaphragm. Such counts can occur from (1) a particle with a several-standard-

deviation, multiple-scattering angle, (2) secondaries from nuclear collisions of beam particles, (3) random room-background particles and (4) knock-on electrons produced by beam particles.

In order to identify rare particles such as K mesons and antiprotons with a 99% certainty, it is necessary to reduce these false counts by at least a factor 10. This is accomplished by requiring that in order to have an "event", besides having a count from C for light pulses greater than half of the average, the light striking the diaphragm mirror and counting in $\bar{C}$ should not exceed a certain fixed level. These light threshold requirements are varied from one situation to another by means of discriminators. With this flexible anti-coincidence feature, the resolution of the counter is equivalent to that obtained by having two Cerenkov counters in coincidence.

The anti-coincidence channel can also be looked upon as an electronic control of the slit-width. Since the ring images at the diaphragm mirror have radial tails, if one requires with the $\bar{C}$ discriminator that less than about 15% of the total light strike the diaphragm mirror, events for which the ring image does not fall directly in the centre of the slit are electronically discarded. By this means the effective slit-width can be reduced by about a factor 2, without losing more than 10% in efficiency.

V. Resolution

The Cerenkov ring-image in the focal plane of the spherical mirror has an angular width and an angular displacement dependent upon the combined effect of four major factors: (1) dispersion of the gas radiator leading to photon emission at differing Cerenkov angles, (2) beam angular divergence, (3) multiple scattering in the gas radiator or before entering the counter, (4) momentum spread. The contribution to $\frac{\Delta\beta}{\beta}$ from an angular deviation $\Delta\theta$ in θ is given by $\frac{\Delta\beta}{\beta} = \tan \theta \cdot \Delta\theta$. A plot of these various contributions to $\frac{\Delta\beta}{\beta}$ for π mesons, K mesons, and protons is given in Fig. 2. Only dispersion and beam divergence are the dominant factors at very high energies, whereas at lower energies, they are dispersion, momentum spread, and multiple scattering. Beam divergence and momentum spread are factors dependent upon the beam layout. The beam may be designed so that they are not the limiting factors in the resolution. With this counter we require, at high momenta, that the beam divergence be $< 10^{-3}$ radians. At lower momenta one may wish to increase the beam divergence in order to increase the counting rate.

The resolution at high momenta is intrinsically limited by dispersion. Dispersion is a fixed property of the gas radiator. Once a gas with a particular dispersion has been chosen, a decrease in the contribution to $\frac{\Delta\beta}{\beta}$ from dispersion can be attained only by going to a smaller Cerenkov angle or by using optical filters. In either case, for a counter of fixed length, the total Cerenkov light intensity would be reduced and a larger fluctuation in the photo-electron number in C would be observed. We have chosen either methane or carbon dioxide as a radiator. Neither gas scintillates and both have low dispersion (± 1.5 — 1.63%) and low multiple scattering. A Cerenkov angle of light emission at 4.5° has been chosen. The gas radiator is 2.5 m in length providing at least 25 photo-electrons in the coincidence channel.

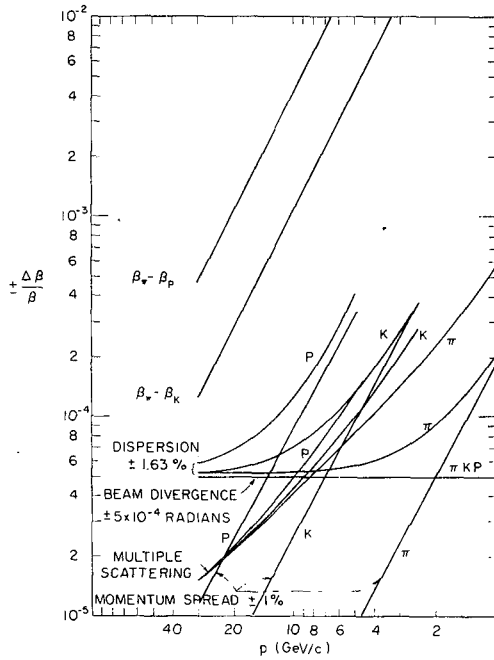


Fig. 2

Contributions to $\frac{\Delta \beta}{\beta}$ from various sources for π mesons, K mesons and protons as a function of momentum

VI. Experimental results

The Cerenkov counter has been tested in various beams at the AGS. This has been done during a programme for surveying the various angular and energy distributions of particles produced at the AGS. The 9° beam-arrangement is shown in Fig. 3. The 30 GeV internal proton-beam strikes an internal beryllium target. Particles which are given off at 9° and pass through collimators are momentum-analysed and bent through an angle of 4° . The Cerenkov counter is positioned between scintillation counters S_2 and S_3 . The last collimator and S_2 define a beam divergence of $\pm 5 \cdot 10^{-4}$ radians and a momentum spread of $\pm 1\%$. The total flight distance between the target and the final S_3 counter is 45 m.

Coincidences between the outputs of $S_1 S_2 S_3$ and $S_1 S_2 S_3 C \bar{C}$ were taken. The electronic block diagram is shown in Fig. 3. The transistorized fanout, discriminator, and coincidence circuit have been designed by R. SUGARMAN [1] of Brookhaven National Laboratory. The discriminator uses 20 mA Esaki diodes (Z61-22) and the discriminator operation is stable for input pulse thresholds from 2 to 20 mA. With this discriminator one can critically adjust the triggering level in the coincidence channel C and the anti-coincidence channel $\bar{C}$. The peak-to-background ratio may be maximized by varying the discriminators, requiring that a large light pulse falls into the 4.5° coincidence channel and that a small or negligible light pulse appears in the anti-coincidence channel.

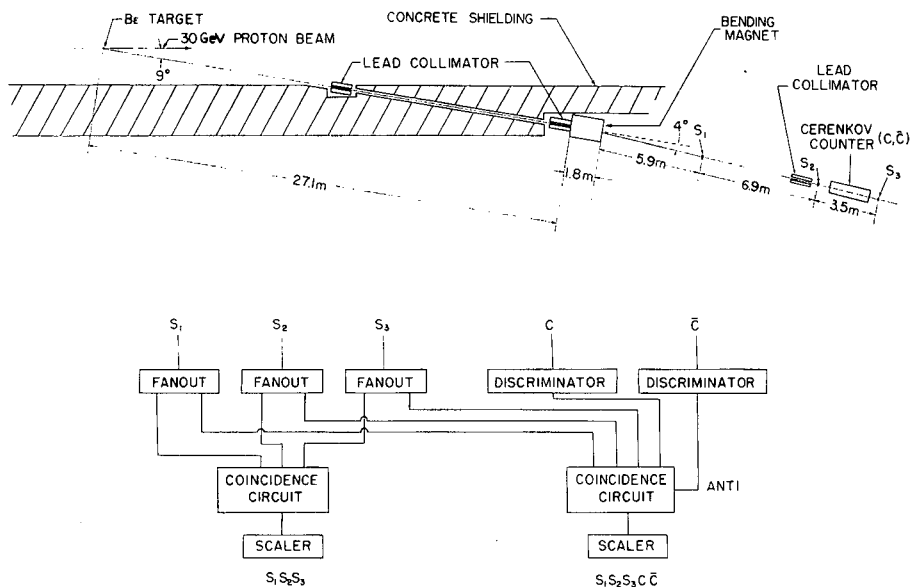


Fig. 3

Schematic diagram of the experimental arrangement

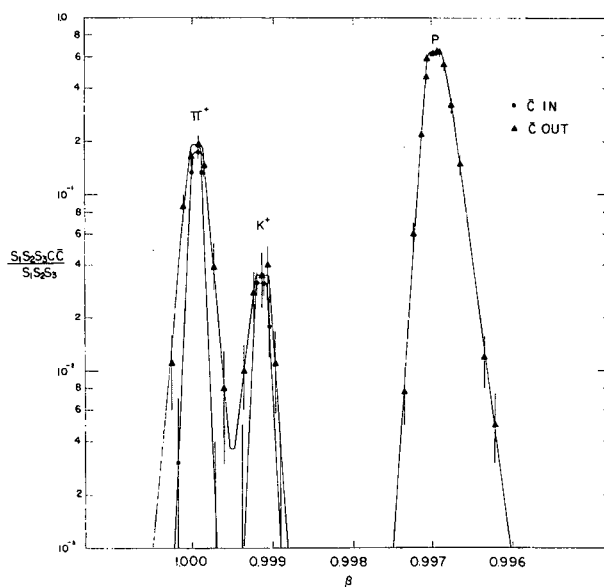


Fig. 4

The velocity spectrum of 12 GeV/c particles emitted at 9° to the direction of the 30-GeV proton beam

When the Cerenkov counter was run in a 12 GeV/c momentum analysed positive beam, the curves shown in Fig. 4 were obtained. All three particle peaks, π mesons, K mesons, protons, are clearly resolved. Fig. 4 shows the effect of the anti-coincidence channel $\bar{C}$. Without the use of $\bar{C}$ the valley between the π and K peaks is 10% of the K peak value. $\bar{C}$ reduces the counting rate between the π and K peaks from 4×10^{-3} to less than 10^{-4} . The widths of the various particle peaks are also decreased. The full width of the pion peak corresponds to a $\frac{\Delta\beta}{\beta}$ of 1.8×10^{-4} . This width indicates that it should be possible to separate K mesons from π mesons at 20 GeV/c since their peaks would have a $\Delta\beta$ separation of 2.8×10^{-4} . When $\bar{C}$ is used the efficiency for counting π mesons and K mesons is reduced by 10%. The proton peak was run without $\bar{C}$. The ring slit used in Fig. 4 corresponded to a $\frac{\Delta\beta}{\beta} = \pm 10^{-4}$. This proved to be slightly too narrow for counting protons with full efficiency. The resultant loss in counting rate for protons amounted to 10%.

ADDENDUM

Recently a velocity spectrum has been obtained for positive particles at 18 GeV/c momentum. The experimental arrangement was different from that shown in Fig. 3 in that the particles were taken at $4\frac{1}{4}^\circ$ to the 30-GeV proton beam and in that the bending magnet was 3.6 m closer to the Cerenkov counter. The central collimator and S_2 defined a beam divergence of $\pm 0.4 \times 10^{-3}$ radians and a momentum spread of $\pm 1.2\%$. From the results which are shown in Fig. 5 it is evident that K^+ mesons can be identified with a certainty in excess of 99%.

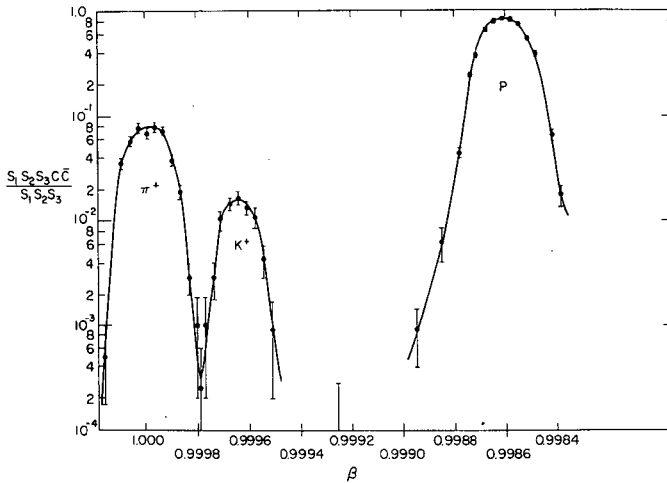


Fig. 5

The velocity spectrum of 18 GeV/c particles emitted at $4\frac{1}{4}^\circ$ to the direction of the 30-GeV proton beam

REFERENCE

- [1] SUGARMAN, R., Proc. Berkeley International High Energy Conference September 1960 (to be published).

NANOSECOND DECAY-TIME TECHNIQUES

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Abstract — Résumé — Аннотация — Resumen

Nanosecond decay-time techniques. The repetitive time-selection technique of fluorescence decay-time measurement as devised by Becquerel in 1859 is limited by the mechanics of the apparatus to a decay-time range of $\geq 10^{-4}$ s. In the original device the fluorescent spot was permitted to move repeatedly past an area of constant illumination and the spot was thereafter observed repeatedly at predetermined time intervals after passage through the illuminated area. In an electronic equivalent of this technique (cf. Dreeskamp and Burton, *Phys. Rev. Letters*, 2, (1959) 45, the luminescent region remains in constant position but the beam from a 30-kV X-ray tube is interrupted after ~ 0.8 ns and the luminescence produced (during a time of ~ 0.4 ns) is thereafter observed repetitively, at predetermined time intervals after the beginning of the cut-off of illumination by the X-ray tube, via an image converter and photomultiplier system. By the use of this technique we have observed decay phenomena which are complete in several nanoseconds and the decay times of which can be established, for example, as 2.2 ± 0.1 ns.

The special virtues of this technique are that the decay curve established is, in principle, not affected by the decay constants of the various parts of the electronic system and is extendable over a broad range of intensity (a factor of 100). Further, the actual curve can be established with a high degree of accuracy so that one is not constrained by preconceived notions to assuming a first-power decay law and the selection of a decay constant based on such a notion. Indeed, although we have now found that in many cases (e.g., *p*-terphenyl scintillator in benzene or cyclohexane solvent) an initial part of the decay curve is apparently first order, we are yet to observe a case in which the decay is singularly first order over the entire observation range made accessible by this technique.

Recent improvements in the accuracy of the technique have made possible a clearer understanding of the mechanism of excitation transfer, and the structure of the luminescent system and the mechanism of quenching. The apparatus is described, some more recent results are given and some speculations regarding the nature of the excitation transfer and quenching mechanisms involved in nanosecond decay are presented.

Techniques de mesure de temps de vie de l'ordre de la nanoseconde. La technique de mesure de la durée de vie de fluorescence par observations répétées, mise au point par Becquerel en 1859, est limitée par la mécanique de l'appareil à des durées de vie supérieures ou égales à 10^{-4} s. Dans le montage original, la tache fluorescente se meut constamment après être passée par une zone d'illumination constante et cette tache est observée ensuite à des intervalles de temps prédéterminés après son passage par la zone d'illumination constante. Dans un montage électronique équivalant à cette technique (cf. Dreeskamp et Burton, *Phys. Rev. Letters*, 2 (1959) 45), la région luminescente demeure fixe, mais le faisceau d'un tube à rayons X de 30 kV est interrompu après environ 0,8 nanoseconde et la luminescence produite (pendant un temps d'environ 0,4 nanoseconde) est observée ensuite à plusieurs reprises, à des intervalles de temps prédéterminés après le début de l'arrêt d'illumination par le tube à rayons X, par l'intermédiaire d'un convertisseur d'image et d'un système photomultiplicateur. Cette technique a permis aux auteurs d'observer des phénomènes de désexcitation complètement terminés en quelques nanosecondes, et dont les durées de vie peuvent être fixées à, par exemple, $2,2 \pm 0,1$ nanosecondes.

L'intérêt particulier de cette technique est que la courbe de décroissance ainsi établie n'est pas affectée — du moins en principe — par les caractéristiques d'arrêt des diverses parties du système électronique, et ensuite que cette technique peut s'appliquer à une large gamme

d'intensités (de x à $x \cdot 10^2$). De plus, la courbe réelle peut être déterminée avec une grande précision, de sorte que l'on n'est pas tributaire de notions préconçues telles que l'hypothèse d'une loi de décroissance du premier ordre et le choix d'une constante de décroissance basée sur cette hypothèse. En fait, bien que les auteurs aient trouvé que dans beaucoup de cas (par exemple, le *p*-triphényle comme scintillateur dans le benzène ou le cyclohexane comme solvants) une partie initiale de la courbe de décroissance était bien du premier ordre, il reste à observer un cas dans lequel la décroissance est uniquement du premier ordre dans tout le domaine d'observation accessible par cette technique.

De récentes améliorations dans la précision de la technique ont permis de mieux comprendre le mécanisme de transfert de l'énergie d'excitation, la structure du système luminescent et le mécanisme de coupage. Les auteurs décrivent l'appareil et donnent certains résultats récents; ils formulent des hypothèses concernant la nature du transfert d'excitation et des mécanismes de coupage intervenant dans les états de durée de vie de l'ordre d'une nanoseconde.

Методы наносекундного времени затухания. Метод повторяющего отбора времени при измерении времени затухания флуоресценции, изобретенный Бекерелем в 1859 году, ограничен прибором до диапазона времени затухания, составляющего $\leq 10^{-4}$ сек. В первоначальной конструкции флуоресцентное пятно несколько раз передвигалось мимо места постоянного освещения, а затем это пятно можно было неоднократно наблюдать через заранее определенные промежутки времени после прохождения его через освещенное место. В электронном эквиваленте этого метода (см. Дресками и Бартон, *Phys. Rev. Letters*, 2 (1959), 45) люминесцентное место остается в постоянном положении, однако пучок из рентгеновской трубки в 30 кв прерывается после $\sim 0,8$ наносекунды, и затем можно через электронно-оптический преобразователь и фотоумножительную систему неоднократно наблюдать вызванную люминесценцию (в течение $\sim 0,4$ наносекунды) через заранее определенные промежутки времени, начиная с выключения освещения рентгеновской трубкой. С помощью этого метода мы наблюдали явления распада, которые завершались в течение нескольких наносекунд и время затухания которых может быть установлено, например, как $2,2 \pm 0,1$ наносекунды.

Особыми преимуществами этого метода является то, что на полученную кривую распада в принципе не влияют постоянные затухания различных частей электронной системы и что ее можно увеличить сверх широкого диапазона интенсивности (коэффициент 100). Кроме того, можно получить действительную кривую с высокой точностью, что позволяет не считаться с предвзятым мнением, основанном на каком-то законе затухания первой степени и выборе постоянной затухания. Действительно, хотя в настоящее время мы обнаружили, что во многих случаях (например, *p*-терфениловый сцинтиллятор в бензоле или циклогексановом растворе) начальная часть кривой затухания представляет собой, совершенно очевидно, величину первого порядка, нам еще предстоит наблюдать случаи, когда затухание является исключительно величиной первого порядка среди всех наблюдений, которые доступны благодаря этому методу.

Последние усовершенствования в точности этого метода позволили более ясно понять механизм передачи возбуждения, структуру люминесцентной системы и механизм гашения. Дается описание приборов, приводятся некоторые последние результаты, а также высказаны предположения относительно характера передачи возбуждения и механизмов гашения, происходящих при наносекундном затухании.

Técnicas para la medición de tiempos de extinción del orden del nanosegundo. El método de medición de periodos de extinción de la fluorescencia por selección repetida de tiempos, que fue establecido por Becquerel en 1859, no puede aplicarse a periodos inferiores a 10^{-4} s debido a las limitaciones inherentes a los aparatos que se utilizan. En el dispositivo originalmente empleado, el punto fluorescente se hacía pasar repetidamente por una zona de iluminación constante, para observarse cada vez al cabo de un intervalo de tiempo predeterminado. Con arreglo a una técnica electrónica equivalente (Dreeskamp y Burton, *Phys. Rev. Letters*, 2 (1959) 45), la región luminiscente permanece inmóvil, pero en cambio el haz procedente de un tubo de rayos X de 30 kV se interrumpe después de aproximadamente 0,8 ns y la luminiscencia

producida (durante aproximadamente 0,4 ns) se observa luego repetidamente a intervalos predeterminados, a partir del momento en que comienza la interrupción de la iluminación por el tubo de rayos X, mediante un sistema de convertidor de imágenes y fotomultiplicador. Utilizando este procedimiento, los autores han podido observar fenómenos de extinción de algunos nanosegundos de duración y en que el período de extinción puede establecerse, por ejemplo, en $2,2 \pm 0,1$ ns.

La principal ventaja de esta técnica consiste en que la curva de extinción que se obtiene no resulta afectada, en principio, por las constantes de extinción de los diferentes componentes del sistema electrónico y en que permite abarcar un amplio intervalo de intensidades (factor de 100). Además, la curva real puede establecerse con mucha precisión, sin las limitaciones derivadas de hipótesis previas como, por ejemplo, la de que la variación de la extinción obedece a una ecuación de primer orden, lo que obliga a determinar una constante de extinción. En efecto, si bien los autores han hallado ciertos casos (por ejemplo, un centelleador de *p*-terfenilo con benceno o ciclohexano como solvente) en que la parte inicial de la curva de extinción es aparentemente de primer orden, no han podido encontrar ningún caso en que la extinción varíe linealmente en todo el intervalo de observación que el método descrito permite abarcar.

La exactitud de esta técnica ha sido mejorada recientemente, lo que ha permitido comprender con más claridad el mecanismo de las transferencias de excitaciones, la estructura del sistema luminescente y el mecanismo de extinción. Los autores describen el aparato, proporcionan algunos de los resultados recientemente obtenidos y formulan ciertas hipótesis sobre la naturaleza de la transferencia de la excitación y sobre los mecanismos de extinción que intervienen cuando los períodos son del orden del nanosegundo.

I. Techniques of luminescence-decay measurement

Typical of the techniques which may be employed for the determination of luminescence-decay times are (a) photoelectric or photomultiplier detection, amplification and display on an oscilloscope, (b) phase-shift, (c) repetitive time selection.

The first method, i.e., the oscilloscopic-display technique, is limited to decay times which make no undue demands on the decay characteristics of the circuitry itself. The total circuitry must be capable of a precise response well within the decay time of the system studied. For practical purposes, this requirement limits observations to luminescent systems which have decay times no less than 2 ns.

The phase-shift technique involves no similar restriction. It appears, in principle, to extend without limit to shorter and shorter decay times. On the other hand, it demands a certain pre-knowledge of the order of the process studied. It has been customary to treat luminescence-decay processes as first-order and, provided such an assumption is justified, the method seems quite satisfactory. However, our recent results indicate no case of simple first-order decay in any fast process studied; i.e., in the precise range in which phase-shift technique would appear to be most promising, it is inapplicable.

The repetitive-time-selection technique, as exemplified by the early mechanical Becquerel phosphoroscope [1] is useful and independent of any presumptions concerning the order of the luminescence-decay processes. In its primitive, mechanical form its application is limited to decay times of $\sim 10^{-4}$ s but recently developed electronic equivalents have extended the range of application to the nanosecond region without introduction of any strain on the decay characteristics of the circuitry itself. Electronic circuitry of the original device of DREESKAMP and BURTON [2] is described in detail in a recent publication [3].

II. Repetitive-time-selection technique

The principle of operation of this technique may be summarized in the following statements:

(a) The luminescent system is irradiated repetitively in a predetermined fashion by an approximately square-wave pulse (e.g., 10 ns long) of 30 kV X-rays;

(b) The X-ray pulse lasts long enough to permit the luminescent system to arrive at a steady state;

(c) At a predetermined time, t_d , after the shut-off of X-rays, the light emitted by the luminescent system is indirectly caused to activate a phosphor. The time t_d is fixed precisely within ± 0.15 ns and the time of activation of the phosphor, Δt , is 0.4 ns;

(d) The luminescence resultant in the phosphor in turn activates a photomultiplier (during a period of ~ 50 μ s) and the output is amplified by conventional circuitry;

(e) The total operation is performed repetitively at 60 cycles per second so that the signal from the photomultiplier system may be fed to an integration amplifier IA and the amplified signal for a particular time $t_d = t_1$ may be measured at leisure giving a value for relative intensity I_1 ;

(f) A series of measurements at different values of t_d gives a series of values of I , independent of any foreknowledge of the order of the decay process, from which an intensity-time curve may be constructed.

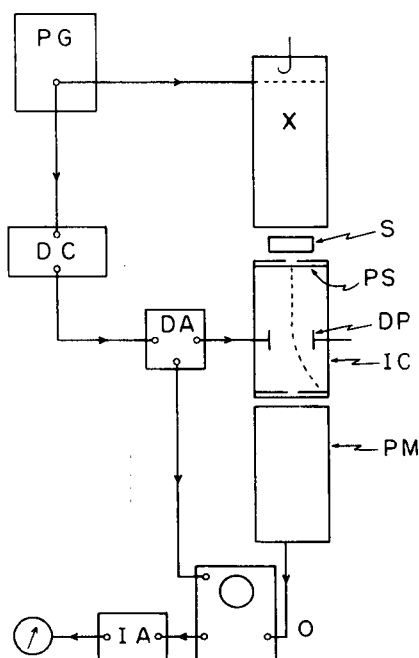


Fig. 1

Block diagram of apparatus: PG — pulse generator; X — X-ray tube; IC — image converter (dotted line indicates initial position of electrons); PS — photosensitive surface; DP — deflection plates; PM — photomultiplier; IA — integration amplifier; S — scintillator; DA — deflection amplifier; DC — delay cables

Fig. 1 shows a block diagram of the electronic system employed. A pulse generator PG serves several functions: it actuates and interrupts an X-ray tube X; through a delay circuit it operates on the deflection plates DP of an image converter IC; it operates through another delay circuit to activate the integration amplifier IA. The X-ray pulse from the tube X activates the scintillator sample S, which can be a plastic or solid material or a liquid contained in a non-luminescent, transparent container. The sample S effectively absorbs all X-rays. Light from S activates the photo-sensitive surface PS of the image converter at a narrow (3 mm) exposed slit; electrons emitted from PS pass in a beam between the deflection plates DP and are focused at a spot determined by the voltage on DP and the optics of the instrument. Ordinarily, the beam is deflected as shown by the dotted line. It is held in this extreme position for an adjustable time t_v until the plates DP receive a voltage pulse from PG, whereupon the beam sweeps across a slit through which it activates the phosphor for a time Δt . The time t_d , after interruption of the X-rays, is the sum of t_v and the fixed time t_f required for the electron beam to move from its position of maximum deflection past the centre of the slit. The time t_f is ~ 5 ns. The time $t_d = t_v + t_f$ is reproducible within 0.15 ns.*

The integrating amplifier IA is made to begin operation just before the time t_d and continues for 50 μ s on each pulse. The average voltage reading can be made conveniently after 4 s on a read-out meter and thus one point is obtained on a decay curve. The value of t_v is then changed by cable adjustments and another reading is made. In this way a complete curve can be obtained in less than two hours.



Fig. 2

Photograph of the optical system

The pointer indicates the scintillator vessel. The X-ray tube is above it and the image converter directly below. The photomultiplier is below the image converter.

* By adjustment of the delay circuit t_v , and thus t_d , may be made negative so that luminescence rise and decay can both be observed.

Figs. 2 and 3 are photographs which more clearly show the size and nature of the apparatus. Detailed circuitry has already been published [3].

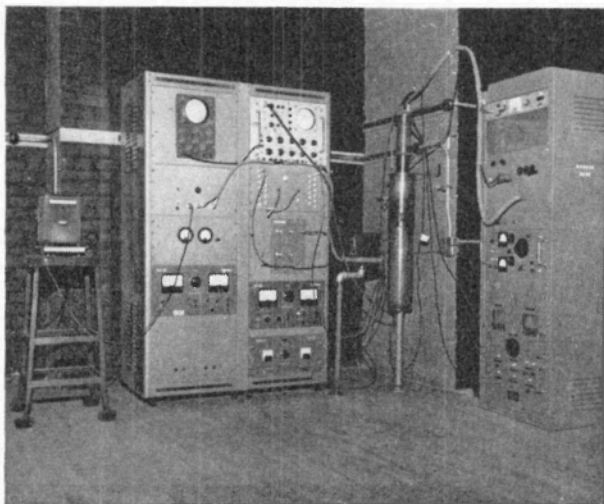


Fig. 3

Photograph of the entire repetitive-time-selection apparatus. Optical portion is in the closed column

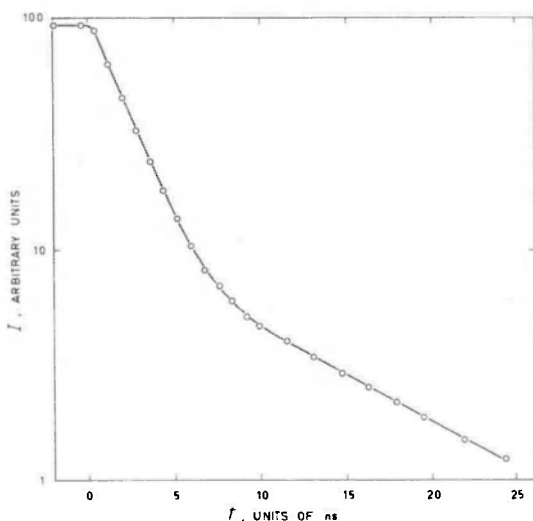


Fig. 4

Luminescence decay curve for the system 7.2 g p-terphenyl per liter of benzene, deaerated. I does not include noise. $\tau_2 = 1.8$ ns. $\tau_3 = 10.8$ ns. (τ_2 and τ_3 are more properly to be called u and v respectively at this stage; cf. Section 5)

A typical decay curve for the system 7.2 g *p*-terphenyl/l in benzene is shown in Fig. 4. It is worth emphasizing that a curve characteristic of simple first-order decay has been obtained by our technique only for the relatively slow decay process represented by the luminescence of crystalline anthracene; we are not confident that it would continue to be first-order over a long time. In no case of a fast luminescence-decay has a curve characteristic of simple first-order decay been observed. The existence of such a complicated decay situation raises two types of questions; namely, of the accuracy of present observations and of the possibilities of refinement of observation to extend both the range and the accuracy of further studies.

III. Source of long decay-time tail

The evidence that the long-decay-time (low-intensity) tail shown in Fig. 4 and in all other fast-decay-time studies is real and characteristic of the scintillator system itself, not of containers nor of the electronic system, may be summarized in the following sets of statements.

(i) Consider the general form of the luminescence curve represented by Fig. 5, which shows a complete record of luminescence both preceding and subsequent to t_i , the time of initiation of irradiation by X-rays. The initiation time is, of course, before time $t = 0$, as that quantity has been defined. The intensity I_n prior to t_i is a measure of the noise level of the circuitry. The intensity I_p is the luminescence intensity in the steady state, a quantity which is determined by the X-ray intensity and by the properties of the scintillator system. The quantity I_n is a function of I_p as shown in Fig. 6. The conclusion is that some record of the luminescence intensity persistent in the total system between pulses is responsible for the dark current. A further conclusion is that this record is made (i.e., the noise level is set) in the image converter itself (or in the scintillator system; but cf. III, iv) because that is the only portion of the instrumentation

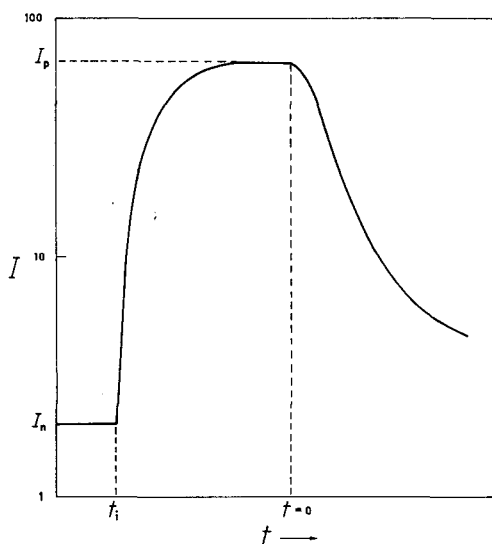


Fig. 5

Diagrammatic representation of a complete luminescence decay curve. I includes noise

which is affected at all times by the maximum luminescence intensity level, as represented by I_p . The photomultiplier and the attendant amplification system are unaware of the level of I_p unless they are actually being used to measure individual points at that level. At any one reading (cf. the individual points in Fig. 4) they are affected only by the intensity level, at the luminescent screen of the image converter, corresponding to that reading. Thus, whatever dark current is represented by the level of I_n is determined before the effect on the photomultiplier and amplification system.

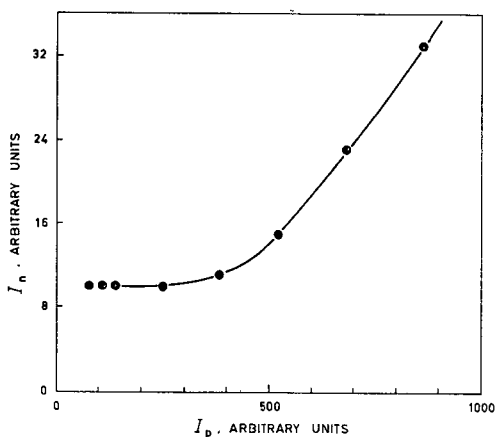


Fig. 6

Relation between noise level and intensity in the steady state

(ii) When the X-ray intensity is reduced by a factor of 10 the shape of the decay curve characteristic of a given scintillator system (such as shown in Fig. 4) is not thereby affected although, of course, its vertical displacement is changed. The conclusions are that the shape is not attributable to (a) possible non-linear response of the image converter—photomultiplier combination, (b) possible non-linear response of the detecting circuitry, or (c) noise, which Fig. 6 shows is not proportional to I_p , i.e., scintillator intensity.

(iii) An increase in duration of the X-ray pulse by a factor of ~ 2 has no effect on the shape of the decay curve. The conclusions are that the long-decay-time component is not properly attributable (a) to deterioration of the sweep signal after passage through long lengths of delay cable, or (b) to increase in noise inside the image converter as a function of time after initiation of the scintillation signal. In other words, this result establishes the conclusion that noise level is the same at $t = 0$ as at times ($t = t_d = t_1, t_2$, etc.) at which each point of the decay curve, including the long component, is observed.

(iv) The possibility has been considered that the tail of the decay curve is itself a record of the late receipt of luminescent light by the image-converter as the result of multiple reflection within the scintillator system itself. A variety of experiments in which the character of the possible reflection surfaces, the number of possible reflectors, the length of possible reflected light path, etc. were varied, showed that the long-decay-time tail is not related to such a phenomenon.

(v) The shapes of the luminescence decay curves (such as shown in Fig. 4) are affected by changes in the nature of the scintillator, the scintillator concentration, the solvent, and the presence of quencher, such as oxygen. The conclusion is that the long-decay-time tail is characteristic of the scintillator system (not merely of the scintillator) and not at all of the instrument as we have employed it.

IV. Possibilities for the improvement of measurement and refinement of accuracy

The X-ray tube gives only an "almost-square" pulse of X-rays. The rise-time and the fall-time may reasonably be assumed to be equal; such an assumption does not affect either the validity of the data or our interpretations. The fall-time is estimated from the initial shape of the decay curves for luminescence from solutions of *p*-terphenyl in cyclohexane or relatively concentrated solutions of the same solute in benzene. The value estimated is 0.8 ns, but the shape of the X-ray decay curve is merely reasonably guessed to be linear. That shape is determined in part by the control grid of the X-ray tube. Although we have no way directly to measure the shape of the X-ray output curve, we might more reasonably infer that shape from direct knowledge of the shape of the voltage curve on the grid.* We have not yet made such a measurement but the availability of ultra fast oscilloscopes, with rise times of < 1 ns, may make such an effort reasonable and the results meaningful. A "correct" X-ray intensity vs time curve thus inferred would improve our knowledge of the meaning of the initial part (shortly after $t = 0$) of the luminescence-decay curve.

The long-decay-time tail is difficult to observe, particularly for scintillator solutes which can be present at only low concentration (e.g., *p*-terphenyl in cyclohexane) or for solutions containing a relatively high concentration of quencher, because of the very low intensity of the light signal compared with the noise of the system itself. We hope to improve this aspect of our technique by the use of an X-ray tube which can operate at about 4 times the intensity of the one used in the present reported work. It is expected that this increase in intensity can be effected without an increase in the fall-time of the X-ray tube. Eventually, we would hope to decrease this fall-time.

However, the real problem, whenever we consider the advantages to be gained by employment of a more intense X-ray source, is that the noise level seems to be determined by the initial luminescence intensity (i.e., I_p) of the scintillator solution (cf. section III, i). Thus, a more intense source does give considerable advantage for the study of solutions giving normally low luminescence intensity; e.g., dilute solutions, solutions containing large quantities of quencher, solutions containing poor scintillators, etc. It does not help in a study of the long-decay-time, low-intensity, luminescence tail. In our present system the decay curves can be accurately determined only up to 24 ns after X-ray cut-off (i.e., at $t < 24$ ns). Beyond this point, in every system studied by the technique here reported, the signal to be measured is comparable to the noise and the measurement cannot be accurate.

In section III (i) it is shown that the troublesome noise does not arise either in the amplification system or in the combination of photomultiplier and amplification system. Neither is noise observed in the absence of the activation of luminescence—even though the X-ray tube may be normally operative. Further, the noise level I_n is directly established by the steady-state luminescence intensity I_p but is not affected by duration of irradiation

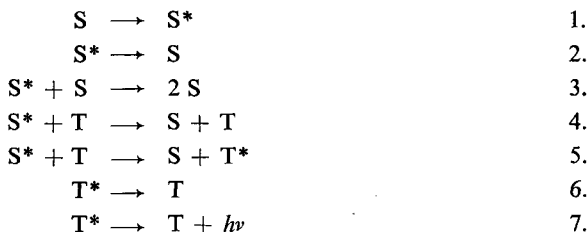
* The X-ray tube used in our early work is that described by PHILLIPS and SWANK [4]. According to one of their oscilloscope pictures the time required to activate the grid with their pulse generator could have been about 1 ns.

of the scintillator. The time delay between pulses is too great (i.e., $\sim 1/60$ s) to attribute the noise level I_n to time delay in receipt of the light signal. We have concluded that the troublesome noise originates in the image converter itself and is attributable to the set-up of a steady-state of gaseous conductivity determined *on the average* by the steady-state luminescence intensity. This conductivity may be set up and maintained on each cycle, as a result of acceleration of the photo-electrons by the normal 5 kV cathode-plate voltage and bombardment of some constituent of the tube (e.g., its wall or possible residual gas). We do not fully understand how such noise is solely dependent on the illumination intensity. However, we hope to eliminate this possible source of noise by pulsing a control grid inside the image converter so that the photo-electrons can travel the full length of the tube only at a time t very closely approaching t_d .

Thus, our immediate effort will be addressed to further refinement of the decay-time measurements. However, they have been sufficiently accurately made so that we can now make a few reliable statements about the shapes of these decay curves and the correlated implications.

V. Analysis and interpretation of luminescence decay curves

Consider the simple system composed of a solvent S with decay time τ_1 for the excited species S^* and scintillator solute T with decay time τ_2 for the excited species T^* . The possible reactions pertinent to this examination are



Then

$$\frac{1}{\tau_1} = k_2 + k_3[S] + (k_4 + k_5)[T] \quad (1)$$

$$\frac{1}{\tau_2} = k_6 + k_7 \quad (2)$$

where the k 's are rate constants and the brackets indicate concentrations. The experimental luminescence intensity I , at low $[T]$ and over a limited range of time t after cut-off of a "square" X-ray pulse, is adequately represented by the equation

$$I = I_0 \frac{\tau_1}{\tau_1 - \tau_2} \left(e^{-t/\tau_1} - \frac{\tau_2}{\tau_1} e^{-t/\tau_2} \right) \quad (3)$$

which follows from straightforward consideration of the mechanism given. At sufficiently high $[T]$, $1/\tau_1$ has such a high value that the first term in the parenthesis is effectively negligible and the decay curve is simple first-order. Apart from the minor correction resultant from the 0.8 ns fall-time of the X-ray pulse, this situation exists for benzene solutions containing more than 4.5 g *p*-terphenyl per liter and for all cyclohexane solutions so far studied.

At such adequately high concentrations of scintillator solute, the simple first-order decay is not maintained when observations are extended over a long period (cf. Fig. 4). Instead, another decay process enters; the luminescence intensity (apart from the initial correction) is represented by a general equation of the form

$$I = A e^{-t/u} + B e^{-t/v} \quad (4)$$

where neither u nor v are necessarily decay times in the sense in which we customarily employ those terms.

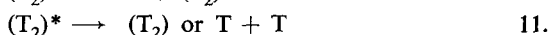
Various mechanisms may be suggested in explanation of this result. In this paper we indicate in only the briefest way the mathematical consequences of two such suggestions: extension of the domain hypothesis to the solute and a form of solute self-quenching.

1. CONSIDERATIONS OF SOLUTE "DOMAINS"

According to the domain hypothesis as applied to solvents [5] [6] [7] molecules of the same kind tend to aggregate in small domains as a result of geometric convenience; chemical forces are negligibly involved in such domain formation and the domains have no relation to ordinary concepts of dimers, trimers, tetramers, etc. On the other hand, the regularity within a domain is so great that excitation transfer within the domain (exciton motion) is postulated to occur with great freedom and great rapidity [8]*. In consequence, the probability of light emission within a domain is decreased and the decay time of an isolated domain may be thereby increased, although the character of the emission spectrum is not necessarily significantly affected. It is suggested that at sufficiently high concentrations of solute, solute domains containing two molecules (i.e., (T_2)) exist in concentration determined by equilibrium considerations, so that



and, in addition to the reactions already given, we should also consider



If we define τ_3 by

$$\frac{1}{\tau_3} = k_{11} + k_{12}$$

it follows that in the "high solute concentration" region

$$I = I_0 \frac{k_5 k_7 \tau_2}{k_5 k_7 \tau_2 + k_9 k_{12} K_8 [T] \tau_3} \left[e^{-t/\tau_2} + \frac{k_9 k_{12} K_8 [T]}{k_5 k_7} \cdot \frac{\tau_3}{\tau_2} e^{-t/\tau_3} \right] \quad (5)$$

where K_8 is the equilibrium constant for reaction 8. Equation (5) is of the same form as (4) and, in this view, u and v really represent decay times. Justification for the possible

* The matter of velocity of excitation transfer is discussed extensively by Magee, Förster and various discussants [8]

use of equation (5) depends on analysis of the effects of pre-exponential terms on the shapes of the actual decay curves as affected by concentration.

2. CONSIDERATIONS OF TRANSIENT DIMERS

In an alternative view of the cause of the low-intensity tail we examine the implications of the self-quenching theory as proposed by FÖRSTER [9] [10] [11]. In such case we ignore the possibility of reactions 8—12 and consider instead the reactions



where T_2^* is a dimer resultant from resonance interaction between two solute molecules, one excited and the other unexcited. It is not our purpose in this paper to develop the full mathematical implications; it is enough to say that the resulting luminescence-time relationship is of the form of equation (4) but that u and v are not unique decay times. They are instead mixed functions of decay times and rate constants for reactions 13 and 15. Also, the relationship between A and B is more complicated than that shown by equation (5).

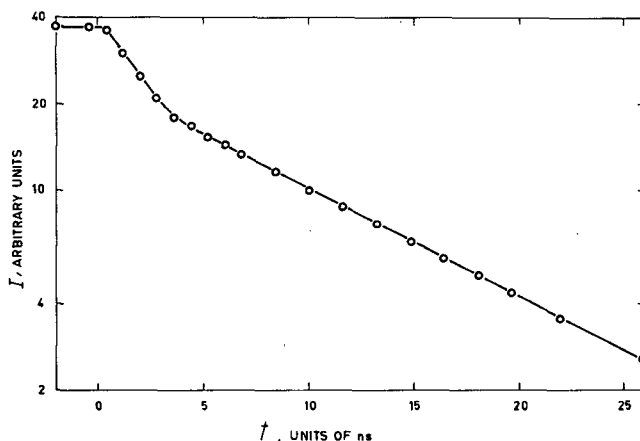


Fig. 7

Luminescence decay curve for 12 g PPO per liter of cyclohexane, deaerate I does not include noise. $\tau_2 = 1.6$ ns, $\tau_3 = 11.6$ ns. (cf. Fig. 4 for comment on τ_2 and τ_3)

In the same connection, mention should be made of the suggestion by BERLMAN [12] that a second luminescence process



* BERLMAN [12] gives some results for solutions in xylene based on an oscilloscopic display technique.

is responsible for a long-decay-time tail. The mathematical consequences are as shown by equation (5) but such a view entails the notion that the low-intensity tail refers to luminescence of wavelength distribution different from that shown in the initial portion of the luminescence. According to Berlman, the emission spectrum of PPO (2, 5-diphenyl-oxazole) in xylene varies significantly with concentration, as might be expected on the basis of his suggestion. The concentration effect is shown in Berlman's paper for a concentration of 100 g liter⁻¹. In our work we find evidence for significant contribution of τ_3 even at the lowest solute concentrations employed, so that it is not certain that his finding is germane to an analysis of our results.

Fig. 7 shows a typical luminescence decay curve for PPO dissolved in deaerated cyclohexane. In that case we find $\tau_2 \sim 1.6$ ns and $\tau_3 \sim 11.6$ ns*. Fuller details of this and other work, in which we examine the applicability of the various theories to our various results, are described in forthcoming papers.

ACKNOWLEDGEMENT

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DISCUSSION

E. Gatti (Italy): Would it be possible to combine your technique of time analysis of light emission with a wavelength analysis by placing filters before the image converter and looking at decay wave-forms at different wavelengths?

M. Burton (United States of America): We have already done this in one case, but we were not satisfied with our work at that time and we are repeating it. At the present moment we are examining the fluorescence spectra and as soon as we have the fluorescence spectra established as a function of concentration, we will be in a better position to select appropriate filters and we will then do exactly what you suggested.

C. J. Borkowski (United States of America): I should like to inquire whether the effect of the X-rays on the structure of the image amplifier is completely negligible in your measurements. Does it produce any tail, for example, and is this subtracted out?

M. Burton: This is in fact described in the paper. An experiment we did completely eliminated the possibility that the tail was noise. There is no possibility that X-rays are getting through to that point because the glass of our scintillator container is too thick for 30-kV X-rays to penetrate. We did the experiment with the chamber in place.

L. Reiffel (United States of America): I am aware of micro-wave cavity studies which show that the emission-time of electrons from surfaces is short, and of the order of about 10^{-13} s, but can you be sure of the linearity of the photo-emitter in these times with complex multi-alkali cathodes?

M. Burton: I do not know. I have always assumed that in the time of 10^{-10} s, whatever electrons were going to be emitted from the photo-emitter would be emitted and I know of no evidence to the contrary on that point. I would really like to know if there is evidence against that. In our paper we mention that the shapes of our logarithmic decay curves are independent of the steady-state luminescence intensity, within a factor of 10 for the latter.

L. Reiffel: I know only of this study at 10^{-13} for the emission time at low levels, while for fancier photocathodes I understand that there are some time-dependent effects, but I do not know the details.

M. Burton: But 10^{-13} s is three orders of magnitude less.

L. Reiffel: Yes, I realize that, but at these higher intensities I wondered whether a problem would exist at the longer times.

M. Burton: Do you mean there would be a saturation effect which would slow up the emission of electrons?

L. Reiffel: A fatigue effect of some sort.

M. Burton: All I can say is that these times would be very long for atoms. This is what we must remember. For an atom which would normally emit at 10^{-13} s a time of 10^{-10} s is like eternity. Perhaps I am entirely wrong, but it never occurred to me that there would be any possibility of a fatigue of 10^{-10} s. I would really like information on this point.

J. B. Birks (United Kingdom): The deviation from a simple exponential decay in the scintillation emission of liquid solutions in the time region around 10 ns, reported by Professor Burton, is a surprising result. It differs from the results reported by others, notably the Argonne group (Swank, Buck, Philips, Basile) who observed simple

exponential decay in the toluene-terphenyl system over several decades and over a wide concentration range. The slow (ion-recombination) component has a decay time of around 100 ns, so that Professor Burton's results indicate either a faster delayed component than this, or alternatively some error in the experiments. The experiments on cyclohexane solution are not directly relevant to liquid scintillators since cyclohexane is not a π -electron system and is not used as a scintillator solvent.

We have been studying the decay of photo-fluorescence of liquid solutions using optical excitation by a Malmberg-type hydrogen lamp, and observing with a 56 AVP photomultiplier and pulse-sampling oscilloscope. In some systems, e.g. pyrene solutions, the emission can be separated into two components by optical filters. The first component, which is prompt and decays exponentially, is due to the monomer, and decreases in intensity with increase in concentration. The second component, which shows a finite rise-time and also decays exponentially, is due to the excited dimer (eximer) emission. The intensity increases and the rise-time decreases with increase in concentration. Similar dimer emission of lower intensity may occur in other systems, and could account for non-exponential decays which depend on concentration. It is essential to use optical excitation to distinguish such effects from those due to ionization.

M. Burton: We hope ourselves, perhaps this summer, to use light sources with our apparatus and we may then be able to refine to another order of magnitude some of the experiments which have been done with optical excitation. I am very glad to know about Dr. Birk's work and I hope to see the results of it. As for the comparison of our work with that of the Argonne group, we have worked in close and appreciative contact with them and are acquainted with their results. They worked over an intensity range of one decade; our work is frequently over a range of 2 decades or more. Any disagreement with the results of the Argonne group is in part in the intensity region to which their experiments have not adequately penetrated, and, in part, results from application of such data. The slow decay time, it may be noted from this report, is around 10 ns, not 100 ns as stated by Dr. Birks. I should note that we have done experiments with benzene as well as with cyclohexane, the full details of which appear in other publications. Benzene transfers energy considerably less rapidly than does cyclohexane; cyclohexane is a particularly good solvent for mechanism studies because the transfer time from solvent to solute is immeasurably small and thus does not interfere with determination of other quantities. Dr. Birks' suggestion of an ion-recombination component does not seem to pertain to our results.

THE NON-PROPORTIONAL RESPONSE OF NaI(Tl) TO γ -RAYS AND ELECTRONS AND ITS EFFECT UPON THE CRYSTAL RESOLUTION

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Abstract — Résumé — Аннотация — Resumen

The non-proportional response of NaI(Tl) to γ -rays and electrons and its effect upon the crystal resolution. Measurements have been made of the scintillation efficiency (light output L , per unit energy input, E) for γ -rays absorbed in NaI(Tl) crystals. The results were sufficiently accurate to allow the evaluation of dL/dE for γ -rays and hence to demonstrate the variation of dL/dE with density of ionization along the path of the photo-electrons ejected by the primary γ -rays.

The resolution of a crystal for the total absorption of γ -rays was shown to vary in a similar way to previously published results. Experiments indicated that variations throughout a crystal in the efficiency of light collection do not appreciably affect the resolution. Owing to the non-proportional response of NaI(Tl) to electrons, the light output resulting from the total absorption of a γ -ray varies according to the number and energy of electrons amongst which its energy is distributed. Approximate calculations show that this effect makes a considerable contribution to the anomalous crystal resolution.

La réponse non proportionnelle de NaI(Tl) aux rayons γ et aux électrons, et ses effets sur le pouvoir de résolution des cristaux. L'auteur a mesuré le rendement de scintillation (quantité de lumière produite L , par unité d'énergie fournie E) pour des rayons gamma absorbés par des cristaux de NaI(Tl). Les résultats sont suffisamment précis pour permettre une évaluation de dL/dE pour les rayons γ et, en conséquence, pour démontrer que dL/dE varie avec la densité d'ionisation le long du parcours des photoélectrons éjectés par les rayons γ primaires.

L'auteur a montré que le pouvoir de résolution d'un cristal pour l'absorption totale des rayons γ varie d'une manière analogue à celle que révélaient les résultats publiés antérieurement. Il ressort des expériences faites que les variations, dans l'ensemble du cristal, du rendement de collection de la lumière n'influent pas sensiblement sur le pouvoir de résolution. Etant donné la réponse non proportionnelle de NaI(Tl) aux électrons, la quantité de lumière produite, qui résulte de l'absorption totale d'un rayonnement γ , varie selon le spectre des électrons. Des calculs approximatifs montrent que cet effet contribue considérablement aux anomalies du pouvoir de résolution des cristaux.

Отклонение от пропорциональной ответной реакции кристалла NaI(Tl) на воздействие гамма-лучей и электронов и влияние этого отклонения на разрешающую способность кристалла. Были проведены измерения эффективности сцинтилляции (световой выход L на единицу подаваемой энергии E) для гамма-лучей, поглощенных кристаллами NaI(Tl). Полученные результаты были достаточно точными, чтобы сделать возможным определение соотношения dL/dE для гамма-лучей и, исходя из этого, выявить изменения соотношения dL/dE в зависимости от плотности ионизации на пути прохождения фото-электронов, испускаемых первичными гамма-лучами.

Было установлено, что разрешающая способность кристалла в отношении суммарного поглощения гамма-лучей изменяется аналогично результатам, уже опубликованным ранее. Опыты показывают, что переменная эффективность сбора света во всей толще кристалла не оказывает заметного влияния на его разрешающую способность. Ввиду отступлений от пропорциональности ответной реакции кристалла NaI(Tl) на воздействие электронов, световой выход, получающийся в результате суммарного поглощения гамма-

лучей, изменяется в зависимости от числа тех электронов и их энергии, среди которых эта энергия распределяется. Приблизительные подсчеты показывают, что аномалии в разрешающей способности кристалла должны быть в значительной мере приписаны этому воздействию.

Respuesta no proporcional del NaI(Tl) a los rayos gamma y a los electrones, y su efecto sobre la resolución del cristal. El autor ha efectuado mediciones de la eficacia luminosa (emisión de luz L , por unidad de energía recibida, E) de cristales de NaI(Tl) al absorber rayos γ . Los resultados son suficientemente exactos para poder evaluar el cociente dL/dE para los rayos γ y, por lo tanto, ver como varía con la densidad de ionización a lo largo del recorrido de los fotoelectrones arrancados por el rayo γ primario.

Se demuestra que la resolución de un cristal para la absorción total de rayos γ varía de forma similar a la expuesta en publicaciones anteriores. Los experimentos indican que las variaciones en la eficiencia de colección de luz en el volumen de un cristal no afectan de manera apreciable a la resolución. Como la respuesta del NaI(Tl) a los electrones no es proporcional, la emisión de luz resultante de la absorción total de un rayo varía según el número y las energías de los electrones entre los que se distribuye la energía del fotón. Un cálculo aproximado muestra que este efecto contribuye notablemente a la resolución anómala del cristal.

I. The non-proportional response of NaI(Tl) to γ -rays

1. INTRODUCTION

ENGELKEMEIR [1] has shown that the response of NaI(Tl) crystals to γ -rays is not proportional to energy. Over an energy range of 0.01 to 1.3 MeV he found that the scintillation efficiency, light output per unit energy, varied by $\sim 15\%$. LOMONOSOV *et al.* [2] have made similar measurements and for two of their three crystals they found variations which were similar to those detected by Engelkemeir. However, one crystal showed much smaller effects, particularly for energies above 50 keV, where the changes in efficiency were only $\sim 4\%$.

In the present experiment, accurate measurements have been made of the scintillation efficiency for the total absorption of γ -rays with energies between 0.046 to 1.333 MeV. The crystal used was $1\frac{1}{2}$ in in diam. and 1 in long and was cut from material provided by Hilger & Watts Limited. Amplified pulses from the photomultiplier were recorded on a multi-channel analyser and the whole system was frequently calibrated by a precision pulse generator. The temperature of the multiplier and crystal was kept constant to within 0.2°C and calibrations with a standard γ -ray source were made to check for drifts in the multiplier gain. Only γ -rays of well established energies were used for measurement.

2. RESULTS AND DISCUSSION

The scintillation efficiency L/E , where L represents the light output and E the energy, is plotted as a function of energy in Fig. 1. Over the range covered by the full line, the values of L/E are likely to have errors of less than 0.3% . The dotted line at the low energy end represents less accurate measurements made using X-rays emitted by K — capture isotopes.

Above 0.2 MeV, L varies almost linearly with E . This is demonstrated by the broken line in Fig. 1 which shows values of dL/dE calculated from the results by using the

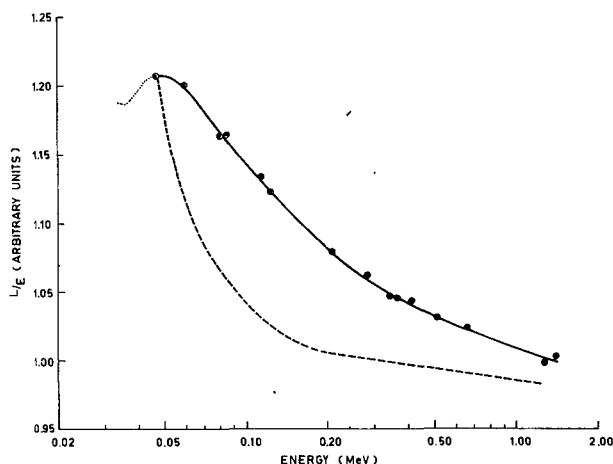


Fig. 1

L/E (full line) and dL/dE (broken line) v. energy for the $1\frac{1}{2} \times 1$ in crystal

full curve in the same figure to smooth the experimental data. Between 0.2 and 1.3 MeV dL/dE varies by only 3% and the light output is given by

$$L = \text{constant} \times (E + 21 \text{ keV}).$$

Below 0.2 MeV the majority of absorptions take place by photoelectric capture in the K-shell of the iodine atom, which gives rise to an electron with an energy less than that of the original quantum by 33 keV, the K absorption energy for iodine. In this region the values of dL/dE for a given energy of γ -ray can be related directly to

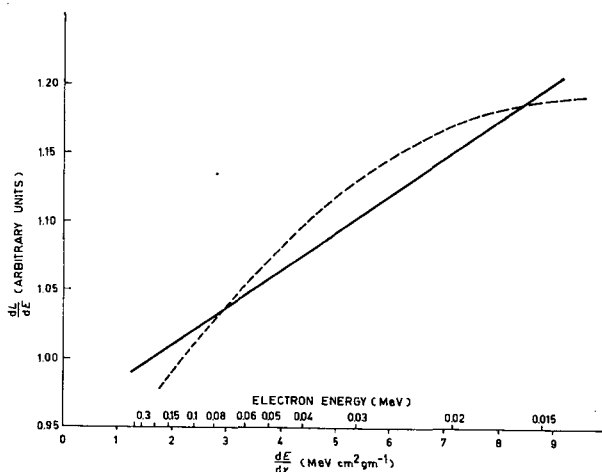


Fig. 2

dL/dE v. dE/dx for electrons in sodium iodide. The full line is for the present experiment. The broken line represents the semi-empirical theory of Meyer and Murray

a particular energy of photo-electron and hence to its rate of energy loss, dE/dx . dL/dE versus dE/dx for an electron is shown as the full line in Fig. 2. The broken line on the same graph shows the predicted variation of dL/dE from the semi-empirical theory of MEYER and MURRAY [3].

Five other crystals were subjected to a more limited series of measurements of L/E . Although the results were substantially the same, there were significant differences. The measurements represented by Fig. 1 showed that L/E at 50 keV exceeded that at 1.3 MeV by 20.0%. In other crystals the excess varied between 17.2% and 20.0%. The variations between crystals are greater than the inaccuracies of measurement.

Most crystals for which measurements have been published exhibit similar degrees of non-proportionality and only the one measurement by NEMILOV *et al.* [2], which has been mentioned above, has produced results very dissimilar to those presented here. It may be that large differences of response do exist but that by growing crystals to give a high scintillation efficiency the degree of non-proportionality is being determined at the same time. Such effects would be detected by investigating the response of crystals grown under different conditions and with varying Thallium contents.

II. The resolution of NaI(Tl) crystals for γ -rays

1. INTRODUCTION

The important factors which affect the resolution of a scintillation spectrometer for γ -rays fall into two groups. One represents variations in the amount of light produced within the crystal and in the efficiency with which it is transferred to the photocathode to produce electrons, the second, the effect of the photomultiplier, arising from the statistical nature of the photo electric emission and the multiplication processes. KELLY *et al.* [4] have shown that an instrument with a resolution of 7.7% at 0.66 MeV, has a contribution of 4% from the photomultiplier and one of 6.6% from the crystal.

BISI and ZAPPA [5] found that over a considerable range of energies the resolution of an instrument, R , varied with the γ -ray energy, E , according to the equation

$$R^2 = a + \beta/E$$

where a and β are constants. A formula of this type can be derived from the theoretical expressions given by BREITENBERGER [6]. This shows that if the number of photons produced within the crystal varies normally, the term a represents the effect of variations in transfer efficiency, i.e. in the efficiency with which a photon is collected to produce a useful photo-electron, and the term β/E represents the photomultiplier contribution. Because of the similarity of the experimental and theoretical equations, Bisi and Zappa suggested that the variations in transfer efficiency together with the photomultiplier statistics could account for the observed values of the resolution.

2. VARIATIONS IN TRANSFER EFFICIENCY

In the present experiment measurements of the instrument resolution for the $1\frac{1}{2} \times 1$ -in crystal gave a value of 7.9% for 0.66 MeV, and showed a variation with energy very similar to that found by Kelly *et al.* and Bisi and Zappa. An attempt to estimate the variations in transfer efficiency was made by measuring the differences in pulse-height arising when various parts of the crystal surface were irradiated by a narrow collimated beam of low-energy γ -rays (0.0597 MeV). The maximum differences

in pulse-height, due to the scintillations being produced in various parts of the crystal, were 2%. The same result was obtained with a 2×2 -in crystal of a similar resolution.

In order to irradiate only the part of the crystal near to the photocathode, a small piece of active indium foil producing 0.191 MeV γ -rays was placed between the crystal and the multiplier. The pulse-height in this case was only 1% different from that obtained when the same source irradiated the opposite face of the crystal.

If the pulse-heights from a crystal have a rectangular distribution between limits 2% apart, there is a contribution to the resolution of 1.3%. This cannot account for the experimental value of α determined by Bisi and Zappa, which is equivalent to a resolution of 6.7%, nor the intrinsic crystal resolution measured by Kelly *et al.*

3. THE EFFECT ON THE RESOLUTION OF THE NON-PROPORTIONAL RESPONSE OF NaI(Tl) TO ELECTRONS

In the total absorption of a γ -ray there is a distribution in the number and energy of electrons taking part. As the light produced by an electron is not exactly proportional to its energy, the light output for a γ -ray will vary according to the number of electrons involved in the absorption and the way in which the energy is shared amongst them. Two processes have been found to be important. The first is the spread in number of Compton encounters involved, the second the variation in number and energy of δ -rays produced in the slowing down of the electrons which originally share the γ -ray energy. To a first approximation the two effects are independent and so they are considered separately.

(a) *The effect of Compton encounters*

In the energy region considered a γ -ray can be totally absorbed in a crystal by photoelectric capture or by one or more Compton encounters followed by photoelectric absorption. It is necessary to determine the distribution in number of Compton collisions involved and, because the calculation is complex, drastic simplifications have been made.

The energy range 0–1.1 MeV was divided into 0.1 MeV intervals and the properties of γ -rays in an interval were said to be the same as that of its mean energy. The relative numbers of γ -rays undergoing Compton and photoelectric encounters comes directly from the cross-sections and the distribution in energy of the scattered quanta can be calculated from the Klein Nishina formula. Scattered γ -rays from the first and all subsequent encounters were assumed to be emitted isotropically and to be uniformly distributed over the central plane of the crystal. The probability of interaction of a scattered quantum could then be calculated using the crystal efficiencies given by VEGORS, MARSDEN and HEATH [7].

The results are illustrated in Fig. 3 which shows the probability that N Compton collisions will be involved in the total absorption of a γ -ray of 0.66 MeV. Calculations were made for a $1\frac{1}{2} \times 2$ -in crystal because this was the smallest for which suitable efficiencies were available. For comparison, results for an infinite crystal are also shown. Although the functions are discontinuous, the points representing each size of crystal have been connected by curves so that they can be distinguished from each other. It can be seen that the number and distribution of Compton encounters does not vary rapidly with crystal size, and for this reason the present figures for a $1\frac{1}{2} \times 2$ -in crystal have been used in the following calculations and the results compared with those for other crystal sizes.

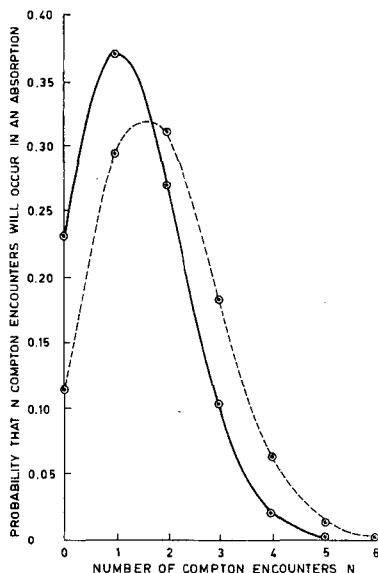


Fig. 3

The probability that N Compton collisions will occur in the full absorption of γ -ray of 0.66 MeV

The full curve is for a $1\frac{1}{2} \times 2$ in crystal and the dotted curve for an infinite crystal

It is necessary, in order to simplify the calculations, to find a convenient expression giving the variation of light output with energy for electrons. For energies greater than 0.15 MeV, dL/dE is almost constant and hence above this energy L_e , the light output, and E_e , the energy, are connected by:

$$L_e = \text{constant} (E_e + K) \quad (1)$$

The value of the constant K which can be expressed in units of energy can be estimated from the previous measurements of L/E for γ -rays in the following way.

When a γ -ray is absorbed as a result of N Compton encounters followed by photoelectric absorption $N + 1$ energetic electrons will be produced and it is probable that all of them will obey equation (1). The total light produced can therefore, be expressed as:

$$L_\gamma = \text{constant} \left[\sum E_e + (N + 1)K + C \right] \quad (2)$$

The first two terms represent the sum of the contributions from the fast electrons, while the term C represents the electrons produced by the processes of emission and capture of X-rays which follow photoelectric absorption. In the majority of cases absorption will take place in the K-shell of the iodine atom and C can be regarded as a constant. Its value can be obtained from the previous measurements of light output for X-rays of energy just above the K absorption edge for iodine. The mean value of N for a given γ -energy comes from the calculations above and so if a value for K is assumed L/E for γ -rays can be calculated. When K is chosen as 11.5 keV a good fit to the results in Fig. 1 is obtained over the energy range 0.2 to 1.1 MeV.

Equation (3) shows that there is a spread in light output arising from variations in N ; all other terms in the equation are constant. The results illustrated in Fig. 3 show that for a 0.66 MeV γ -ray, N has a standard deviation of 1.0. This is equivalent to a standard deviation in the light output of 1.0×11.5 keV and produces a contribution of 4.1% to the crystal resolution.

(b) *The effect of δ -rays*

In the slowing down of an electron of 0.66 MeV roughly 30 δ -rays of energy > 1 keV are produced and approximately 3 > 10 keV. These will in general be more efficient at producing scintillation light than the more common processes of energy loss, and because the number of δ -rays varies statistically there will be a resulting spread in light output.

The response of a crystal to an electron of energy e can be obtained from the previous results as the difference in light produced by two energies of X-ray, one of 33 keV, the K absorption energy for iodine, and one of $33 + e$ keV. This will give the total contribution to a scintillation of a δ -ray of energy e . When such a δ -ray is not produced it is assumed that the energy is dissipated by other processes which have a scintillation efficiency equal to the average of that for fast electrons. If, in any energy interval, the number of δ -rays is assumed to vary normally, the contribution of those with energy > 1 keV to the resolution for an electron of 0.66 MeV is found to be 3.2%.

The values used for the scintillation efficiency of δ -rays of energy > 10 keV were not very accurate and the effect of those of 1 keV upon the resolution has been ignored. Both these apparent sources of error are unimportant because the greatest contribution to the resolution comes from the small number of δ -rays with energies above 10 keV and for these the errors are likely to be small.

The number of δ -rays produced per unit energy loss by a fast electron does not vary rapidly with primary energy and so the number resulting from the total absorption of a γ -ray is roughly the same, irrespective of the way in which the primary γ -ray energy is shared amongst the electrons in the original absorption process. To a first approximation, therefore, the effect of δ -rays on the resolution for a γ -ray is the same as the contribution to that of electron of the same total energy.

(c) *Sum of contributions to the crystal resolution*

The total contribution to the resolution of the effects discussed above are illustrated in Fig. 4 in which graphs are plotted of R^2 against energy. Curve (a) shows the measurements of intrinsic crystal resolution made by KELLEY *et al.* [4]. Curve (b) shows the component due to variations in the number of Compton encounters while (c) shows the effect of δ -rays. Assuming that the maximum variations in transfer efficiency were 2% a contribution represented by line (d) is obtained. The sum of these effects, assuming them to be independent, is represented by line (e).

The calculated values of the crystal resolution are at all energies similar to those from the experimental results of Kelley *et al.* Thus the non-proportional response of NaI(Tl) to electrons makes a very important contribution to the resolution owing to the variations in number and energy of electrons which finally dissipate within the crystal the energy of the γ -rays. The calculations are only approximate but the similarity of the computed and experimental results show that the non-proportional response could be completely responsible for the hitherto unexplained crystal resolution.

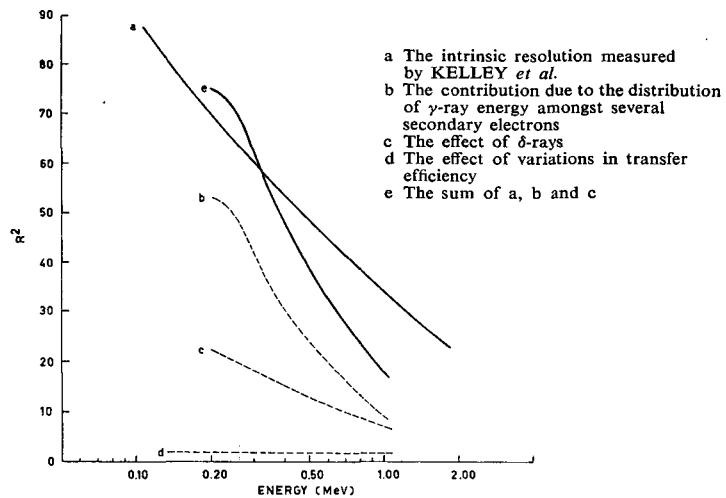


Fig. 4
 The intrinsic resolution of a crystal

The resolution for an electron should be less than that for a γ -ray of the same energy because there will be no component due to Compton collisions. Measurements of the crystal response for electrons and γ -rays of the same energy could therefore give an experimental check of some of the above calculations. The electron could be produced within the crystal by Compton scattering, and the energy defined by a second counter operated in coincidence, so that only those events in which a γ -ray scatters through a particular angle are selected. A second experimental check is suggested by the work of DER MATEOSAN *et al.* [8], which indicated that the variations in scintillation efficiency which exist at room temperature are modified by cooling the crystals. Measurements of the degree of non-proportionality and of resolution at different temperatures might, therefore, indicate the way-in which these two properties are connected.

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SOME EFFECTS OF TEMPERATURE ON THE PERFORMANCE OF SCINTILLATION COUNTERS

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Abstract — Résumé — Аннотация — Resumen

Some effects of temperature on the performance of scintillation counters. Increasing industrial application of scintillation counters has focused attention on those factors governing stability, resolution and speed of response. In this paper the effects of temperature are considered.

The mean and single-pulse light output of a number of phosphors have been examined. In sodium iodide there is not a continuous change. It has been shown that below 20°C the height of the photo-peak decreases with decreasing temperature whereas the mean current increases. Above 20°C the mean current decreases as the temperature increases and the photo-peak amplitude remains unchanged. Similar effects have been observed in other phosphors. The time-response of light output in sodium iodide has also been examined over the temperature range + 60°C to - 60°C. The magnitude of these effects depends on the dose rate and the total dose delivered to the phosphor. Explanations are associated with temperature dependence of radiationless transitions and with metastable states in the phosphor.

Using light from a sodium iodide crystal and observing mean current and photo-peak amplitude, venetian blind type photomultipliers with SbCs₃ photo cathodes exhibited a decrease in gain with increase in temperature. The gain variations include short and long time-constant components, the former due to direct thermal effects on the electrodes and the latter to caesium migration within the tube.

The photo cathode has been shown to contribute about one-half of the total observed effect.

Quelques effets de la température sur le comportement des compteurs à scintillation. Etant donné l'emploi croissant des compteurs à scintillation dans l'industrie, on s'attache de plus en plus à l'étude des facteurs régissant la stabilité, le pouvoir de résolution et la vitesse de réponse. Le mémoire examine quels sont les effets de la température.

Les auteurs ont étudié la quantité de lumière produite par une impulsion unique et en moyenne dans plusieurs scintillateurs. Dans l'iodure de sodium, il n'y a pas de variation continue. Il a été démontré qu'au-dessous de 20°C, l'amplitude du pic photoélectrique diminue lorsque la température décroît, tandis que le courant moyen augmente. Au-dessus de 20°C, le courant moyen décroît lorsque la température augmente, tandis que l'amplitude du pic photoélectrique reste inchangée. Des effets analogues ont été observés pour d'autres scintillateurs. Le temps de réponse dans l'iodure de sodium a également été examiné pour les températures comprises entre + 60°C et - 60°C. L'importance de ces effets dépend de l'intensité de dose et de la dose totale fournie au scintillateur. Les explications sont fondées sur les variations des transitions non radiatives en fonction de la température et sur des états métastables dans le scintillateur.

Lorsque l'on emploie la lumière émise par un cristal d'iodure de sodium et que l'on observe le courant moyen et l'amplitude du pic photoélectrique, les photomultiplicateurs du type E.M.I. N° 6097, munis de photocathodes en SbCs₃, accusent une diminution du gain lorsque la température augmente. Les variations du gain englobent les composantes constantes de courte et de longue durée, les premières dues aux effets thermiques directs sur les électrodes, et les secondes aux migrations du césium à l'intérieur du tube.

Les auteurs montrent qu'environ la moitié de l'effet observé est attribuable à la photocathode.

Некоторые влияния температуры на работу сцинтилляционных счетчиков. Так как сцинтилляционные счетчики стали больше применяться в промышленности, это заставляет

сосредоточить внимание на факторах, действующих на устойчивость, разрешающую способность и скорость ответных реакций. В настоящем докладе рассматриваются некоторые аспекты влияния температуры.

Был изучен средний и единичный выход световых импульсов целого ряда люминофоров. Изменения в йодистом натрии происходят неравномерно. Было установлено, что при температурах ниже 20°C амплитуда фотопика уменьшается по мере падения температуры, тогда как средняя интенсивность тока возрастает. Свыше температур в 20°C средняя интенсивность тока падает по мере поднятия температуры, а амплитуда фотопика остается без изменений. Аналогичные явления наблюдались и в других люминофорах. В интервале температур от $+60^{\circ}\text{C}$ до -60°C была изучена также временная характеристика светового выхода в йодистом натрии. Величина этих воздействий зависит от мощности дозы и от подаваемой люминофору суммарной дозы. Объяснения этих явлений связаны с зависимостью от температуры неизлучающих переходов и от метастабильных состояний в люминофоре.

Путем использования света, излучаемого кристаллом йодистого натрия, и наблюдения за средней интенсивностью тока и амплитудой фотопика было установлено, что венецианские фотоумножители слепого типа с фотокатодами из SbCs_3 дают меньшее усиление по мере возрастания температуры. Колебания величины усиления включают в себя короткие и длинные компоненты константы времени, причем первая из них вызывается непосредственным термическим воздействием на электроды, тогда как вторая объясняется миграцией цезия в электронной лампе.

Было установлено, что приблизительно половина общего наблюдаемого воздействия должна быть приписана действию фотокатода.

Algunos efectos de la temperatura sobre el funcionamiento de los contadores de centelleo. Las aplicaciones industriales cada vez más extensas de los contadores de centelleo hacen que la atención se centre en los factores que rigen su estabilidad, su poder de resolución y su velocidad de respuesta. La presente memoria estudia los efectos de la temperatura.

Los autores han examinado en diversas sustancias luminiscentes, la intensidad media de la luz emitida, así como la correspondiente a un solo impulso. No se observa un cambio continuo en el yoduro sódico. Se muestra como por debajo de los 20°C , la altura del pico fotoeléctrico decrece al disminuir la temperatura, mientras que la corriente media aumenta. Por encima de 20°C , la corriente media disminuye al aumentar la temperatura, mientras que la amplitud de los picos fotoeléctricos permanece constante. Se han observado efectos similares en otras sustancias. También se ha estudiado el tiempo de respuesta de la generación de luz en el yoduro sódico en el intervalo de temperatura de 60°C a -60°C . La magnitud de estos efectos depende de la intensidad de irradiación y de la dosis total que reciba la sustancia. La explicación de estos fenómenos va asociada a la influencia que ejerce la temperatura sobre transiciones no radiativas y a los estados metastables que se producen en la sustancia.

Cuando se emplea la luz de un cristal de yoduro sódico y se observa el valor medio de la corriente y la amplitud de los picos fotoeléctricos, los fotomultiplicadores del tipo de persiana veneciana (E.M.I. Hayes, Middlessex, tipo 6097) con fotocátodo de Cs_3Sb muestran una disminución de ganancia al aumentar la temperatura. Las variaciones de la ganancia incluyen componentes de constante de tiempo corta y larga. Las primeras se deben a efectos térmicos directos en los electrodos y las segundas a la migración del cesio en el interior del tubo.

Se muestra cómo aproximadamente la mitad del efecto total observado se debe al fotocátodo.

I. Introduction

Increasing scientific and industrial application of scintillation counters has focused attention on factors which govern gain stability, resolution and speed of response. In this paper some effects of temperature on the efficiency and time response of energy conversion in the phosphor and on the characteristics of the photomultiplier are reported.

1. THE PHOSPHOR

Previous work [1 — 5] on the temperature-dependence of mean light output from different phosphors subject to a constant intensity of gamma-radiation has shown that, for all phosphors examined, the mean light output decreases with increasing temperature so that at some temperature, usually a few hundred degrees centigrade, luminescence is reduced to zero. This result is accountable in terms of the increasing probability of radiationless transitions.

Unfortunately, from such a simple model and from the more sophisticated models recently proposed by VAN SCIVER [6] and by MEYER and MURRAY [7] [8], it is not possible to predict the variation of pulse spectrum with temperature in the commonly used alkali-halide phosphors.

We have confirmed the general form of variation of mean-light output with temperature in a number of phosphors and have measured the change in Cs^{137} pulse spectrum from a single crystal of NaI(Tl) over the temperature range $+60^\circ\text{C}$ to -60°C . It is shown that, in general, the variations observed fit a model in which energy transfer occurs by electrons through metastable states of long life-time.

The response of phosphors to transient changes in radiation intensity is of importance in many industrial applications. Response times are due to phosphorescence and, in NaI(Tl) , vary markedly with temperature. Results given below show the magnitude of variations, which appear to be associated with three discrete energy levels of electron traps.

2. EFFECTS OF TEMPERATURE ON PHOTOMULTIPLIER GAIN

Changes of gain with temperature in a variety of photomultipliers have been investigated by a number of authors [4] [5] [9] [10] [11], and although significant variations in temperature co-efficient have been found in tubes of the same construction, for any single tube results are reproducible and free of hysteresis. Using light from a phosphor, a decrease in gain with increase in temperature has consistently been reported [4] [9] [10] [11], the magnitude of this negative temperature co-efficient being within the range 0.2 to 0.5% per $^\circ\text{C}$. With a monochromatic light-source of wavelength less than $4500\text{ \AA}$, which is the region of maximum intensity for phosphors used in scintillation counting, a negative temperature co-efficient was also found, in agreement with results obtained using a phosphor as light source. At longer wavelengths, however, photo-multiplier tubes have been shown to exhibit positive temperature co-efficients [5] [12] [13] [14].

Variations in temperature change both sensitivity to photo-electron emission of the photocathode and secondary electron emission at the dynodes. The results reported conflict as to which component is most responsible for gain variations [9] [13].

The experiments described below were initiated to find the effects of temperature on types of photomultipliers not previously investigated. Negative temperature co-efficients of tube-gain were obtained and it was found that whilst both photocathode and dynodes contribute, the predominant effect is attributable to the photocathode.

II. Apparatus

1. TEMPERATURE CONTROL OF PHOSPHOR AND PHOTOMULTIPLIER

The apparatus used to obtain independent control of the temperature of phosphor and photomultiplier is shown in Fig. 1. Phosphor and photomultiplier were mounted

in a duralumin container and separated by a perspex light guide, 10 cm long, optically coupled at the interfaces with a high-viscosity silicone oil. Two lengths of copper tubing wound round the duralumin enclosure acted as heat-exchangers to maintain temperatures at the required values and the whole system was thermally lagged.

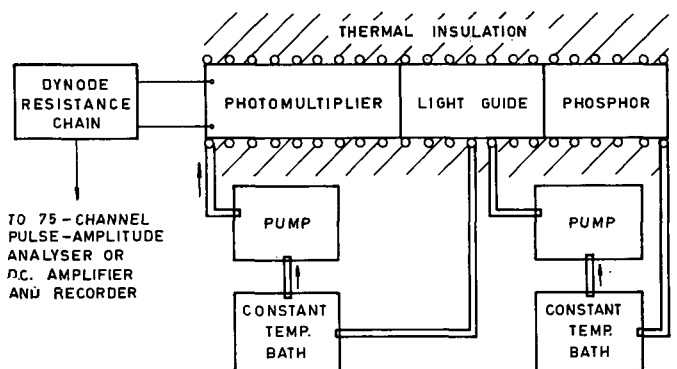


Fig. 1

Diagram of experimental arrangement used to obtain independent temperature control of the phosphor and photomultiplier

For operation at temperatures above ambient, water was used as the heating medium and was circulated through the copper tubing by a centrifugal pump. The same arrangement was used for low-temperature operation but the circulating fluid was trichloroethylene refrigerated by passing it through a heat-exchanger containing solid carbon dioxide dissolved in trichloroethylene. The temperature at the centre of the light guide reached 25°C in 30 minutes after a change in temperature of the circulating fluid from 20 to 25°C. The temperatures quoted are those of the circulating fluid.

2. ELECTRONICS

Fig. 2 shows the circuits used to measure the mean anode current and pulse spectrum from the photomultiplier. The use of low-impedance (200 k Ω) interdynode resistors avoided pulse saturation and the final two dynodes were decoupled with large (1 μ F) capacitors. The dynode resistor chain was enclosed in polyethylene tubing and mounted in a separate compartment adjacent to the photomultiplier. Mean anode current was measured with a high-gain amplifier and recorder. The pulse output was recorded on a 75-channel pulse-amplitude analyser.

3. MEASUREMENTS ON PHOTOMULTIPLIERS

The effects of temperature on photomultipliers were investigated using light from a NaI(Tl) crystal. After assembly of the apparatus in daylight several hours dark-adaptation time was necessary to avoid spurious effects arising from phosphorescence in the phosphor and photomultiplier. To avoid variations in photomultiplier gain caused by current-induced "fatigue" in the dynodes, the maximum anode current was never allowed to exceed 1 μ A [15] [16].

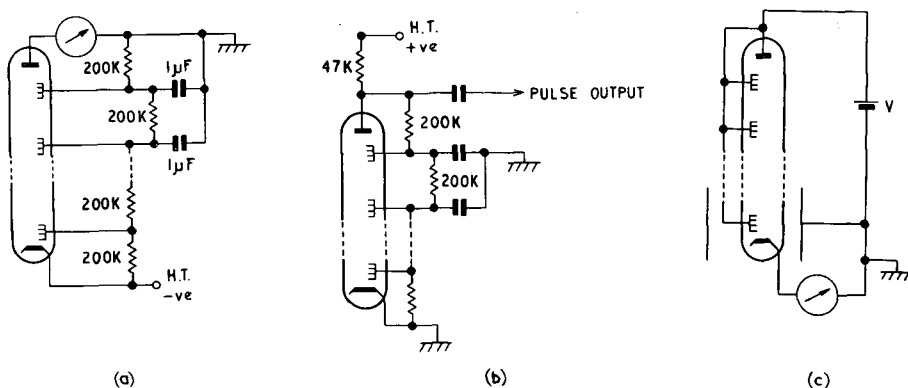


Fig. 2

Photomultiplier and photocell current-monitoring circuits

For pulse-height measurements a $0.5 \mu\text{C}$ Cs^{137} source was used. When measuring the mean anode current, in order to keep thermionic electron current less than 1% of the total anode current at 60°C , it was found necessary to use a more intense source (5 mc of ^{60}Co) delivering a dose rate of 50 mr/h to the crystal. With the resulting light intensity only some 600 V could be applied to the eleven-stage photomultiplier since at higher voltages the mean anode current exceeded $1 \mu\text{A}$ and fatigue effects became important.

To differentiate the contribution to changes in gain from temperature effects on the photocathode and dynodes, attempts were made to control the temperature of the photocathode during normal operation of the photomultiplier. With a non-inductive spiral heating-element adjacent to the photocathode surface and a perforated copper disc this was unsuccessful and the method finally chosen was to operate the photomultiplier as a photocell by short-circuiting the dynodes. The circuit used is shown in Fig. 2 (c). For these measurements the photocathode pin was surrounded by an earthed guard ring of colloidal graphite.

4. MEASUREMENT OF PHOSPHORS

Pulse measurements were restricted to an examination of the spectrum from $\text{NaI}(\text{Tl})$ irradiated with a $0.5 \mu\text{C}$ source of Cs^{137} .

Mean current measurements were made on four types of phosphor. The Zn S (Ag) and plastic phosphors were excited by beta particles from a 5 mc $\text{Sr}^{90}/\text{Y}^{90}$ source and the $\text{NaI}(\text{Tl})$ and liquid phosphors by gamma-radiation from a source of 5 mc Co^{60} . In all cases the photomultiplier voltage was adjusted to give a mean anode current less than $1 \mu\text{A}$.

5. THE EFFECT OF TEMPERATURE ON THE OPTICAL COUPLING SYSTEM AND ON THE INTER-DYNODE RESISTORS

To exclude the possibility of changes observed in mean current and pulse spectrum being due to variation in the transmission characteristics of the light-coupling system,

the stability of guide and coupling fluid with changes in temperature were investigated independently. The temperature of a central section of the guide, about 6 cm long, was varied between -60°C and $+60^{\circ}\text{C}$, the ends of the guide being held constant at $+20^{\circ}\text{C}$, the same temperature as the phosphor and photomultiplier. No changes were observed.

The effect of temperature on the fluid interface was investigated using a Pyrex photocathode window optically coupled between two 10-cm long Perspex light guides, the ends of which were coupled to a NaI(Tl) phosphor and photomultiplier. Raising the temperature of the double Pyrex/Perspex interface from 18°C to 49.5°C resulted in only 1% decrease in mean anode current in the photo-multiplier in the first 2 hours and no change in the following 24 hours operation.

Independent variation of dynode resistor temperatures between -60°C and $+60^{\circ}\text{C}$ had no observable effect on the mean anode current of the photomultiplier.

III. Observations of some temperature effects in phosphors

1. EXPERIMENTAL RESULTS

The variations in meanlight output of a number of phosphors irradiated over the temperature range $+60^{\circ}\text{C}$ to -60°C with gamma-rays from Cs^{137} are shown in Fig. 3. For each phosphor, the change in light output was measured by the change in anode current in the associated photomultiplier, using the arrangement shown in Fig. 1, the variation with temperature being plotted as the ratio of the current at the observed temperature to the current at $+20^{\circ}\text{C}$.

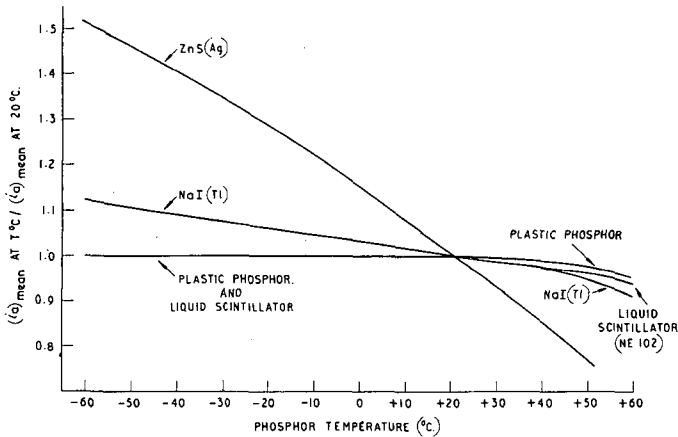


Fig. 3

Variation of photomultiplier mean anode current, (ia) mean with phosphor temperature for a number of phosphors. Curves are normalized to $+20^{\circ}\text{C}$.

It is evident that, of the phosphors examined, the effect of temperature is least in polyvinyl toluene and greatest in ZnS(Ag) . In NaI(Tl) the light output varies

approximately linearly with temperature over the range -60°C to $+20^{\circ}\text{C}$, the slope of the curve being about 0.15% per $^{\circ}\text{C}$. Between $+20^{\circ}\text{C}$ and $+60^{\circ}\text{C}$ however, the slope of the curve gradually increases with increasing temperature.

The effect of temperature on the shape of the spectrum obtained from a NaI(Tl) crystal irradiated with Cs^{137} gamma-rays is shown in Fig. 4. As the temperature increases from $+20^{\circ}\text{C}$ to $+60^{\circ}\text{C}$ there is a slight decrease in amplitude of the photo-peak but as the temperature is reduced from $+20^{\circ}\text{C}$ to -60°C both the photo-peak amplitude and resolution decrease rapidly.

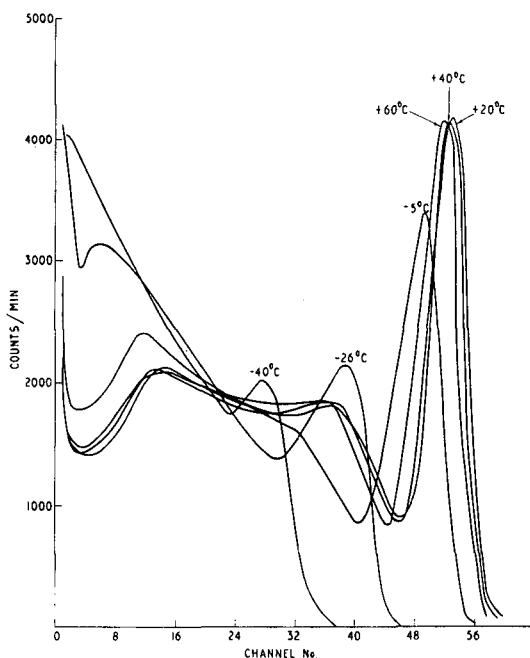


Fig. 4

Variation of Cs^{137} spectrum with temperature of a NaI(Tl) phosphor

The shapes of the photomultiplier output pulses corresponding to the Cs^{137} photo-peak showed a decrease in rate of decay at the lower temperatures.

The magnitude of long duration phosphorescence in NaI(Tl) is apparent from Fig. 5 which shows the decay at room temperature following irradiation at a dose rate of 1 r/h for periods of 2, 5, 10 and 30 min. The longest exposure corresponds approximately to a saturation condition i.e. to a state where increase in exposure time at the fixed dose rate does not result in increased phosphorescent intensity.

The effect of temperature on the decay of phosphorescence in NaI(Tl) is shown in Fig. 6. These results were obtained for saturation conditions following an exposure of one hour at a dose rate of 1 r/h. There is a rapid decay above room temperature, a very long decay around 0°C and an increase in decay rate at lower temperatures.

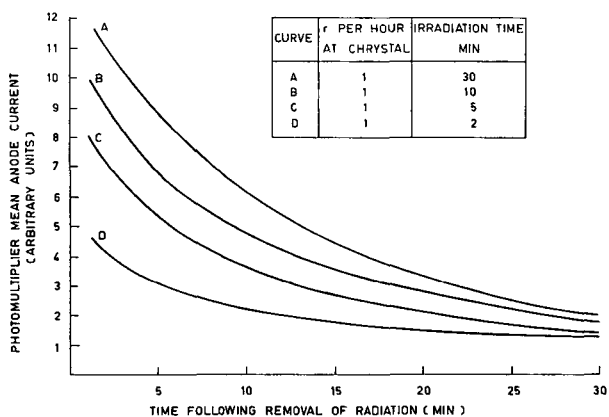


Fig. 5

Phosphorescence in sodium iodide following irradiation at constant dose rate

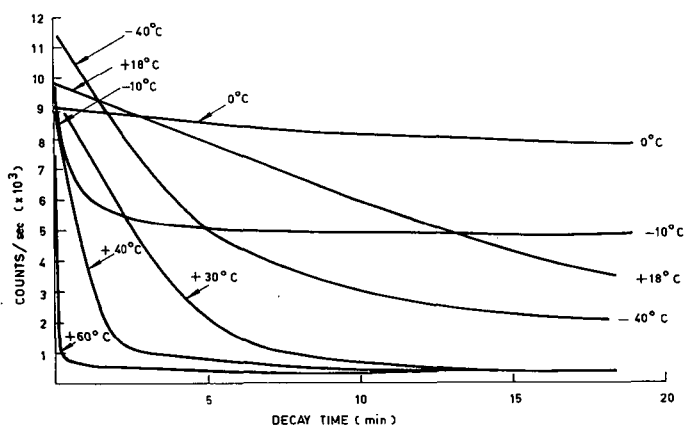


Fig. 6

Temperature dependence of phosphorescence in NaI(Tl) phosphor irradiated for one hour at 1 r/h

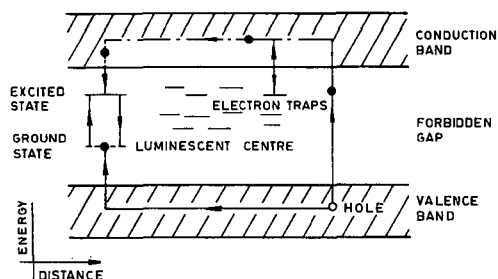


Fig. 7

Theoretical model of processes of fluorescence and phosphorescence

2. DISCUSSION

A theoretical model which explains the results qualitatively is shown in Fig. 7.

The perfect crystal of NaI is an insulator with all allowed energy bands either completely full or empty. During radiation electrons are raised into the conduction band and electrons and holes, either free or bound together as an exciton, move through the crystal. The TI^+ ion which has excited states within the energy range of the forbidden gap acts as the luminescent centre. It may be excited by direct photon interaction, by exciton energy transfer or by electron capture. In the last case a hole must also be captured to conserve charge neutrality, since following the capture of an electron the TI^+ ion is neutralized and is thus electron-negative with respect to the mean crystal potential. With the capture of a hole the neutral TI atom becomes a TI^+ centre in an excited state. The radiation decay to the ground state which follows is independent of the mechanism by which the centre is excited. The probability of direct photon interaction with the luminescent centre is very small in the phosphors used here on account of their low activator concentrations.

It is unlikely that the initial conversion of high-energy gamma photons to excitons, or electrons and holes, is in any way temperature dependent, because the energy transfers involved are so much higher than thermal kinetic energies. Temperature is therefore considered to influence only the final stages of the luminescent process: that is the transfer of energy to radiative or non-radiative centres.

Although conclusive evidence for energy transfer by free electrons or excitons is not yet available, in sodium iodide irradiated by gamma radiation, it has been suggested that a large fraction of the luminescence is due to capture of first, an electron and then a hole [6]. This mechanism makes it possible for the thallium centre to be placed in a metastable state not normally accessible to the exciton. Electron energy transfer thus favours intense thermoluminescence as found in NaI(Tl).

Besides TI^+ ions, a normal crystal also contains other impurities such as F-centres and lattice defects which may be capable of capturing an electron, or an exciton, and are important in determining the thermoluminescent characteristics of the system. Evidence of the influence of other trapping centres is given by VAN SCIVER [6] who reports only half the intensity of thermoluminescence radiation in NaI (10^{-6} TI) as compared with NaI (10^{-3} TI) and weak luminescence in the pure crystal.

The model of Fig. 7 is also applicable to Zn S (Ag) but in this case energy transfer is by free electrons [17].

It is assumed here that when irradiated at a uniform rate, electrons in traps are in thermal equilibrium with electrons in the conduction band and the mean light output is then independent of the lifetime of the metastable trapping sites. The effect of reducing the temperature of the crystal when irradiated at constant intensity is to raise the Fermi level so that a new population of traps become important in determining the thermoluminescent characteristics of the phosphor.

It is clear from Fig. 3 that the effect of temperature on mean light output is largest in Zn S (Ag) and in NaI(Tl) where electron-energy transfer is important and smallest in the liquid scintillator and plastic phosphor where energy transfer is mainly by excitons.

The variation of Cs^{137} photo-peak amplitude and resolution with temperature as shown in Fig. 4, demonstrates the dependence of light output on the presence of metastable states and supports the assumption that electrons are mainly responsible for energy transfer. Between $+20^\circ\text{C}$ and $+60^\circ\text{C}$ the mean time spent by electrons

in metastable states is short due to the high thermal energy of the lattice. Between $+20^{\circ}\text{C}$ and -60°C , under constant radiation intensity, the Fermi level moves through a region of high trap concentration resulting in long-lived metastable states in the system.

Explanation of the change in spectral shape with temperature is clear if we consider events following the production of a photo-electron in the phosphor. Degradation of the photo-electron energy to thermal energies results in the production of secondary electrons, some of which are captured at the luminescent centres whilst others are held at metastable trapping sites. At temperatures above 20°C it is suggested that electrons from the metastable sites are recombined at the luminescent centres within the resolving time of the electronic system ($0.1\ \mu\text{s}$) and before the next primary event occurs in the phosphor. At low temperatures, however, the life-times of metastable states are long compared with the electronic resolving time, so that some electrons arising from a photoelectric event are likely to be held back in traps and released at a later time. This diminishes the amplitude of the photo-peak and increases the number of lower energy events.

It is clear from the curves of Fig. 6, that the long-duration phosphorescence in NaI(Tl) does not vary monotonically with temperature and this is compatible with a system having two or more quasi-discrete energy levels of metastable states. One possible transition has been suggested by Van Scliver [6]. The long duration of decay at 0°C indicates an energy region having a maximum number of metastable states. At temperatures below 0°C these states are "frozen in" and other higher energy states become involved in the phosphorescent process.

Phosphorescence decay-curves at room temperature for a number of crystals have been plotted logarithmically and show three exponential components. The rapid part of the decay is associated with exponentials having half periods of approximately 1 and 5 min and the long-duration decay with a half-period of about 40 min. The presence of these three components of decay is further evidence of three levels of metastable states in the crystal.

Following irradiation at constant intensity, the time-to-decay to some fraction of the steady-state light output depends both on dose rate and on the total exposure of the crystal. For long exposures an equilibrium is reached when electrons in traps and long life-time metastable states are in thermal equilibrium in the crystal. Curve A of Fig. 5 approaches this condition.

From the evidence presented it is suggested that the distribution of metastable states in the crystals of NaI(Tl) which have been examined is not optimum for room temperature operation. Improved speed of response is possible with higher temperature operation.

IV. Effect of temperature on "venetian blind"-type photomultipliers

1. VARIATION OF MEAN ANODE CURRENT

The mean anode current decreases with increasing temperature and the change in current following an abrupt change in temperature was found to have components of both short and long duration. Curves typical of results from a number of photomultipliers are shown in Fig. 8. On heating there is a relatively large fall in mean current during the first few hours and this is followed by a smaller decrease extending over a longer period. The magnitude of the changes depends on the temperature and on

the tube. Although there are significant variations from tube to tube, the general pattern remains the same. The rate of recovery of the anode current when the tube is cooled to the initial temperature is also shown in Fig. 8. Besides being dependent on the initial temperature change, the time of recovery also depends on the time during which the tube is held at the elevated temperature. The time-constant of the long-term component of recovery is longer than that for heating. Total recovery may take several days.

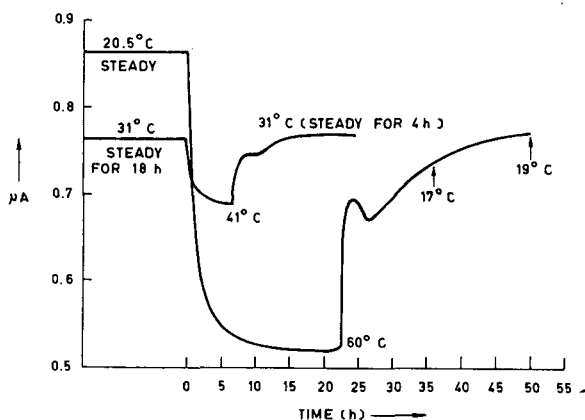


Fig. 8

Variation with time of mean anode current of a photomultiplier

Evidence that the results were not due to current-induced fatigue was obtained by repeating one series of measurements, but only applying the photomultiplier voltage

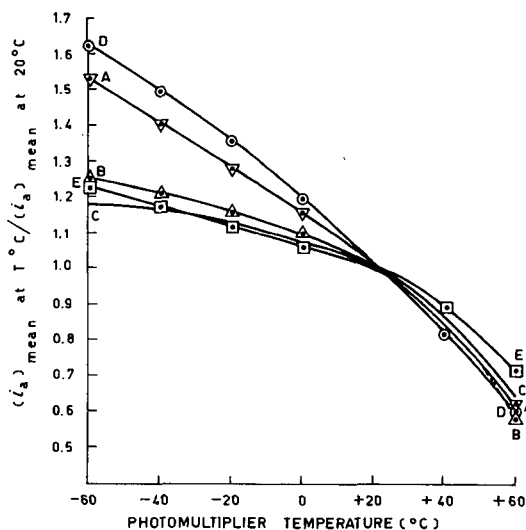


Fig. 9

Variation of mean anode current, (i_a) mean with photomultiplier temperature

periodically. The results obtained were almost identical with those for the same tube operated with the voltage continuously applied.

The magnitude of the variation of mean current with temperature thus depends on the time of measurement, at least up to the time when the long term effect has stabilized. In Fig. 9, curves are shown for a number of tubes operated over the range -60°C to $+60^{\circ}\text{C}$, each point being recorded 5 h after the initial temperature change. All the tubes examined show negative temperature co-efficients but variations from tube to tube are large even though all were of the same type.

To find the relative contribution of photocathode and dynodes to the gain change with temperature, several photomultipliers were operated as photo-cells using the first dynode as collector. Curves of cathode current versus applied voltage with this arrangement operating at $+20^{\circ}\text{C}$ and $+60^{\circ}\text{C}$ are shown in Fig. 10. The radiation intensity was the same as used to obtain the curves of Fig. 9.

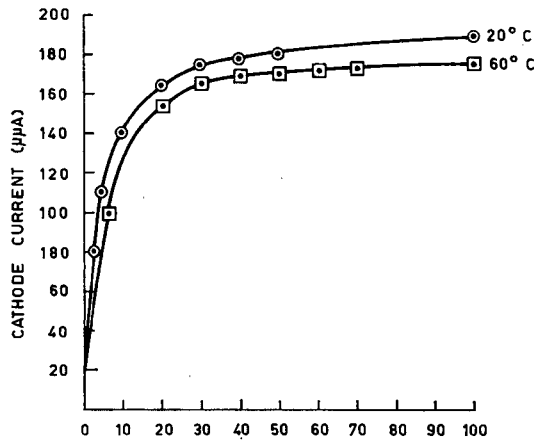


Fig. 10

Variation of photocathode current with applied voltage

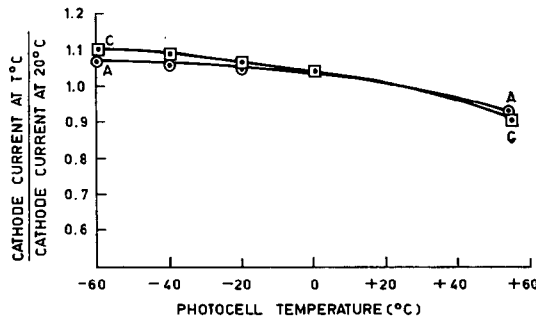


Fig. 11

Variation of photocathode current with temperature

The variation of cathode current with temperature for two tubes operated at 90 V is shown in Fig. 11. The value of current at each temperature was taken three hours after the temperature was changed.

By comparing Figs. 9 and 11, it is clear that the contribution of the photocathode to the total change in gain with temperature in a photomultiplier is many times that of a single dynode and may approach half the total observed effect in the tube.

The change in photocathode current with time after heating from $+37^{\circ}\text{C}$ to $+60^{\circ}\text{C}$ is shown in Fig. 12. In the first part of this curve the source was present only whilst the cathode current was being measured. There is no long-term component. In the second part of the curve the source was permanently in position and the long-term component is very marked. By comparing this curve with those of Fig. 8, it is seen that the initial decrease in current from the photocathode, when subject to continuous illumination, is more rapid than in the complete photomultiplier and the long-term component relatively more important.

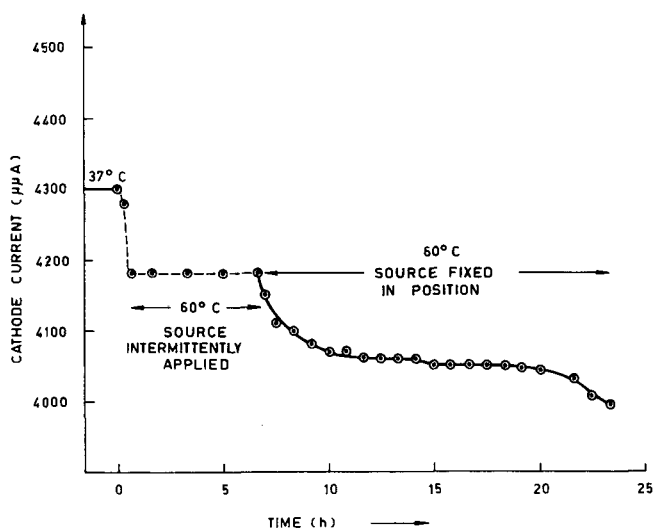


Fig. 12

Variation of photocathode current during operation at $+60^{\circ}\text{C}$

2. VARIATION OF Cs^{137} SPECTRUM

Fig. 13 shows a typical series of spectra measured with a 75-channel pulse-amplitude analyser for a photomultiplier operated in the temperature range $+60^{\circ}\text{C}$ to -60°C . The curves are similar and the main effect is a change in gain. In fact, by increasing the photo-multiplier voltage to compensate for the decrease in gain at the higher temperatures, the curves can be very nearly superimposed. It was found that after a change in temperature of about 20°C the photo-peak stabilized in about 2 h and there was no long-term component of change as observed in the DC measurements.

It was also observed that the photo-multiplier voltage had a negligible influence on the results. Measurements made at 400 and 1500 V, with the external amplification adjusted to give the same overall gain, resulted in the same change in pulse amplitude

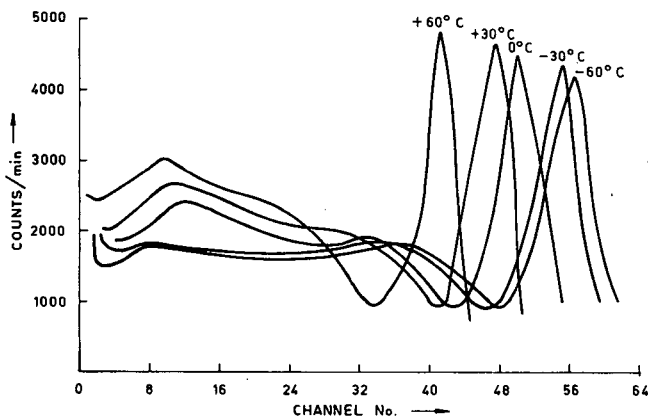


Fig. 13
Change in Cs ^{137} spectrum with photomultiplier temperature

and the same stabilizing period when the temperature was increased from $+19^\circ\text{C}$ to $+55^\circ\text{C}$.

A long-term decrease in pulse amplitude of similar magnitude to those indicated in Fig. 12, was only observed with the photocathode at $+60^\circ\text{C}$ following sustained irradiation with a light intensity equal to that used in the mean current measurements.

3. DISCUSSION OF THE TEMPERATURE-INDUCED CHANGE IN PHOTOMULTIPLIER GAIN

The observed variations in photomultiplier gains with temperature are largely due to changes in photo-electron emission efficiency at the cathode and secondary-electron emission efficiency at the dynodes.

We shall consider the process of secondary-electron emission in three stages, viz:

- (1) Formation of the secondary electrons;
- (2) Diffusion of the electrons to the vacuum surface;
- (3) Escape of the secondary electrons across the surface dipole barrier. The model is shown in Fig. 14.

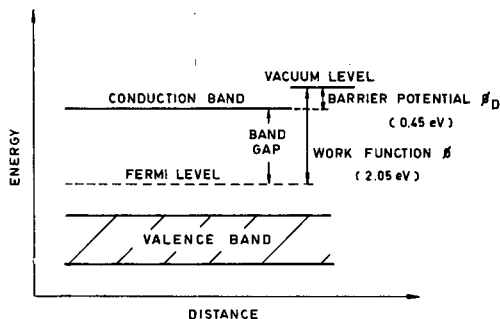


Fig. 14

Illustrating potential barrier, Φ_D , and work function, Φ of an SbCs_3 semi-conductor photo cathode or dynode

The process of secondary-electron formation is independent of temperature but the number of secondary electrons which diffuse to the vacuum surface depends on the frequency of electron-phonon collisions and this is strongly temperature-dependent [18]. Interactions with lattice electrons, electron traps and donor levels also occur in the diffusion process but in a semi-conductor these are not as important as the effect of lattice interactions [19].

The escape probability for electrons which reach the surface is only weakly dependent on the surface dipole barrier since the average energy of the secondary electrons is about 6–8 eV and the barrier potential Φ_D (Fig. 14) is 0.45 eV [20]. Although the total work function Φ is, to a first order, not intrinsically temperature-dependent, changes in Φ and Φ_D are likely to occur as a result of caesium evaporation and redistribution throughout a tube operating at elevated or depressed temperatures. Caesium redistribution can occur even in the absence of a temperature differential as the relative amounts adsorbed on different materials in the photomultiplier will vary with absolute temperature. Loss of caesium from the dynodes will increase the work function and decrease the electron escape probability.

Similar effects will occur in the photocathode and, as the initial energy (about 3 eV) of the photo-electrons is lower than the mean energy of the secondary electrons at the dynodes, changes in lattice-energy and the barrier potential energy are likely to have a greater effect on the photocathode efficiency than on the secondary emission ratio of the dynodes. In addition, the cathode resistance is known to increase with decreasing temperature [13, 21] and this will distort the potential field at the photocathode and result in loss of collector current at the first dynode.

Thus, on decreasing the temperature, decreased lattice interactions will increase the tube gain, increased photocathode resistance will decrease the gain and redistribution of caesium can increase or decrease the gain depending on its redistribution. According to which of these effects predominate the tube gain can thus increase or decrease. However, because of the predominant contribution by the photocathode, the effect of temperature may also depend on the wavelength of the incident radiation.

It has recently been shown that for wavelengths below 5000 Å, which is the range relevant to the phosphor-emission spectrum, the sensitivity of an SbCs_3 photocathode at first increases and then decreases as the temperature is reduced. [13] This result is possibly due to the initial predominance of lattice interactions giving way to increased photocathode resistance and this explanation is further substantiated by the fact that when the photocathode conductivity is increased, the drop at lower temperature disappears.

It would be expected from the above discussion that the contribution of the photocathode to the overall change in gain of a photomultiplier with temperature should be greater than that of a single dynode. As the contribution to the gain from an individual dynode in an 11-stage photo-multiplier is about one tenth of the total, it is apparent that this is true. Increases in photocathode and dynode efficiencies with decreasing temperature are thus probably due to a combination of reduced lattice vibrational energy and lower barrier potentials.

An increase in photocathode sensitivity should also result in a small improvement in resolution but the accuracy of the spectral measurements was insufficient to show this change.

It remains to explain the rapid and delayed changes in mean current following abrupt changes in temperature observed during the measurements of mean current. It is suggested

that the initial fall with increasing temperature is due to an increase in lattice energy and electron-phonon interactions. The delay is probably attributable to the time required for the temperature change induced in the outer metal container to penetrate the glass envelope and reach the electrodes. This is substantiated by the more rapid initial change in the photocell current, compared with that in the photomultiplier. The long time-constant component, mainly in the photocathode, but partly in the dynodes is probably due to fatigue, which results from a redistribution of caesium. It was not observed in the pulse measurements because the intensity of illumination of the photocathode was much smaller than when the mean anode current was measured.

When the temperature of the photo-multiplier is reduced after a long period of high-temperature operation, the initial recovery of gain has a time-constant similar to that of the initial drop, supporting the electron-phonon interaction theory. The long time-constant component of recovery is longer than that during the heating process, probably due to reduced mobility at the lower temperatures.

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A XENON-HELIUM GAS-SCINTILLATION COUNTER

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Abstract — Résumé — Аннотация — Resumen

A xenon-helium gas-scintillation counter. A gas-scintillation counter is developed. The gas is a 10% xenon and 90% helium mixture and is streaming through. The counter is used for discrimination between the heavy and the light fission fragment.

Un compteur à scintillation, à l'hélium et au xénon. Les auteurs ont mis au point un compteur à scintillation à gaz. Le gaz est un mélange de 10% de xénon et de 90% d'hélium et passe à travers le système. Ils utilisent ce compteur pour faire la discrimination entre les fragments de fission lourds et les fragments de fission légers.

Газовый (ксенон-гелий) сцинтилляционный счетчик. Разработан газовый сцинтилляционный счетчик. Газ состоит на 10 процентов из ксенона и на 90 процентов из смеси гелия и пропускается через этот счетчик. Счетчик используется для различения тяжелых и легких осколков деления.

Contador de centelleo de gas xenón-helio. Los autores han perfeccionado un contador de centelleo de gas. Este gas fluye a través del aparato y consiste en una mezcla de 10 por ciento de xenón y 90 por ciento de helio. El contador se emplea para discriminar entre fragmentos de fisión ligeros y pesados.

I. Introduction

The gas-scintillation counter has been studied by several investigators [1—10] and has been used in several laboratories for some years. The pulse height of the counter is independent of the charge and mass of the ionizing particle. It is a linear relationship between the energy of the particle and the pulse height and the energy resolution is good. The decay time is about a few nanoseconds [3] [4]. The counter can work as a fission-fragment counter in the high background of a pile beam.

The light emission from a gas scintillator depends strongly upon the purity of the gas [2] [3] [4] [5] [9]. Organic vapours, carbon dioxide and oxygen have a strong quenching effect. To achieve a satisfactory light emission, it is therefore necessary to use only very pure gases, to avoid leakages in the scintillation chamber, to degas the chamber carefully and to avoid gaskets and o-rings of organic materials. The light emitted from the noble gases has wavelengths mostly in the ultraviolet region [2] [4] [6]. The window of the chamber should therefore have a large transmission for ultraviolet light, or the wavelength has to be shifted inside the chamber. The walls of the chamber should be treated in such a way as to give good reflection for the actual light.

It was decided to build a gas-scintillation counter for a fission experiment, where the energy spectrum of neutrons from thermal fission of U^{235} in different directions relative to the fragment direction is measured by time-of-flight. The gas-scintillation counter is the start counter which also discriminates between the heavy and the light fragment. The counter should be simple and stable.

II. Preliminary measurements

The pulse height and the energy resolution of the gas-scintillation counter have been studied as a function of the sort of gas or gas mixture, the gas pressure, the geometry of the chamber, the surface of the chamber, the wavelength shifter and the material of the window. The α -line of U^{234} and the fission fragment spectrum have been used as standards in these measurements.

A useful scintillator gas is the mixture of argon and nitrogen [2] [5]. The amount of nitrogen necessary for maximum pulse height is dependent on the purity of the gases. Largest pulse heights were obtained for a mixture of 90% argon and 10% nitrogen, in agreement with the result of EGGLER *et al.* [2]. The impurity in both argon and nitrogen was less than 0.001% O_2 with smaller amounts of other impurities. According to NORTHROP *et al.* [8], another very useful gas mixture is 10% xenon and 90% helium. From our measurements this mixture gave 4 times higher pulse heights than the argon-nitrogen mixture. The xenon-helium mixture had an impurity of 0.006% O_2 , 0.0002% H_2 , 0.0017% N_2 and 0.3% Kr.

The pulse height was measured as a function of the gas pressure. The largest pulse height was obtained with a gas pressure as low as possible, still having the particles stopped in the gas. A conical shape of the chamber gave a 20–25% larger pulse height than a cylindrical shape. A soft etching of the aluminium walls of the chamber gave 20% increase in the pulse height. Northrop *et al.* [8] have tested the efficiency of different wavelength shifters. He found that p, p'-diphenylstilbene had the best efficiency, better than p-quaterphenyl. Our measurements were in agreement with their results. However, p-quaterphenyl poisons the gas less than p, p'-diphenylstilbene. A quartz window coated with p-quaterphenyl had about 8% larger transmission than an ordinary glass window coated in the same way. The photocathode had a S-11 response.

III. Final construction

Fresh gas was continuously streaming from a supply bottle through the scintillation chamber and a mercury gas trap into the air. A reduction valve reduced the gas pressure from the level of the supply bottle down to the actual pressure inside the chamber. The streaming rate was adjusted by a needle-valve in the outlet pipe. The mercury gas trap was used to avoid diffusion of air through the needle-valve into the chamber. Fig. 1 shows a detailed drawing of the scintillation chamber and the photomultiplier. The chamber was made of aluminium and shaped conically. The walls were polished mechanically and etched 2 to 3 min in 6 n NaOH. The target or the source and the collimator, 24 mm in diam., were placed at the bottom of the chamber. A quartz or glass window was used. The inner surface of the window was coated with p-quaterphenyl. The quaterphenyl layer was obtained by vacuum evaporation and was about $30 \mu\text{g}/\text{cm}^2$ thick. The gasket and the o-rings were made of teflon. An RCA 6810A photomultiplier was used. White optical paraffin made the optical contact between the window and the photocathode. A gas mixture of 10% xenon and 90% helium was used. Sufficient pressure for stopping the fission fragments was found to be 4 atm. The streaming rate was set to $25 \text{ cm}^3/\text{h}$, i.e. the gas in the chamber was on an average changed in 4 h.

The target or source consisted of UO_2 , $1.24 \text{ mg}/\text{cm}^2$ thick, on a platinum backing. The uranium was enriched to 94% in U^{235} and contained also 1% U^{234} . The collimator was of aluminium, 2.5 mm thick and the holes were 0.8 mm diam. The α -spectrum

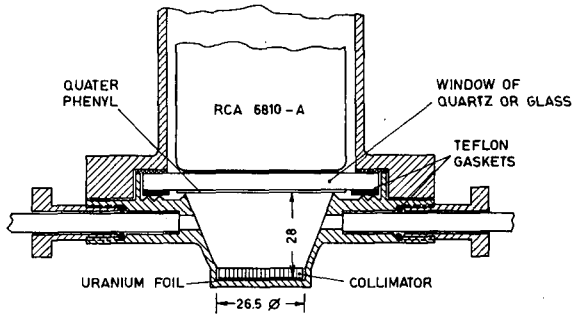


Fig. 1

Gas scintillation chamber

of the source was mainly the 4.76 MeV α -line from U^{234} . The resolution as found from this line was about 20%. Fig. 2 shows a typical energy spectrum of the fission fragments from the slow fission of U^{235} . The target was put in a collimated pile beam from JEEP with a flux of slow neutrons of about 10^7 neutrons/cm² s. For comparison a calculated energy spectrum from a foil of the actual thickness is shown in Fig. 3. The calculation is based upon the energy distribution of fission fragments as measured by BRUNTON *et al.* [11], and measurements by FULMER of the energy of fission fragments as a function of range [12]. As an approximation [13] the stopping power of gold was used instead of UO_2 . The calculation indicated that the main contribution to the resolution came from the slowing down in the uranium foil itself. The position of the two peaks shows an unlinearity which is not understood. With the discriminator level set as indicated, about 6% of the light fragments were counted in the heavy group and vice versa. The resolution obtained with the gas-scintillation counter as a start counter and a plastic scintillator as a stop counter in the time-of-flight experiment was 2.5 ns. The long-term stability of the counter was reasonably good.

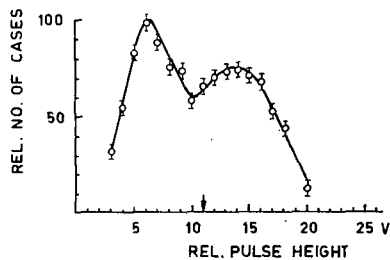


Fig. 2

Experimental energy spectrum of the fission fragments from the slow fission of U^{235} . The target consisted of UO_2 , 1.24 mg/cm² thick

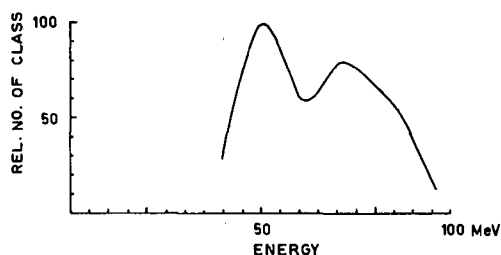


Fig. 3

Calculated energy spectrum of the fission fragments from the foil quoted in Fig. 2

ACKNOWLEDGEMENT

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MISE AU POINT D'UN SCINTILLATEUR GAZEUX DE GRANDES DIMENSIONS DESTINÉ À L'ÉTUDE DE LA SECTION EFFICACE DE FISSION DE L'URANIUM-233 PAR LA MÉTHODE DU TEMPS DE VOL

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Abstract — Résumé — Аннотация — Resumen

Developing a large gaseous scintillator for the study of the fission cross-section of U^{233} by the time-of-flight method. Gaseous scintillators seem to be of value for two purposes: as neutron detectors, and as detectors of ionizing particles when the quantity of material observed is large. A gaseous scintillator of the second type has been developed.

The intention was to study the fission cross-section of U^{233} by the time-of-flight method. It is most important, when using this method, to observe the largest possible quantity of material. A decision was therefore made to observe 2 g of U^{233} (3.4×10^8 a/s g) with a minimum of photomultipliers, a simple and robust arrangement, and a fission detection efficiency of about 70%.

The preliminary tests have shown that absorption in the gas was small, but that absorption on the walls was abnormally high whatever reflector was used.

The use of indium joints and an aluminium housing made it possible to evolve a filling technique which gave good results.

After these tests, the authors were able to design and construct a scintillator comprising six photomultipliers, each viewing 320 mg of U^{233} , divided into four deposits measuring 9×6 cm, with 1.5 mg/cm². They expect to try out this scintillator in the near future.

Very satisfactory results have already obtained with 70 mg of U^{233} per photomultiplier. The electronic equipment to be used with the detector has also been developed; it consists of a rapid diode discriminator, a diode pulse lengthener and a transistorized monostable circuit with a very high trigger sensitivity.

Mise au point d'un scintillateur gazeux de grandes dimensions destiné à l'étude de la section efficace de fission de ^{233}U par la méthode de temps de vol. Il semble que les scintillateurs gazeux présentent de l'intérêt dans deux cas: comme détecteurs de neutrons, et comme détecteurs de particules ionisantes lorsque la quantité de matière observée est grande. On a procédé à la mise au point d'un scintillateur gazeux du deuxième type.

Il s'agissait d'étudier la section efficace de fission de ^{233}U par la méthode de temps de vol. Il est du plus grand intérêt, dans cette méthode, d'observer la plus grande quantité possible de matière. Les auteurs se sont donc fixé pour but d'observer 2 g de ^{233}U ($3.4 \cdot 10^8$ a/s g) avec un minimum de photomultiplicateurs, dans de bonnes conditions de simplicité et de robustesse et avec une efficacité de détection des fissions d'environ 70%.

Les essais préliminaires ont démontré que l'absorption dans le gaz était faible mais que, par contre, l'absorption dans les parois était anormalement élevée quel que soit le réflecteur utilisé.

L'utilisation de joints d'indium et d'une enceinte en aluminium a permis l'élaboration d'une technique de remplissage donnant de bons résultats.

Les auteurs ont pu, après ces essais, dessiner et construire un scintillateur comprenant six photomultiplicateurs, regardant chacun 320 mg de ^{233}U répartis en quatre dépôts 9×6 cm — $1,5$ mg/cm². Ce scintillateur doit être essayé prochainement.

Actuellement, ils ont déjà obtenu des résultats très satisfaisants avec 70 mg de ^{233}U par photomultiplicateur. Ils ont également mis au point l'électronique associée au détecteur; elle comprend un discriminateur rapide à diode, un allongeur à diode et un monostable transistorisé à très grande sensibilité de déclenchement.

Разработка газового сцинтиллятора большого размера, предназначенного для изучения эффективного сечения деления урана-233 методом времени пролета. Обнаруживается, что газовые сцинтилляторы представляют интерес в двух случаях: как нейтронные детекторы и, как детекторы ионизирующих частиц, когда количество наблюдаемого вещества велико.

Приступили к разработке газового сцинтиллятора второго типа в целях изучения эффективного сечения деления урана-233 методом времени пролета.

Самым интересным в этом методе является наблюдение за как можно большим количеством вещества. Поэтому было установлено наблюдение за двумя граммами урана-233 ($3,4 \times 10^8$ а/сек/грамм) при помощи минимального количества фотоумножителей в очень простых, но надежных условиях и при к.п.д. обнаружения деления около 70%.

Предварительные опыты показали, что абсорбция в газе была слабой, и наоборот, абсорбция на стенках была ненормально повышена независимо от используемого рефлектора.

Совместное использование индия и алюминиевой решетки дало возможность найти способ заполнения, который дал хорошие результаты.

После этих опытов стало возможно описать и сконструировать сцинтиллятор, состоящий из шести фотоумножителей, каждый из которых направлен на 320 мг урана-233, размещенного в 4 местах 9×6 см — $1,5$ мг/см². Этот сцинтиллятор должен быть испытан в ближайшее время.

В настоящее время уже получены весьма удовлетворительные результаты с 70 гр урана-233 на фотоумножитель. Разработана также электроника, присоединенная к детектору. Она включает быстрый диодовый дискриминатор, диодовый удлинитель и транзисторный моностабиль с очень большой разрешающей чувствительностью.

Perfeccionamiento de un centelleador gaseoso de grandes dimensiones destinado al estudio de la sección eficaz de fisión del ^{233}U por el método de tiempo de vuelo. Los centelleadores gaseosos parecen presentar interés en dos casos: como detectores de neutrones, y como detectores de partículas ionizantes cuando la cantidad de sustancia observada es grande. Los autores han puesto a punto un centelleador gaseoso del segundo tipo.

Se trataba de estudiar la sección eficaz de fisión del ^{233}U por el método del tiempo de vuelo. Cuando se emplea este método, es muy importante poder observar la mayor cantidad posible de sustancia; por tanto, los autores se fijaron como meta observar dos gramos de ^{233}U ($3,4 \cdot 10^8$ a/s g) con un mínimo de fotomultiplicadores, en una instalación sencilla y robusta, y con un rendimiento de detección de las fisiones del orden del 70%.

Los ensayos preliminares demuestran que la absorción en el gas es débil, siendo en cambio anormalmente elevada en las paredes, sea cual fuera el reflector empleado.

El empleo de juntas de indio y de una envoltura de aluminio permitió desarrollar una técnica de relleno que da resultados satisfactorios.

Tras estos ensayos, los autores pudieron diseñar y construir un centelleador que comprende seis fotomultiplicadores, cada uno de los cuales está enfrentado a 320 mg de ^{233}U repartidos en cuatro depósitos de 9×6 cm, cuyo espesor se eleva a $1,5$ mg/cm². Este centelleador se ensayará en fecha próxima.

Los autores han obtenido ya resultados muy satisfactorios con 70 mg de ^{233}U por fotomultiplicador. Han puesto también a punto los dispositivos electrónicos asociados al detector: comprenden un discriminador rápido de diodo, un alargador de diodo y un monoestable transistorizado de muy elevada sensibilidad de disparo.

Introduction

La section efficace de fission de ^{233}U par la méthode du temps de vol doit être mesurée prochainement en utilisant l'accélérateur linéaire de Saclay comme source de neutrons pulsée. Si l'on veut utiliser pleinement les possibilités de cet appareil, il est nécessaire d'observer une assez grande quantité de matière. A titre d'exemple, les mesures de section efficace de fission de ^{235}U effectuées par A. MICHAUDON *et al.* [1] ont été faites avec 2 g d'uranium contenus dans une chambre à fission.

L'utilisation d'une quantité analogue de ^{233}U demandait la mise au point d'un détecteur plus rapide que les chambres à fission, ceci à cause de la forte activité α de ^{233}U ($3,4 \cdot 10^8$ α /s g). Du fait de la petite taille des détecteurs à couche actuellement mis au point, notre choix s'est porté sur les scintillateurs gazeux.

BOLLINGER [2] et HAVENS [3] avaient déjà utilisé ces scintillateurs pour l'étude de la section efficace de fission de ^{239}Pu et de ^{235}U . Toutefois, les performances de leurs détecteurs nous ont paru assez faibles, et nous avons été amenés à étudier systématiquement le dessin et la technologie d'un scintillateur de grande taille.

Les problèmes que nous avons dû résoudre étaient donc essentiellement technologiques et, en ce qui concerne la physique du phénomène, nous nous sommes appuyés essentiellement sur les travaux de WU [4] et de KOCH [5].

Les buts fixés étaient les suivants:

1. Réalisation technologique aussi simple que possible.
2. Bonne stabilité dans le temps et si possible sans recyclage de gaz.
3. Observation d'environ 2 g de matière fissile avec le plus petit nombre possible de photomultiplicateurs.
4. Réduire le plus possible la quantité de matière non fissile située dans le faisceau de neutrons et n'utiliser que des matériaux dont la section efficace soit plate dans la région d'énergie intéressante.

Nous allons reprendre tous ces points en détail.

Choix du gaz et des réflecteurs

Il nous est apparu nécessaire d'éviter, dans la mesure du possible, l'emploi de plastiques changeurs de longueur d'onde, à cause de la dérive dans la scintillation qu'ils produisent à la longue.

Nous avons comparé le rendement lumineux d'un mélange argon-azote à celui du xénon pur. Il nous est apparu que, si l'on utilise une optique en verre, les deux solutions étaient sensiblement équivalentes. Au contraire, si l'on utilise une optique de quartz, le xénon pur est environ 2,4 fois plus lumineux que le mélange $\text{Ar} + \text{N}_2$. Comme, d'autre part, le xénon donne une scintillation beaucoup plus rapide que le mélange argon-azote, nous avons donc décidé d'utiliser du xénon.

En ce qui concerne le réflecteur, nous avons constaté que la magnésie donnait des résultats légèrement supérieurs à ceux obtenus avec de l'aluminium. Toutefois, l'emploi de la magnésie est peu pratique, et nous avons adopté en définitive un réflecteur en aluminium.

Technologie de l'enceinte

On pouvait concevoir deux types d'enceintes, les unes en verre scellé et les autres en métal. Le premier type nous a paru difficile à mettre en œuvre sur le plan technolo-

gique. Nous avons donc essayé d'utiliser des enceintes en aluminium fermées par des fenêtres de quartz. Les joints de fixation étaient en indium.

On a trouvé que cette solution donnait de bons résultats en ce qui concerne la stabilité. On a constaté que l'on avait intérêt à procéder en trois étapes pour le remplissage:

1. Pompage trois jours.
2. Premier remplissage. On laisse se stabiliser le scintillateur pendant huit jours.
3. On vide à nouveau et l'on fait immédiatement le remplissage définitif.

Dans ces conditions, on a obtenu une stabilisation au bout de deux jours; on ne notait pas de dérive appréciable entre le troisième jour et la fin du deuxième mois après le remplissage.

Détermination de l'épaisseur des dépôts

Pour déterminer l'épaisseur des dépôts, on a tracé les spectres de fission de ^{235}U pour différentes valeurs de celle-ci. Une courbe typique est celle obtenue avec un dépôt de $250\text{ }\mu\text{g/cm}^2$ d'uranium naturel (fig. 1).

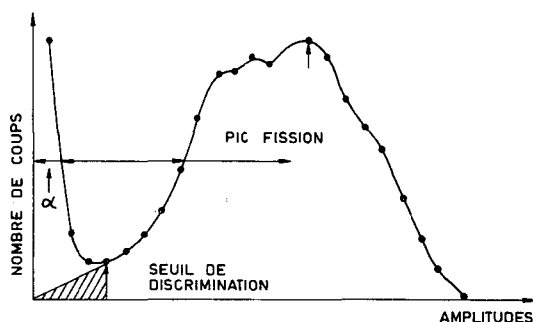


Figure 1

Spectre différentiel des fragments de fission.

La partie hachurée correspond à la perte dans l'efficacité de détection des fissions lorsque l'on place le seuil du discriminateur de façon à ne compter que des fissions.

La quantité hachurée sur la figure représente une estimation de la perte d'efficacité sur la détection des fissions lorsque l'on place un seuil de discrimination tel que l'on ne compte aucun alpha de la radioactivité naturelle.

Dans ces conditions, si l'on représente cette perte d'efficacité en fonction de l'épaisseur des dépôts, on trouve la courbe présentée sur la Figure 2.

On voit que l'épaisseur des dépôts n'est pas un facteur critique. Nous avons choisi une épaisseur de $1,5\text{ mg/cm}^2$.

De plus, pour améliorer les qualités optiques du scintillateur, nous avons été amenés à évaporer une couche d'aluminium de $50\text{ }\mu\text{g/cm}^2$ sur ces dépôts.

Détermination de la géométrie du scintillateur

Un certain nombre de conditions géométriques nous étaient imposées. Les dépôts devaient être perpendiculaires à la photocathode des photomultiplicateurs, et la dimension des dites photocathodes nous était donnée.

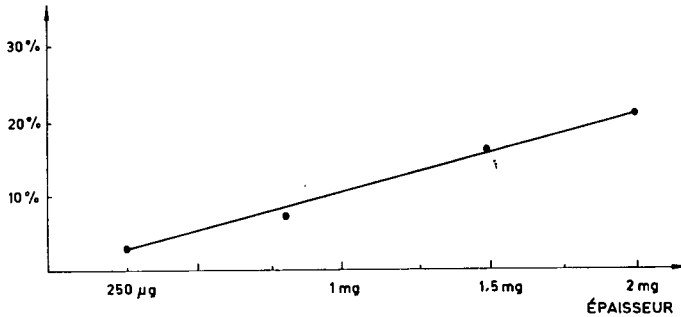


Figure 2

Pertes d'efficacité dans la détection des fissions en fonction de l'épaisseur des dépôts.

Il nous est apparu qu'il était plus facile de concevoir le scintillateur comme un assemblage de cellules individuelles regardées chacune par un photomultiplicateur, ceci à cause des difficultés qui résultent de l'ajustage des gains de deux photomultiplicateurs regardant la même enceinte.

Il nous restait donc essentiellement à déterminer la profondeur maximum des cellules.

Pour cela, nous avons étudié l'amplitude du pic alpha dû à une source de petite dimension dont la distance au photomultiplicateur pouvait varier entre 2 et 20 cm.

Nous avons comparé les résultats obtenus pour différents mélanges de gaz, différents réflecteurs et différentes pressions des gaz.

Nous avons également comparé ces résultats expérimentaux au résultat théorique donnant le flux sortant d'un cylindre aux parois réfléchissantes (coefficient de réflexion T) et provenant d'un point lumineux situé à une distance x de la sortie du cylindre (cf. fig. 3).

On a

$$\Phi = 1 + (t-1) \sum_{n=0}^{n=\infty} t^n \frac{1}{\sqrt{1 + \left[(2n+1) \frac{1}{x} \right]^2}}.$$

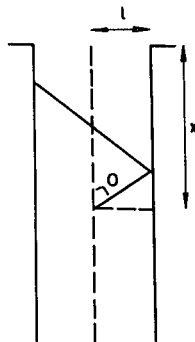


Figure 3

Notations utilisées dans le calcul du flux sortant d'un cylindre réflecteur.

La figure 4 représente une courbe typique telle qu'on a pu l'obtenir expérimentalement.

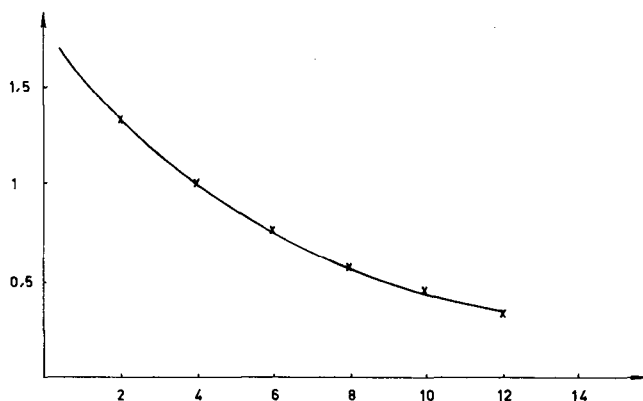


Figure 4

Variations de l'amplitude des impulsions dues à la radioactivité d'une source d'uranium en fonction de la distance de cette source à la fenêtre du photomultiplicateur.

On a remarqué que les courbes expérimentales obtenues dépendaient peu du réflecteur, de la pression du gaz ou de la nature du gaz employé. La valeur de t correspondant à la courbe expérimentale est proche de 0,4. Toutefois, on représente beaucoup mieux les résultats expérimentaux en admettant une valeur du coefficient de réflexion $T = 0,98$ et un coefficient d'absorption dans le gaz $K = 0,03$ par centimètre (3 % par centimètre). Cette absorption n'est due ni au gaz employé (K est indépendant de la pression) ni au dégazage de l'enceinte (K ne dépend pas du temps qui sépare la manipulation du remplissage).

Pour préciser l'influence propre du gaz de remplissage, nous avons étudié la variation de la taille des impulsions alpha émises par la source placée à une distance de 8 cm de la photocathode en fonction de la pression du gaz.

En admettant que la taille des impulsions dépende de la pression selon la loi $H = H_0 e^{-kp}$, on a trouvé que $k < 0,02$ pour $x = 8$ cm. La variation observée peut s'expliquer par les différences de longueur de parcours des particules alpha.

Il semble donc qu'on observe une absorption anormale qui serait due aux vapeurs résiduelles de pompage.

D'après l'expérience, on trouve que le flux lumineux tombe à la moitié de la valeur correspondant à une source située à 4 cm pour une distance de la source à la photocathode d'environ 10 cm.

Si maintenant on dispose un réflecteur parfait à la distance $x = 10$ cm, on voit que, comme le montre la figure 5, chaque événement donnera lieu à une impulsion dont la taille ne dépendra pas du lieu de cet événement.

Avec ces données on a choisi une profondeur de cellule de:

$$\begin{array}{ccccc} & \text{dimension} & & & \\ \text{garde} & \text{du dépôt} & \text{garde} & & \\ 4 \text{ cm} & + 9 \text{ cm} & + 1 \text{ cm} & = & 14 \text{ cm.} \end{array}$$

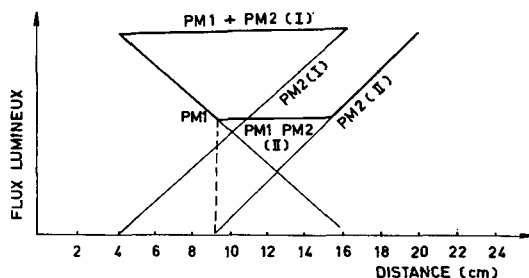


Figure 5

Courant total détecté sur la anode de 2 photomultiplicateurs en fonction de l'emplacement de la source lumineuse.

Courbe I: distance entre les 2 P. M. — 20 cm
 Courbe II: distance entre les 2 P. M. — 24 cm

Dans ces conditions, le même événement donne lieu à des impulsions lumineuses dont la hauteur peut varier dans un rapport 2.

Essais de quelques scintillateurs

Actuellement nous avons effectué des essais de scintillateurs de grande dimension dans trois cas.

a) Un scintillateur contenant quatre dépôts d'uranium naturel de 19×6 cm, épais de $1,5 \text{ mg/cm}^2$, vu par deux photomultiplicateurs et constitué par un mélange argon-azote. Une courbe différentielle du spectre de fission est donnée sur la figure 6.

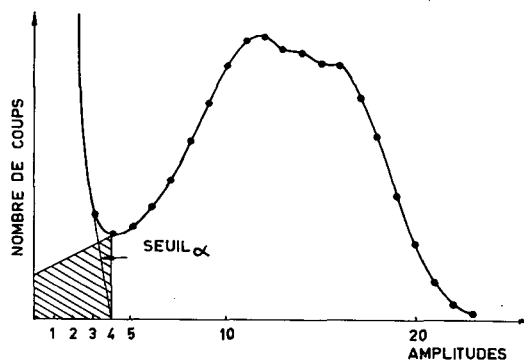


Figure 6

Spectre fission U naturel 2 PM. — Scintillateur 25 cm de long.

4 dépôts $19 \text{ cm} \times 6 \text{ cm}$ $1,5 \text{ mg/cm}^2$

b) Un scintillateur contenant quatre dépôts d'uranium naturel de 5×9 cm, épais de $1,5 \text{ mg/cm}^2$, vu par un seul photomultiplicateur et constitué par un mélange argon-azote. On donne une courbe typique sur la figure 7.

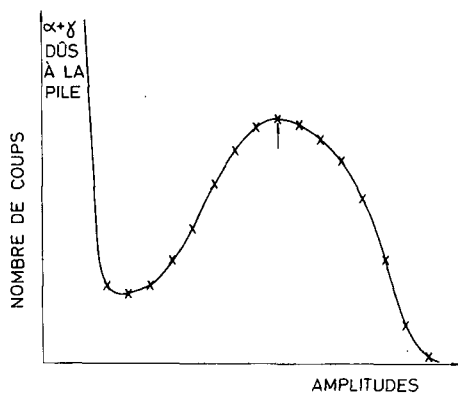


Figure 7

Spectre fission U naturel avec 1 photomultiplicateur.
4 dépôts $9\text{ cm} \times 6\text{ cm}$ épaisseur $1,5\text{ mg/cm}^2$

c) Un scintillateur contenant deux dépôts d'uranium-233 de $7 \times 5\text{ cm}$ et épais de 1 mg/cm^2 , soit en tout 70 mg d'uranium-233, vu par un seul photomultiplicateur. Les résultats sont indiqués sur la figure 8.

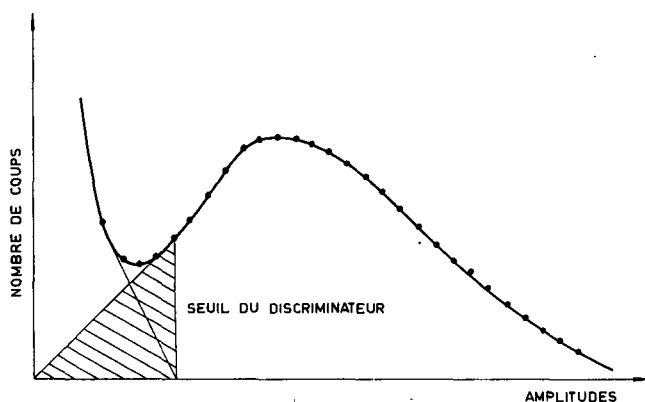


Figure 8

Spectre fission ^{233}U .
2 dépôts $7\text{ cm} \times 5\text{ cm}$ épaisseur 1 mg/cm^2

Le scintillateur définitif actuellement en construction comprendra six cellules indépendantes optiquement. Chaque cellule contiendra quatre dépôts de $9 \times 6\text{ cm}$ de ^{233}U , épais de $1,5\text{ mg/cm}^2$, sur lesquels on a évaporé $50\text{ }\mu\text{g/cm}^2$ d'aluminium. La figure 9 représente cet ensemble.

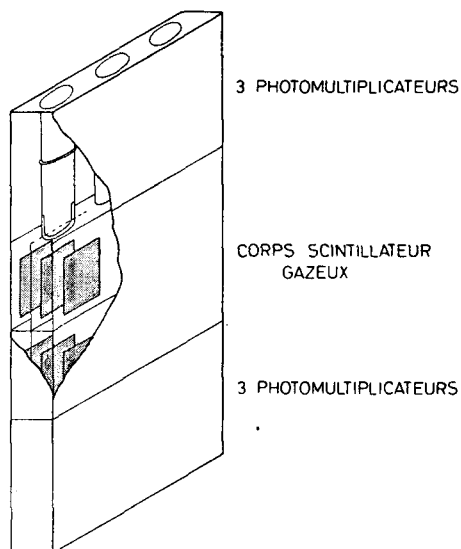


Figure 9

Vue d'ensemble scintillateur gazeux contenant 2 g de ^{233}U .

Dispositif électronique

Nous avons utilisé essentiellement des photomultiplicateurs 55 AVP et 56 UVP de la Radiotechnique. Les problèmes électroniques étaient de deux types.

a) Travail des photomultiplicateurs avec des courants moyens importants. En effet, les rayons alpha de la radioactivité naturelle donnaient des impulsions de l'ordre de 0,15 V à l'anode des photomultiplicateurs avec une charge de 150 Ω , ce qui correspond à un courant crête de 1 mA. Si l'on admet que le photomultiplicateur pouvait voir jusqu'à 10^8 alpha par seconde et que les impulsions ont une largeur de l'ordre de $5 \cdot 10^{-9}$ s, on voit que le courant moyen dû à la radioactivité alpha seule est de l'ordre de 0,5 mA. On voit donc qu'on est alors très près des conditions limites de sécurité de fonctionnement. De plus, ce fort courant modifie les tensions interdynodes et l'on a dû alimenter les photomultiplicateurs avec deux alimentations séparées de telle manière que le courant passant dans les derniers étages du pont soit de l'ordre de 10 mA. On évite ainsi des phénomènes gênants de saturation. Un schéma du pont adopté est donné sur la figure 10.

b) Les impulsions données par les scintillateurs gazeux sont très rapides. Il était donc nécessaire de les allonger pour leur appliquer des méthodes classiques d'analyse d'amplitude. De plus, il a fallu mettre au point un discriminateur sensible (impulsions alpha de l'ordre de 100 mV) et déclenchant sur des impulsions très brèves. L'élément discriminateur allongeur a été constitué par une diode rapide à germanium S 570 G. La sortie de cette diode est envoyée soit sur un dispositif changeur d'impédance fournissant des impulsions à basse impédance qu'on pouvait analyser classiquement, soit sur un monovibrateur très sensible (seuil de 40 mV) donnant des impulsions standard destinées à être envoyées sur l'enregistreur de temps de vol.

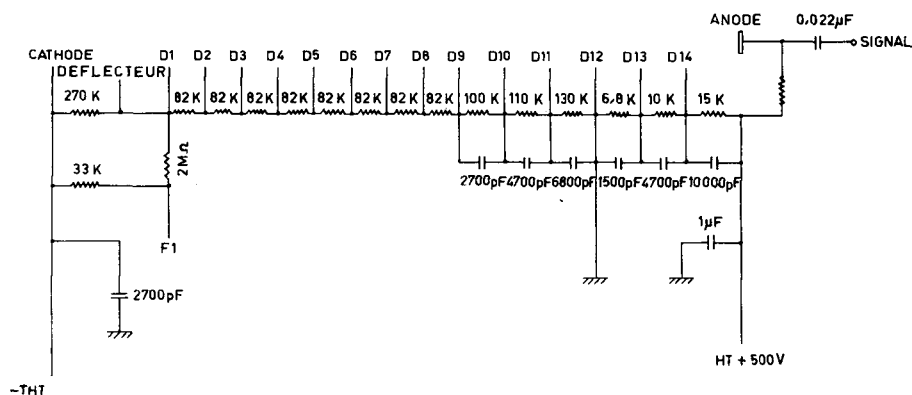


Figure 10

Schéma de câblage de culot du photomultiplicateur 56 UVP.

L'ensemble formé par la diode et le monostable est analogue à un discriminateur pouvant être déclenché par des impulsions de $2 \cdot 10^{-9}$ s, de largeur et d'amplitude supérieure à 300 mV. Le faible seuil du monovibrateur est destiné à éviter la production d'empilements entre la diode et le monostable. La cadence maximum de répétition de l'ensemble est de 50 kHz. La figure 11 représente le schéma électronique décrit ci-dessus.

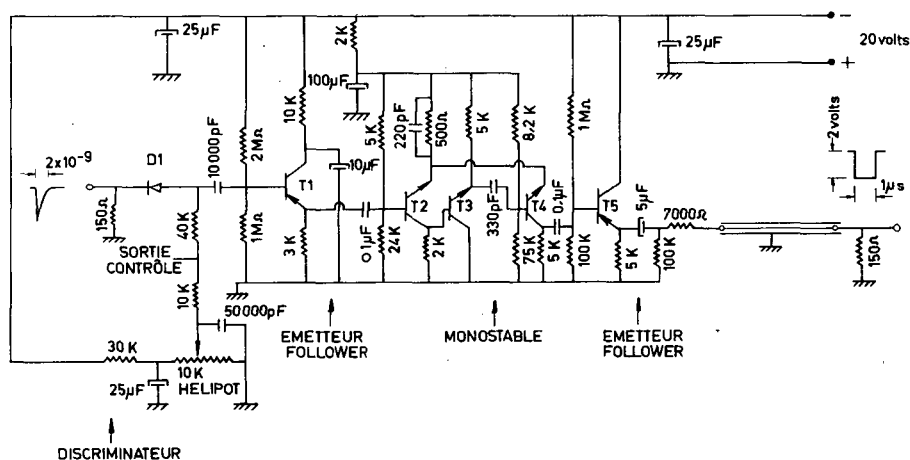


Figure 11

Electronique associée au détecteur.

D1 — S 570 G
 T1 — T5 — OC 170
 T2 T3 T4 — 2N 338

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СЦИНТИЛЛЯЦИОННЫЕ СТЕКЛА, АКТИВИРОВАННЫЕ ЦЕРИЕМ, ДЛЯ ДЕТЕКТИРОВАНИЯ НЕЙТРОНОВ

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СССР

Abstract — Résumé — Аннотация — Resumen

Cerium-activated vitreous scintillators for neutron detection. This paper gives the results of measurements on the resolving times and scintillation efficiency of cerium-activated silicate glasses. The authors show the effect of the Ce concentration on the scintillation efficiency of glass assaying $\text{Li}_2\text{O} \times 0.5 \text{ CaO} \times 0.13 \text{ Al}_2\text{O}_3 \times 4 \text{ SiO}_2$. The effect of temperature on efficiency was determined in the range $-50^\circ \text{C} - +50^\circ \text{C}$. It was found that throughout the entire temperature range the efficiency is constant within the limits of measurement. The paper also indicates the scintillation efficiency of glass assaying $1.5 \text{ Li}_2\text{O} \times 0.13 \text{ Al}_2\text{O}_3 \times 4 \text{ SiO}_2 \times 0.06 \text{ CeO}_2$, in which 0.5 molecules of lithium had been replaced by other alkaline or alkaline-earth elements.

Scintillateur en verre active au cérium pour la détection des neutrons. Le mémoire expose les résultats de mesures du pouvoir de résolution dans le temps et de la fréquence de scintillations des verres de silicate activés au cérium. On montre que la fréquence de scintillations du verre $\text{Li}_2\text{O} \times 0,5 \text{ CaO} \times 0,13 \text{ Al}_2\text{O}_3 \times 4 \text{ SiO}_2$ dépend de la concentration du Ce. On a déterminé la dépendance de la fréquence des scintillations vis-à-vis de la température -50°C et $+50^\circ \text{C}$. Des mesures précises ont révélé que la fréquence est constante pour toutes ces températures. Le mémoire indique la fréquence des scintillations pour les verres du type $1,5 \text{ Li}_2\text{O} \times 0,13 \text{ Al}_2\text{O}_3 \times 4 \text{ SiO}_2 \times 0,06 \text{ CeO}_2$ où 0,5 de la molécule de lithium sont remplacés par un autre élément alcalin ou un métal alcalino-terreux.

Сцинтилляционные стекла, активированные церием, для детектирования нейтронов. В настоящем докладе излагаются результаты измерений временного разрешения и сцинтилляционной эффективности силикатных стекол, активированных церием. Приведена зависимость сцинтилляционной эффективности стекла $\text{Li}_2\text{O} \cdot 0,5 \text{ CaO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2$ от концентрации Се. Была определена температурная зависимость эффективности в интервале $-50^\circ \text{C} - +50^\circ \text{C}$. Оказалось, что во всем диапазоне температур с точностью измерений эффективность постоянна. Приведена величина сцинтилляционной эффективности для стекол $1,5 \text{ Li}_2\text{O} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$, в которых 0,5 молекулы лития замещено другим щелочным или щелочноземельным элементом.

Centelleador de vidrio activado con cerio para la detección de neutrones. Se exponen en esta memoria los resultados de la medición del poder de resolución en el tiempo y del rendimiento de centelleo de los vidrios de silicatos activados con cerio. Se demuestra que el rendimiento de centelleo del vidrio que responde a la fórmula $\text{Li}_2\text{O} \cdot 0,5 \text{ CaO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2$ depende de la concentración de cerio. También se determinó el rendimiento en función de la temperatura, en el intervalo de -50°C a $+50^\circ \text{C}$. Se comprobó que en esa gama de temperaturas, dentro de la precisión de las observaciones, el rendimiento se conserva constante. Se dan los valores del rendimiento de centelleo para los vidrios cuya composición es $1,5 \text{ Li}_2\text{O} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$, en los cuales la mitad de la molécula de litio se ha sustituido por otro elemento alcalino o alcalino-térreo.

Новый тип сцинтилляторов — активированные стекла [1] [2], открывает новые возможности применения сцинтилляционного метода для избирательного детектирования и исследования ядерных излучений. Наиболее эффективные составы были получены на основе силикатных стекол, активированных церием.

Стекло $\text{Li}_2\text{O} \cdot 0,08 \text{Al}_2\text{O}_3 \cdot 3 \text{SiO}_2$ (Ce) является высокочувствительным детектором тепловых и медленных нейтронов с хорошим временным разрешением [1] [2] [3].

Выход люминесценции таких стекол определяется содержанием CeIII [4]. В восстановительной среде удается большую долю активатора удержать в трехвалентном состоянии и ввести в стекло до 0,1 Ce без заметного окрашивания.

Сцинтилляционная эффективность тонких стекол состава $\text{Li}_2\text{O} \cdot 0,08 \text{Al}_2\text{O}_3 \cdot 3 \text{SiO}_2$ (Ce) практически постоянна при изменении концентрации церия в пределах 0,05—0,1 и при возбуждении свечения электронами составляет 8—9% относительно кристалла NaI (Tl) [3]. Для толстых стекол этого состава оптимальной является концентрация 0,05—0,06 Ce. Отношение световых выходов для электронов и продуктов взаимодействия нейтронов с Li^6 равно 3,4—3,7. При концентрации изотопа Li^6 — 90,5% эффективность этого стекла толщиной 0,2 см для потока тепловых нейтронов, перпендикулярного плоскости стекла, ~ 90%. На рис. 1 приведен амплитудный спектр импульсов напряжения на выходе сцинтилляционного счётчика со стеклом $\text{Li}_2\text{O} \cdot 0,08 \text{Al}_2\text{O}_3 \cdot 3 \text{SiO}_2 \cdot 0,1 \text{CeO}_2$, полученный при возбуждении свечения продуктами реакции Li^6 (n, α)T. Полуширина пика — 22,5%.

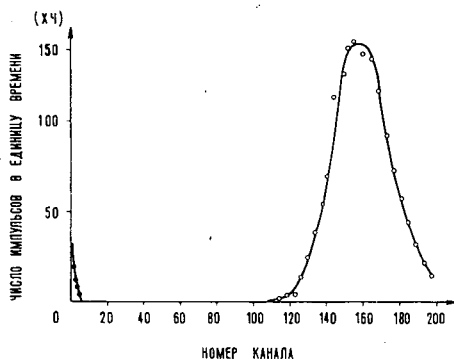


Рис. 1

Амплитудное распределение импульсов сцинтилляционного счетчика со стеклом $\text{Li}_2\text{O} \cdot 0,08 \text{Al}_2\text{O}_3 \cdot 3 \text{SiO}_2 \cdot 0,1 \text{CeO}_2$
 о — регистрируются тепловые нейтроны
 ● — шумы фотоумножителя

Дальнейшее повышение сцинтилляционной эффективности может быть достигнуто при введении в стекло некоторых дополнительных компонент, благоприятствующих, по-видимому, сдвигу равновесия CeIII—CeIV в сторону CeIII.

В таблице I приведена величина сцинтилляционной эффективности для стекол $1,5 \text{Li}_2\text{O} \cdot 0,13 \text{Al}_2\text{O}_3 \cdot 4 \text{SiO}_2 \cdot 0,06 \text{CeO}_2$, в которых 0,5 молекулы лития замещено другим щелочным или щелочноземельным элементом.

Частичное замещение лития натрием или калием резко снижает сцинтилляционную эффективность. В меньшей степени гасящими свойствами обладает цезий. Стекло $\text{Li}_2\text{O} \cdot 0,5 \text{Cs}_2\text{O} \cdot 0,13 \text{Al}_2\text{O}_3 \cdot 4 \text{SiO}_2 \cdot 0,06 \text{CeO}_2$ может быть использовано для регистрации γ -излучения по фотоэффекту на цезии.

Интересно отметить anomальное поведение рубидия, практически не меняющего световой выход стекла. Замещение лития бериллием или барием уменьшает, а

Таблица I

№	Состав стекла	Сцинтилляционная эффективность относительно кристалла NaI (Tl) при возбуждении электронами
1.	$1,5 \text{ Li}_2\text{O} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$	5,5—6
2.	$\text{Li}_2\text{O} \cdot 0,5 \text{ Na}_2\text{O} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$	1,1—1,3
3.	$\text{Li}_2\text{O} \cdot 0,5 \text{ K}_2\text{O} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$	0,9—1
4.	$\text{Li}_2\text{O} \cdot 0,5 \text{ Rb}_2\text{O} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$	5,6—6,0
5.	$\text{Li}_2\text{O} \cdot 0,5 \text{ Cs}_2\text{O} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$	2,7—3,0
6.	$\text{Li}_2\text{O} \cdot 0,5 \text{ BaO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$	3,0
7.	$\text{Li}_2\text{O} \cdot 0,5 \text{ MgO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,05—0,08 \text{ CeO}_2$	9—11
8.	$\text{Li}_2\text{O} \cdot 0,5 \text{ CaO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06—0,1 \text{ CeO}_2$	10—11
9.	$\text{Li}_2\text{O} \cdot 0,5 \text{ SzO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$	7,5—8,5
10.	$\text{Li}_2\text{O} \cdot 0,5 \text{ BaO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2 \cdot 0,06 \text{ CeO}_2$	2

другими щелочноземельными элементами повышает сцинтилляционную эффективность. Наибольший световой выход имеют стекла, содержащие магний и кальций.

Ряд эффективных составов, полученных на основе диопсида, активированного церием, приведен в [5] [6]; наибольшая сцинтилляционная эффективность была достигнута при полном замещении кальция литием, алюминием и церием. В [5] [6] отмечается, что кальций оказывает гасящее действие. По нашим данным, частичное замещение лития кальцием или магнием повышает световой выход до одной и той же величины.

На рис. 2 показана зависимость сцинтилляционной эффективности стекла $\text{Li}_2\text{O} \cdot 0,5 \text{ CaO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2$ от концентрации Ce (толщина стекла 0,3—0,4 см). Эффективность стекла этого состава для тепловых нейтронов (обогащение по Li^6 до 90,5%, толщина стекла — 0,2 см) — 80%. Стекло практически нечувствительно к быстрым нейтронам (эффективность для нейтронов с энергией 2,5 мэв — 0,07%). Эффективность регистрации γ -лучей с энергией ~ 1 мев, определенное по числу импульсов в области пика от реакции $\text{Li}^6(n, \alpha)\text{T}$, составляет 0,5%. Время высвечивания стекла $\sim 0,15$ мсек.

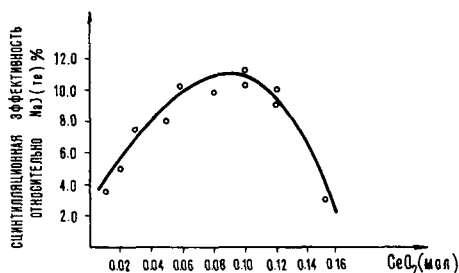


Рис. 2

Зависимость сцинтилляционной эффективности от концентрации церия для стекла $\text{Li}_2\text{O} \cdot 0,5 \text{ CaO} \cdot 0,13 \text{ Al}_2\text{O}_3 \cdot 4 \text{ SiO}_2$

Для активированных церием силикатных стекол была определена температурная зависимость сцинтилляционной эффективности в интервале $-50^{\circ}\text{C} - +50^{\circ}\text{C}$. Свечение стекла возбуждалось тритонами и α -частицами из реакции $\text{Li}^6(\text{n}, \alpha)\text{T}$. Оказалось, что во всем диапазоне температур с точностью измерений ($\sim 10\%$) сцинтилляционная эффективность постоянна. Таким образом, сцинтилляционное стекло в сочетании с фотоумножителем, параметры которого не зависят от температуры (ФЭУ-11Б, ФЭУ-13), позволяет создать детектор излучений, нечувствительный к температурным изменениям в широких пределах.

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ПЛАСТМАССОВЫЕ СЦИНТИЛЛЯТОРЫ ДЛЯ РЕГИСТРАЦИИ ТЕПЛОВЫХ НЕЙТРОНОВ

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СССР

Abstract — Résumé — Аннотация — Resumen

Plastic scintillators for recording thermal neutrons. The method of thermal polymerization was used to produce plastic scintillators on a polystyrene base with a high concentration of lithium salts. The scintillators are intended for recording thermal neutrons. Scintillation spectra have been obtained for thermal and fast neutrons and for gamma rays. Analysis of these spectra shows that the efficiency for recording thermal neutrons is many times greater than the efficiency for recording fast neutrons or gamma quanta: with a 10% concentration (in weight) of lithium carbonate (90% Li^6) and a scintillator thickness of 4 mm an efficiency of 26% can be obtained for recording thermal neutrons, while the efficiency for recording fast neutrons (Po - Be) is 0.6% and that for gamma quanta (Co^{60}) 0.2%.

Scintillateurs en matière plastique pour l'enregistrement des neutrons thermiques. La méthode de la polymérisation thermique a été employée pour la fabrication de scintillateurs en matière plastique dont la substance de base est le polystyrène avec une forte teneur en sels de lithium. Les scintillateurs sont destinés à l'enregistrement des neutrons thermiques. Les auteurs indiquent les spectres des scintillations pour les neutrons thermiques et rapides et pour les rayons gamma. L'analyse de ces spectres montre que le taux d'enregistrement des neutrons thermiques est sensiblement supérieur à celui des neutrons rapides ou des rayons gamma. Ainsi, lorsque la teneur (en poids) en carbonate de lithium (90% de ^6Li) s'élève à 10% et que le scintillateur a une épaisseur de 4 mm, on peut porter le taux d'enregistrement des neutrons thermiques à 26%, alors que celui des neutrons rapides (Po - Be) est de 6% et celui des rayons gamma (^{60}Co) de 0,2%.

Пластмассовые сцинтилляторы для регистрации тепловых нейтронов. Методом термической полимеризации изготовлены пластмассовые сцинтилляторы на основе полистирола с высокой концентрацией солей лития. Сцинтилляторы предназначены для регистрации тепловых нейтронов. Приведены спектры сцинтилляций для тепловых и быстрых нейтронов и для γ -лучей. Из анализа этих спектров следует, что эффективность регистрации тепловых нейтронов во много раз больше эффективности регистрации быстрых нейтронов или γ -квантов. Так, при весовой концентрации карбоната лития (90% Li^6) 10% и толщине сцинтиллятора 4 мм можно получить эффективность регистрации тепловых нейтронов 26% при эффективности регистрации быстрых нейтронов (Po - Be) 0,6% и γ -квантов Co^{60} 0,2%.

Centelleadores de material plástico para el registro de neutrones térmicos. Por el método de la polimeración térmica los autores han preparado centelleadores de material plástico a base de poliestireno con una elevada proporción de sales de litio. Estos centelleadores se utilizan para el registro de neutrones térmicos. Se han obtenido espectros de centelleo de neutrones térmicos y rápidos y de rayos γ . El análisis de estos espectros muestra que la eficiencia del registro es mucho mayor para los neutrones térmicos que para los neutrones rápidos o los fotones γ : con una concentración de 10 por ciento en peso de carbonato de litio (90 por ciento de ^6Li) y con un centelleador de 4 mm de espesor se puede lograr una eficiencia de 26 por ciento en el registro de neutrones térmicos, mientras que para los neutrones rápidos (Po - Be) la eficiencia de registro es de 0,6 por ciento y para los fotones γ (^{60}Co) de 0,2 por ciento.

Действие сцинтилляционных счетчиков тепловых нейтронов основано либо на регистрации сцинтилляций от заряженных продуктов реакции $\text{He}^3(n, p)\text{H}^3$,

$\text{Li}^6(n, \alpha)\text{H}^3$ и $\text{B}^{10}(n, \alpha)\text{Li}^7$, либо на регистрации γ -лучей реакций (n, γ) . Характеристики этих счетчиков имеются в обзорах [1] [2] (см. также [3]—[6]). В данной статье мы сочли целесообразным привести результаты исследования некоторых свойств разработанного нами сцинтиллятора для регистрации тепловых нейтронов, отличающегося весьма простой технологией изготовления, удобством применения и высокой эффективностью.

Сцинтилляторы представляют собою суспензию неорганических соединений лития или бора в люминесцирующей пластмассе. Они изготавливаются методом высокотемпературной полимеризации стироловых растворов люминесцирующих веществ [7], в которые введены соединения лития или бора в виде мелкодисперсных порошков. Этим методом были изготовлены сцинтилляторы с примесью LiBO_2 , Li_2CO_3 до 15% по весу, $\text{Li}_2\text{B}_4\text{O}_7$ — до 10%, LiCl — до 3%, LiBF_4 до 3%, LiOH — до 3%, B_2O_3 — до 7%. Сцинтилляторы с LiOH и B_2O_3 оказались непригодными из-за недостаточной устойчивости. Механические свойства остальных сцинтилляторов близки к свойствам чистых пластмассовых сцинтилляторов; они обладают хорошей устойчивостью в обычных условиях влажности и температуры.

Наличие суспензированной примеси уменьшает световую отдачу сцинтилляторов. Степень уменьшения зависит от природы примеси, ее концентрации и размеров образца (рис. 1). Из опробованных соединений лучшие результаты дали соли угольной и борных кислот. При возбуждении электронами световая отдача экспоненциально уменьшается с ростом концентрации примесей. Сопоставление результатов для сцинтилляторов толщиной 4 и 10 мм показывает, что уменьшение зависит от количества примеси на единицу поперечного сечения сцинтиллятора:

$$L = L_0 e^{-kc} \quad (1)$$

где $k = 11 \text{ см}^2/\text{г}$ для Li_2CO_3 и $k = 9 \text{ см}^2/\text{г}$ для LiBO_2 или $\text{Li}_2\text{B}_4\text{O}_7$. Следовательно, основной причиной уменьшения световой отдачи можно считать рассеяние света люминесценции примесью. Оно приводит к увеличению пути фотонов в сцинтилляторе и тем самым к увеличению поглощения. Тушения люминесценции эти примеси, по-видимому, не вызывают.

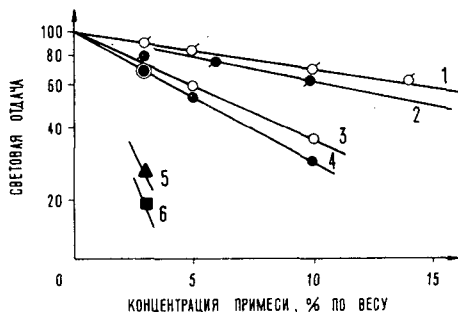


Рис. 1

Зависимость световой отдачи пластмассового сцинтиллятора (15% 1,3,5-трифенил-*A*2-пиразолина в полистироле) от концентрации примеси

Измерено по среднему току ФЭУ-29 при возбуждении β -излучением Ce^{144} - Pr^{144} и по средней величине сцинтилляции для конверсионных электронов Ba^{137} . Сцинтилляторы $\varnothing$ 16 мм. Кривые 1 и 2 — толщина образцов 4 мм, кривые 3—6—10 мм. Примеси:

1 и 3 — LiBO_2 или $\text{Li}_2\text{B}_4\text{O}_7$, 2 и 4 — Li_2CO_3 , 5 — LiBF_4 , 6 — LiCl

ТАБЛИЦА 1

КОЛИЧЕСТВО БОРО- ИЛИ ЛИТИЙ СОДЕРЖАЩИХ ВЕЩЕСТВ (С) НА ЕДИНИЦУ ПОПЕРЕЧНОГО СЕЧЕНИЯ СЦИНТИЛЛЯТОРА И ОТНОСИТЕЛЬНАЯ ВЕЛИЧИНА СВЕТОВОЙ ОТДАЧИ (L/L_0) В ЗАВИСИМОСТИ ОТ ВЕРОЯТНОСТИ ТЕПЛОВОМУ НЕЙТРОНУ ВЫЗВАТЬ ЯДЕРНУЮ РЕАКЦИЮ (p)

P	$B^{10} (n, \alpha) Li^7$		$Li^6 (n, \alpha) H^3$	
	С, мг/см ² для $Li_2B_4O_7$	L/L_0	С, мг/см ² для Li_2CO_3	L/L_0
0,1	2,1	0,98	6,6	0,93
0,3	7,2	0,94	22	0,78
0,5	14	0,88	44	0,61
0,7	24	0,80	76	0,43
0,9	46	0,66	146	0,20

Нейтроны падают по нормали на плоский слой сцинтиллятора, имеющего оптический контакт с катодом умножителя. Люминесцирующая добавка — 1,5% трифенилпирозолина. Бор и литий обогащены по изотопам B^{10} и Li^6 до 90%. L/L_0 вычислено по [1].

Одним из важных требований к детектору частиц является высокая эффективность счета. Для счетчика с описанными выше сцинтилляторами эффективность счета тепловых нейтронов можно представить в виде

$$P = p W_s \quad (2)$$

где p — вероятность того, что нейтрон вызовет внутри сцинтиллятора соответствующую реакцию, и W_s — вероятность зарегистрировать сцинтилляцию от продуктов реакции. Из таблицы 1 видно, что для реакции на изотопе B^{10} величина p близка к 1 при сравнительно небольшом снижении световой отдачи. При использовании реакции $Li^6(n, \alpha) H^3$ требуется больше вещества, что приводит к соответственно большему снижению. Однако в последнем случае величина сцинтилляции все же остается в несколько раз большей. В самом деле, величину сцинтилляции, вызываемой продуктами каждой из этих реакций, можно записать в виде

$$S = s \sum_{\nu} D_{\nu\beta} E_{\nu},$$

где s — удельная величина сцинтилляции для электронов, $D_{\nu\beta}$ — отношение выходов люминесценции частицы ν (начальной энергии E_{ν}) и электрона. В реакции $Li^6(n, \alpha) H^3$ $E_{\alpha} = 2,06$ Мэв и $E_{H^3} = 2,74$ Мэв. Принимая для наших сцинтилляторов значения $D_{\nu\beta}$, полученные с пластмассовыми сцинтилляторами без примесей, а именно $D_{\alpha\beta} = 0,040$ [8] и $D_{H^3\beta} = 0,19$ [9] [10], получим

$$S_{Li} = 600 S_0 L/L_0, \quad (3)$$

где S_0 (кэв⁻¹) — удельная величина сцинтилляции для „чистого“ пластмассового сцинтиллятора. В реакции $B^{10}(n, \alpha) Li^7$ энергия α -частицы в 93,5% случаев равна 1,47 Мэв. Пренебрегая вкладом Li^7 , получим ($D_{\alpha\beta} = 0,034$ [8])

$$S_B = 50 S_0 L/L_0.$$

При $p = 0,9$ имеем $S_{Li} = 3,6 S_B$. Следовательно, использование реакции на Li^6 представляется более удобным.

Для оценки абсолютной величины S , выраженной в числе электронов, поступающих на первый диод умножителя, примем [11] $S_0 = 0,3 \text{ кэв}^{-1}$. Тогда $S_{Li} = 36$ при $p = 0,9$. Этого вполне достаточно для обеспечения вероятности регистрации W_S близкой к 100%.

Для экспериментальной проверки этих оценок, а также для определения эффективности регистрации γ -лучей и быстрых нейтронов, были измерены спектры сцинтилляций при возбуждении тепловыми нейтронами и при возбуждении известным потоком быстрых нейтронов или γ -квантов. Источником нейтронов служил препарат Ро-Ве активностью 1,25 кюри. Тепловые нейтроны измерялись по схеме рис. 2. „Фон“ от быстрых нейтронов, прошедших через парафин, измерялся при наличии кадмиевого чехла на трубе 3 и в отсутствии малого парафинового блока 4*. Источником γ -лучей служил препарат 1,1 мкюри Co^{60} . Сцинтилляторы имели оптический контакт с фото-катодом (парафиновое масло). В качестве отражателя служило покрытие из MgO , нанесенное по способу [12].

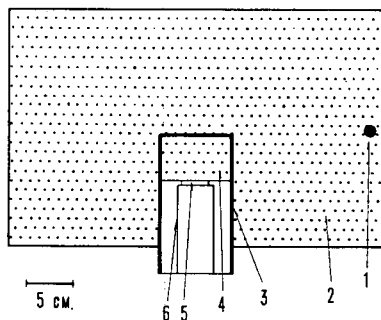


Рис. 2

Условия измерения тепловых нейтронов

1 — источник нейтронов, 2 и 4 — парафин, 3 — труба дюралюминевая, 5 — сцинтиллятор, 6 — умножитель ФЭУ-С

На рис. 3 приведены результаты измерений для $B^{10}(n, \alpha) Li^7$ ($p = 0,41$). По разности скорости счета в отсутствие и при наличии кадмия удается выделить пик, соответствующий S_B . Однако он расположен в области интенсивного фона от закадмиевых нейтронов и частично в области темновых шумов умножителя. Отношение S_B/S_{Li} в этом сцинтилляторе оказалось равным 0,05, что в 1,5 раза меньше приведенных оценок. Основная причина расхождения заключается, по-видимому, в том, что α -частицы теряют часть энергии в самих крупинках примеси. Пробег α -частицы 1,47 Мэв не превышает 1 мг/см^2 , так что при линейных размерах крупинки $\sim 5 \mu$ может быть потеряно около половины энергии. Пробег H^3 при энергии 2,74 Мэв составляет 10 мг/см^2 . Следовательно, поглощение в примеси окажется значительно слабее.

* Контрольные измерения со сцинтиллятором без примесей показали, что фон от γ -лучей реакции $Cd(n, \gamma)$ несущественен в области S_{Li} .

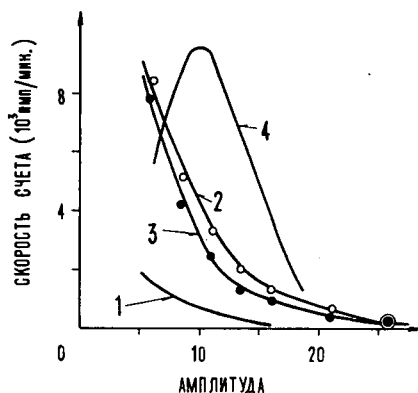


Рис. 3

Спектры сцинтилляций образца с 3% LiBO_2

Примесь обогащена по изотопу B^{10} . Люминесцирующая добавка — 1,5% Трифенилпиразолина. Толщина сцинтиллятора 4 мм, $\varnothing$ 16 мм

Кривая 1 — темновой фон, 2 — тепловые нейтроны, 3 — то же с кадмиевым чехлом, 4 — разность 2 и 3 (ординаты умножены на 10)

На рис. 4 представлены спектры сцинтилляций образца с 10% LiBO_2 (бор-естественный, литий-обогащенный до 90%, $P_{\text{Li}} = 0,30$). Соотношение между эффективностями счета тепловых нейтронов и быстрых нейтронов или γ -квантов зависит от участка спектра, выбранного для регистрации (табл. II). Эффективность счета тепловых нейтронов вычислена по [2] в предположении, что W_s пропорциональна площади под соответствующим участком кривой 3 (рис. 4). Для полной площади принято $W_s = 1$. Эффективности счета быстрых нейтронов (или γ -квантов) получены из отношения интегральной скорости счета для заданного участка амплитуд к потоку нейтронов (или γ -квантов) на сцинтиллятор.

ТАБЛИЦА II

ЭФФЕКТИВНОСТЬ СЧЕТА ТЕПЛОВЫХ НЕЙТРОНОВ (P), БЫСТРЫХ НЕЙТРОНОВ Po-Be (P_n) И γ -КВАНТОВ Co^{60} (P_γ) ДЛЯ НЕСКОЛЬКИХ УЧАСТКОВ СПЕКТРА СЦИНТИЛЛЯЦИЙ ТЕПЛОВЫХ НЕЙТРОНОВ

Н	1,5% трифенилпиразолина в полистироле с примесью 10% $\text{Li}^{10}\text{BO}_2$, толщина 4 мм и $\varnothing$ 16 мм			3% п-терфенила и 0,08% трифенилпиразолина в полистироле с примесью 15% Li_2CO_3 , толщина 2 мм и $\varnothing$ 30 мм		
	P	P_n	P_γ	P	P_n	P_γ
1,6	30	2,1	0,31	39	2,8	0,34
1,15	26	1,3	0,20	34	2,1	0,25
0,75	18	0,8	0,12	27	1,4	0,16

Выделяемый участок спектра расположен симметрично относительно средней величины сцинтилляции для тепловых нейтронов S_{Li} и имеет относительную ширину $H = \frac{S_{\text{max}} - S_{\text{min}}}{\Delta S}$ где ΔS — ширина спектра на полувысоте P, P_n и P_γ — в %.

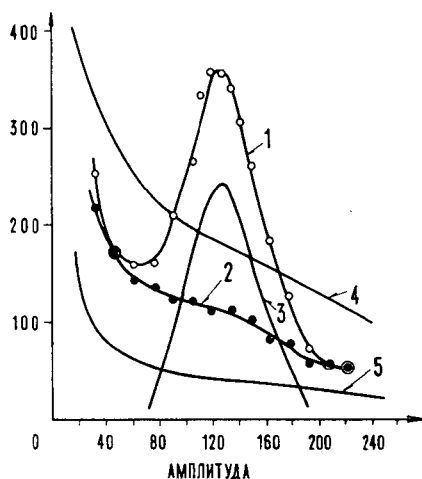


Рис. 4

Спектры сцинтилляций образца с 10% LiBO_2 . Примесь обогащена по изотопу Li^6 . Люминесцирующая добавка — 1,5% трифенилпиразолина. Толщина сцинтиллятора 4 мм, $\varnothing$ 16 мм. Кривая 1 — тепловые нейтроны, 2 — то же с кадмиевым чехлом, 3 — разность 1 и 2, 4 — γ -лучи Co^{60} , 5 — быстрые нейтроны

Величины P_n и P_γ в сильной степени зависят от спектрального состава излучений. Эта зависимость определяется не только сечением рассеяния на водороде (быстрые нейтроны) или сечением образования вторичного электрона (γ -кванты), но и вероятностью того, что эти вторичные частицы дадут сцинтилляцию в выбранном интервале амплитуд. Например, для сцинтиллятора с Li^6BO_2 при $P = 25\%$ интервал регистрируемых сцинтилляций соответствует энергии электронов от 450 до 750 кэВ*. В этот интервал практически не попадут протоны отдачи, если энергии нейтрона меньше 1,5 МэВ, и только при энергии нейтронов $> 2,2$ МэВ будет заполнен весь интервал. Для γ -квантов (комpton-эффект) эти предельные энергии составляют 630 и 950 кэВ соответственно.

Результаты таких измерений для сцинтиллятора с 15% Li_2CO_3 приведены на рис. 5 и в табл. II. Несмотря на то что толщина этого сцинтиллятора была в 2 раза меньше, не было получено существенного выигрыша в соотношении P и P_n , так как относительная ширина спектра для тепловых нейтронов оказалась в 1,8 раза больше.

Уширение спектра не связано с недостаточностью световой отдачи сцинтиллятора, как это видно из сравнения кривых 3 на рис. 5 и 4. Оно также не вызвано слишком большим самопоглощением. Для сцинтилляторов этого типа (люминесцирующие добавки — п-терфенил и трифенилпиразолин) выполняется соотношение (1) с $k = 8,6 \text{ см}^2/\text{г}$ (см. табл. III). При этом разрешение остается плохим и для низкой концентрации примеси. Можно поэтому предположить, что уширение

* См. табл. II и III. Следует иметь в виду, что регистрация быстрых нейтронов может иметь место и по реакции $\text{Li}^6(n, \alpha)\text{H}^3$.

спектра вызвано частичным поглощением энергии продуктов реакции $\text{Li}^6(n, \alpha)\text{H}^3$ в крупинках примеси (особенно энергия α -частицы, которая дает около 14% S_{Li}). Это предположение согласуется с тем экспериментальным фактом, что при возбуждении конверсионными электронами Ba^{137} (624 кэв) оба типа сцинтилляторов дают мало различающиеся спектры (табл. III). Далее, в согласии с (3) средние величины сцинтилляций для тепловых нейтронов и электронов близки друг к другу*.

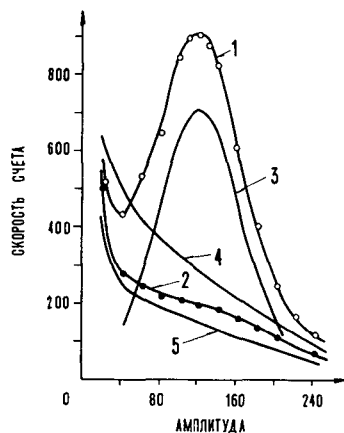


Рис. 5

Спектры сцинтилляций образца с 15% Li_2CO_3

Примесь обогащена по изотопу Li^6 . Люминесцирующие добавки: 3%-пара-терфенила и 0,08% трифенилпиразолина. Толщина сцинтиллятора — 2 мм, $\varnothing$ 30 мм, Остальные — см. рис. 4

Таблица III

СРЕДНЯЯ ВЕЛИЧИНА СЦИНТИЛЛЯЦИИ (S) И РАЗРЕШЕНИЕ (R) ДЛЯ ТЕПЛОВЫХ НЕЙТРОНОВ И КОНВЕРСИОННЫХ ЭЛЕКТРОНОВ Ba^{137}

Сцинтиллятор	Примесь и её содержание	Тепловые нейтронов		Электроны	
		S_{Li}	R %	Se	R %
1,5% трифенилпиразолина в полистироле $h = 4$, $\varnothing \approx 16$ мм	Li^6BO_2 10%	127	47	102	28
3%-пара-терфенила и 0,08% трифенилпиразолина в полистироле $h = 2$, $\varnothing = 30$ мм	Li_2^6CO_3 5%	148	70	148	22
	То же 10%	134	74	130	23
	То же 15%	124	83	117	33

* Электроны теряют в отражающем покрытии 40 кэв (20 мг/см²).

Таким образом, полученные результаты можно сформулировать следующим образом.

- (1) Введение некоторых соединений лития в состав пластмассового сцинтиллятора по предложенному методу позволяет получить сцинтилляторы с достаточно большой световой отдачей при высокой эффективности регистрации тепловых нейтронов.
- (2) Эффективность счета тепловых нейтронов примерно в 20 раз превышает эффективность счета быстрых нейтронов и в 100 раз эффективность счета γ -квантов.
- (3) Увеличение дисперсности вводимой примеси должно привести к дальнейшему улучшению качества сцинтилляторов.

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СЦИНТИЛЛЯЦИОННЫЙ СЧЕТЧИК МЕДЛЕННЫХ НЕЙТРОНОВ, НЕЧУВСТВИТЕЛЬНЫЙ К γ -ИЗЛУЧЕНИЮ

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СССР

Abstract — Résumé — Аннотация — Resumen

A slow neutron scintillation counter insensitive to gamma radiation. A slow neutron scintillation counter is described; the detector consists of a mixture of dihydrodecaborane with zinc sulphide. The recording efficiency for neutrons is 10% at a neutron energy of 1 eV and about 1.5 to 2% at an energy of 50 eV. The counter is almost completely insensitive to gamma radiation.

Compteur à scintillations pour neutrons lents, insensible aux rayons gamma. L'auteur décrit un compteur à scintillations pour neutrons lents; comme scintillateur, il utilise un mélange de dihydrodécaborane et de sulfure de zinc. Le taux d'enregistrement est de 10% pour une énergie neutronique de 1 eV et d'environ 1,5 à 2% lorsque cette énergie est de 50 eV. Le compteur est pratiquement insensible aux rayons gamma.

Сцинтилляционный счетчик медленных нейтронов, нечувствительный к γ -излучению. Описывается сцинтилляционный счетчик медленных нейтронов; детектором служит смесь дигидродекаборана с сернистым цинком. Эффективность регистрации нейтронов составляет 10% при энергии нейтронов 1 эв и около 1,5—2% при энергии 50 эв. Счетчик практически полностью нечувствителен к γ -лучам.

Contador de centelleo para neutrones térmicos insensible a las radiaciones gamma. En esta memoria se describe un contador de centelleo para neutrones térmicos; el detector consiste en una mezcla de dihydrodecaaborano con sulfuro de zinc. La eficiencia de registro es de 10 por ciento para neutrones de 1 eV, y de 1,5 a 2 por ciento para neutrones de 50 eV. El contador es prácticamente insensible a los rayos γ .

Специфическим сцинтиллятором, позволяющим регистрировать нейтроны на фоне интенсивного γ -излучения, является сернистый цинк. Возможность применения смесей различных веществ с сернистым цинком исследовалась в работе [1]. Наилучшие результаты были получены для смесей B_2O_3 , и $ZnS(Ag)$, и BN , и $ZnS(Ag)$; но даже для оптимальных смесей эффективность регистрации нейтронов в тепловой области составляла несколько процентов. Объясняется это непрозрачностью сцинтиллирующих смесей и малым процентным содержанием В в смеси.

Нами был предложен в качестве боросодержащего вещества дигидродекаборан $B_{10}H_{14}$ [2]. При весовом содержании В не менее 80% декаборан обладает хорошей прозрачностью; коэффициент преломления кристаллического декаборана близок к коэффициенту преломления сернистого цинка, что должно заметно уменьшать поглощение света в смеси.

Сцинтиллирующий состав изготовлялся путем спекания смеси порошков дигидродекаборана с сернистым цинком (светосостав К-5, размер кристалликов $ZnS(Ag)$ — 10—50 микрон). Навески смеси в 25 мл колбочке нагревались в масляном термостате при температуре 106° С до расплавления дигидродекаборана. Затем расплав быстро, при интенсивном перемешивании, охлаждался и после извлечения из колбы размельчался в яшмовой ступке. Порошок просеивался

через сита с отверстиями 0,23 мм и 0,9 мм и дальнейшие эксперименты производились только со средней фракцией.

При работе с дигидродекабораном необходимо соблюдать крайнюю осторожность: дигидродекаборан весьма летуч и легко взрывается. С помощью Po-Be источника были проверены зависимость эффективности регистрации тепловых нейтронов от количества сернистого цинка в 1 грамме дигидродекаборана (рис. 1) и влияние толщины сцинтиллятора на эффективность (рис. 2). На рис. 3 показаны дискриминационные кривые; они имеют вид обычных для сцинтилляторов с сернистым цинком.

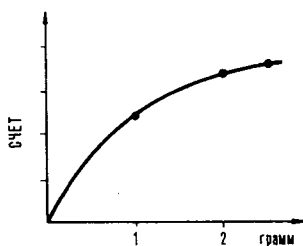


Рис. 1

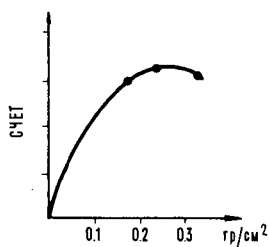


Рис. 2

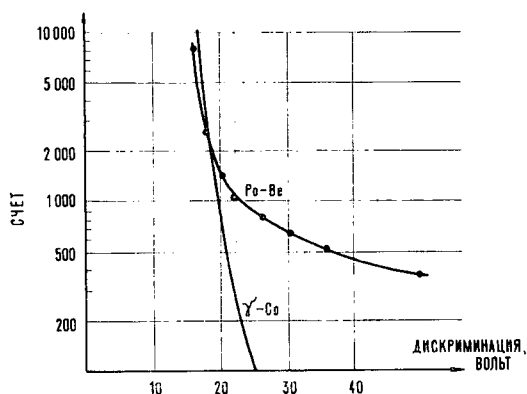


Рис. 3

Изготовленный сцинтиллирующий состав с отношением по весу ZnS(Ag) к дигидродекаборану 2,5:1 был нанесен непосредственно на фотокатод умножителя ФЭУ-3Бс и закрыт отражателем (алюминиевая фольга). Всего на фотокатод с площадью около 300 см^2 было нанесено 45 грамм сцинтиллятора. Эффективность регистрации счетчиком нейтронов различной энергии определялась на нейтронном направлении циклотрона с „мигающим пучком“ [3]. Снимались энергетические спектры медленных нейтронов в интервале энергий от 0,03 эв до 100 эв. Эти же спектры были получены с помощью батареи из 6 штук стандартных (СПМ-3) нейтронных газовых счетчиков. На рис. 4 приведены отношения эффективностей декаборанового и газового счетчиков f_2/f_1 , а также абсолютная эффективность f_2 исследуемого сцинтилляционного счетчика.

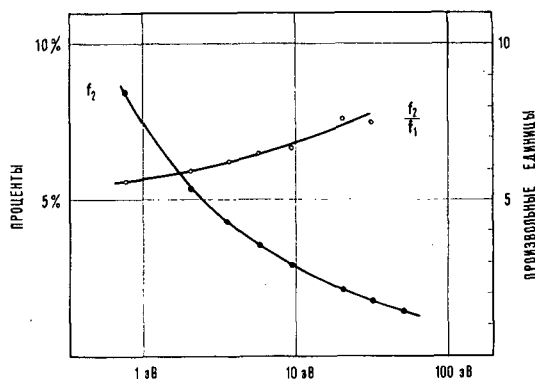


Рис. 4

Величина эффективности сильно зависит от уровня дискриминации, определяемого интенсивностью γ -фона. При дискриминации, соответствующей практически полной нечувствительности счетчика к γ -лучам, при интенсивности излучения порядка 10^5 квантов/см/сек (Co^{60} -источник), эффективность регистрации нейтронов достигает 15—18% в тепловой области, 10% при энергии 1 эв и 2% для нейтронов с энергиями 40—50 эв.

В заключение считаю своим приятным долгом выразить благодарность сотрудникам Института, способствовавшим проведению эксперимента: К. Г. Игнатьеву, В. В. Павлову, И. А. Радкевичу, В. В. Соколовскому и С. И. Сухоручкину.

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II.

INTENSIFIER SYSTEMS, PHOTOMULTIPLIERS AND LUMINESCENT CHAMBERS

(SESSION 2)

AN IMAGE-INTENSIFIER SYSTEM FOR THE STUDY OF RARE DECAY MODES OF ELEMENTARY PARTICLES

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Abstract — Résumé — Аннотация — Resumen

An image-intensifier system for the study of rare decay modes of elementary particles. Filamentary chamber-image intensifier systems have been developed which yield pictures of charged-particle tracks which are limited in spatial resolution only by the unit filament size, and which exhibit a time-resolution of about one microsecond. This device, used in conjunction with auxiliary particle counters, is well suited to the study of rare decay modes of elementary particles such as, for example, π - and K-mesons. The method employs a filamentary chamber divided into two or more regions. In one of the regions the incident mesons stop and subsequently decay. The other regions are traversed by the decay products. One face of the chamber is viewed by the image-intensifier system and the opposite face is viewed by photomultiplier tubes, one for each of the separate chamber regions. It is required to trigger the image intensifier systems that a counter telescope, including one of the chamber photomultipliers, indicates that a meson has stopped in the proper region, and also that appropriate delayed coincidences obtain between that stopping event and pulses from the other chamber photomultipliers which indicate the passage of a decay particle. Under these conditions the event is photographed and, in addition, the time sequence of the several counter outputs is available for recording. The system is capable of utilizing a large-incident meson current and accepts decay-product particles over a large solid angle. The counter selection procedure limits the number of photographs necessary to observe a given decay mode and facilitates the extraction of useful data from the photographs that are taken. Such a system, with a two-section chamber $2\text{ in} \times 2\text{ in}$, has recently been employed in a measurement of the lifetime of the π^+ meson and in a preliminary attempt to observe directly the decay mode, $\pi^+ \rightarrow \mu^+ + \nu + \gamma$. The lifetime measurement was intended mainly to investigate sources of background in this technique in preparation for later experiments, including further measurements of π - and K-meson lifetimes. By appropriate selection criteria, the triggering of the system due to $\pi^+ \rightarrow \mu^+ + \nu + \gamma$ with a branching ratio of about 10^{-4} relative to $\pi^+ \rightarrow \mu^+ + \nu$ was enhanced by approximately the ratio of the muon to pion lifetime. With about 3.5×10^3 pions stopping in the chamber per minute, the system recorded an average of about 5 events per minute for a total, based on preliminary scanning, of about 8×10^3 events satisfying criteria applied to both the space and time information.

Renforceurs d'images pour l'étude de modes rares de désintégration des particules élémentaires. Les auteurs ont mis au point des systèmes renforceurs d'images dans des chambres à filaments, tels que les images de parcours de particules chargées soient limitées en résolution spatiale, uniquement par les dimensions du filament. Ces systèmes donnent une résolution temporelle de 1 microseconde environ. Employés simultanément avec des compteurs auxiliaires de particules, ils conviennent tout particulièrement à l'étude des modes rares de désintégration des particules élémentaires comme les mésons π et K. La chambre à filament est divisée en deux parties ou plus. Dans une de ces parties, le méson incident s'arrête et se désintègre ensuite. Les autres parties de la chambre sont traversées par les produits de désintégration. Une face de la chambre est vue par le système renforceur d'images et la face opposée par des photomultiplicateurs, un pour chacune des parties distinctes de la chambre. Pour déclencher le système renforceur d'images, il faut, d'une part, qu'un télescope de compteurs et qu'un des photomultiplicateurs indiquent qu'un méson s'est arrêté dans la partie convenable de la chambre et,

d'autre part, que des coïncidences retardées appropriées se produisent entre cet arrêt du méson et les impulsions venant des autres photomultiplicateurs qui indiquent le passage d'une particule de désintégration. Alors seulement l'événement est photographié; de plus, la succession des signaux de sortie des différents compteurs peut être enregistrée. Le système peut être soumis à l'action d'un faisceau intense de mésons incidents et permet l'étude des particules de désintégration dans un très grand angle solide.

La méthode de sélection par compteurs limite le nombre de photographies nécessaires pour observer un mode de désintégration donné et facilite l'extraction des données utiles à partir des photographies prises.

Les auteurs ont employé récemment un tel système, avec une chambre à deux sections ($2'' \times 2''$), pour mesurer la durée de vie du méson π^+ et essayer d'observer directement le mode de désintégration $\pi^+ \rightarrow \mu^+ + \nu + \gamma$. La mesure de la durée de vie avait essentiellement pour objet d'étudier les sources de bruits de fond dans cette technique, en prévision d'expériences futures, notamment d'autres mesures de la durée de vie des mésons π et K .

Par des critères de sélection appropriés, le déclenchement du système renforceur d'images dû à la réaction $\pi^+ \rightarrow \mu^+ + \nu + \gamma$ avec un rapport de branchement de 10^{-4} environ par rapport à la réaction $\pi^+ \rightarrow \mu^+ + \nu$ a été augmenté d'une valeur approximativement égale au rapport entre la durée de vie du muon et celle du pion.

Avec $3,5 \cdot 10^3$ pions/minute environ s'arrêtant dans la chambre, le système a enregistré une moyenne de cinq événements par minute sur un total, basé sur un dépouillement préliminaire, de $8 \cdot 10^3$ événements environ, satisfaisant aux critères appliqués à la fois aux informations spatio-temporelles.

Система усилителей яркости изображений для изучения редких типов распада элементарных частиц. Были разработаны системы усилителей яркости изображений с катодными камерами, которые дают изображения путей заряженных частиц, ограниченных в пространственном разрешении только размером катода, и которые показывают время разрешения порядка одной микросекунды. Это приспособление, используемое вместе с дополнительными счетчиками частей, удобно для изучения редких типов распада элементарных частиц, например π и K -мезонов. Метод основан на применении катодной камеры, разделенной на две или больше зон. В одной из зон случайные мезоны останавливаются и затем распадаются. Через другие зоны проходят продукты распада. Одна сторона камеры видна благодаря системе усилителей яркости изображений, а противоположная сторона видна благодаря электронным фотоумножителям, по одному фотоумножителю на каждую отдельную зону камеры. Для приведения в действие системы усилителей яркости изображений требуется, чтобы телескопическая система счетчиков, включая один из фотоумножителей камеры, указывала, что мезон затормозился в соответствующей зоне, а также что получены запаздывающие совпадения между явлением торможения и импульсами от других фотоумножителей камеры, которые указывают на прохождение частиц распада. При этих условиях явление фотографируется и, кроме того, ведется запись времени последовательных выходов некоторых счетчиков. Система применима для использования большого потока случайных мезонов и принимает частицы продуктов распада под большим пространственным углом. Процедура отбора, производимая счетчиком, ограничивает число фотоснимков, необходимых для наблюдения заданного типа распада, и облегчает отбор нужных данных со сделанных фотоснимков. Такая система из делящихся на две части камер $2'' \times 2''$ была недавно использована для измерения времени жизни мезона π^+ и при предварительной попытке непосредственно наблюдать тип распада $\pi^+ \rightarrow \mu^+ + \nu + \gamma$. Измерение времени жизни производилось главным образом с целью исследования источников фона в этом методе для подготовки дальнейших экспериментов, включая дальнейшие измерения времени жизни π - и K -мезонов. Благодаря соответствующему отбору критериев триггирование системы в результате распада $\pi^+ \rightarrow \mu^+ + \nu + \gamma$ с коэффициентом ветвей распада около 10^{-4} по отношению $\pi^+ \rightarrow \mu^+ + \nu$ было усилено примерно на коэффициент соотношения времени жизни мю-мезона к пи-мезону. При торможении в камере около

$3,5 \times 10^3$ пи-мезонов в минуту система записала в среднем около 5 явлений в минуту в целом, основываясь на предварительном сканировании и около 8×10^3 явлений, удовлетворяющих критериям, применимым к информации о пространстве и времени.

Sistema intensificador de imágenes para el estudio de modos de desintegración poco frecuentes de partículas elementales. Los autores han construido sistemas intensificadores de imágenes basados en cámaras de filamentos con los que se obtienen imágenes de las trazas de partículas cargadas. El único límite de la resolución espacial lo impone el tamaño del filamento, y la resolución en el tiempo es del orden del microsegundo. Este dispositivo, empleado con contadores auxiliares de partículas, se presta para el estudio de modos de desintegración poco frecuentes de partículas elementales como, por ejemplo, mesones π y mesones K. El método se basa en el empleo de una cámara de filamentos dividida en dos o más secciones. Los mesones quedan frenados en una de las secciones y seguidamente se desintegran. Los productos de desintegración atraviesan las otras secciones. El sistema intensificador registra las imágenes de una de las caras de la cámara, y las de la cara opuesta son abarcadas por tubos fotomultiplicadores, una por cada sección de la cámara. Para que se dispare el sistema intensificador de imágenes, es preciso que un telescopio contador, que incluye a uno de los fotomultiplicadores de la cámara, indique que un mesón ha quedado frenado en la sección apropiada, y también que se haya obtenido la coincidencia retardada necesaria entre el suceso de frenado y los impulsos de los demás fotomultiplicadores de la cámara que indiquen el paso de una partícula formada en la desintegración. Si se cumplen estas condiciones, el suceso es fotografiado y, además, se puede registrar el orden cronológico de los impulsos procedentes de los diversos contadores. El sistema puede utilizar una corriente muy intensa de mesones incidentes y acepta partículas producidas por desintegración dentro de un amplio ángulo sólido. El procedimiento de selección limita el número de fotografías necesario para observar un proceso de desintegración determinado y facilita la interpretación de las fotografías. Recientemente se ha utilizado este sistema, con una cámara de dos secciones de 2×2 pulgadas (5×5 cm), para medir el período del mesón π^+ , y en un primer intento de observar directamente el proceso de desintegración $\pi^+ \rightarrow \mu^+ + \nu + \gamma$. La medición del período tenía como finalidad principal investigar posibles orígenes del ruido de fondo de este sistema como preparación de experimentos posteriores, entre otros, nuevas mediciones del período de los mesones π y de los mesones K. Aplicando criterios selectivos adecuados, se logró que el disparo del sistema, debido a $\pi^+ \rightarrow \mu^+ + \nu + \gamma$ con una razón de ramificación del orden de 10^{-4} relativa a $\pi^+ \rightarrow \mu^+ + \nu$, quedase aumentado, aproximadamente, en el cociente período del muón/período del pión. Al quedar frenados en la cámara unos $3,5 \times 10^3$ piones por minuto, el sistema registró un promedio de unos 5 sucesos por minuto para un total, basado en una exploración preliminar, de unos 8×10^3 sucesos que satisfacen los criterios aplicados tanto a la información con respecto al espacio, como con respecto al tiempo.

The goal of particle detectors in high-energy physics has been to produce a device that can be triggered and has good spatial and time-resolution while precisely defining the processes of interest. The expansion cloud chamber was an early attempt at such a device. It had good spatial resolution and could be triggered but its time resolution was about $1/10$ s. At the other extreme is the counter hodoscope, whose time-resolution is several nanoseconds but whose spatial resolution is at best several centimeters and which is, by its very nature, limited in the number of constituent elements.

The filamentary chamber-image intensifier system [1] promised to provide the time-resolution of a counter array, a spatial resolution between that of the bubble chamber and the hodoscope and a system that was selective and could be triggered. Because of the numerous resolution elements available and because of the way in which they are assembled, it afforded a flexible and versatile detection system.

The filamentary chamber-image intensifier system, Fig. 1, consists of a chamber, an intensifier system, a counter array and logic and control circuitry. The chamber is a matrix of plastic scintillator filaments, say 1 mm diam. by 1 in long, each of which acts as a light pipe. Our early chambers contained about 2500 filaments while our present chamber has about 10000 filaments. Layers of filaments are frequently interspaced with high-density plates (e.g., gold) to increase the stopping power of the chamber or to provide several radiation lengths for gamma-ray conversion or the production of electron showers.

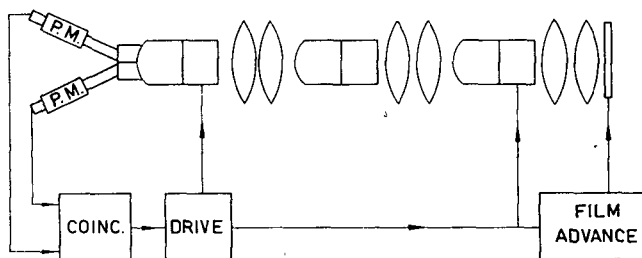


Fig. 1

A block diagram of the filamentary chamber-image intensifier system

The chamber is viewed by a six-stage light-intensifying system followed by a camera. Each stage consists of a photocathode, an accelerating region for the photo-electrons and a phosphor. The first stage has a thin window, 1 mm thick, against which the chamber is placed. This permits good coupling of the filaments to the first photocathode with a small loss of resolution. The first tube demagnifies the chamber image to 1 in, the aperture of the succeeding amplifying stages. Our present first-stage tube has a 9-in input aperture. The first stage has a P15 output phosphor, Fig. 2, a fast phosphor with a lifetime in the microsecond region.

Normally the second and last stages of the system have their accelerating voltage turned off. If the counter array indicates that the desired process has occurred in the chamber, then the second stage is pulsed on for about one microsecond and the last stage for several milliseconds. Since the first phosphor has a short lifetime, the chamber can be exposed to a high-intensity particle beam without an appreciable track overlap on the film, which makes it possible to photograph desired events with an absence of background tracks.

The chamber is also viewed by several photomultipliers. Since each of the viewed regions is optically isolated from all the others, these photomultipliers, in conjunction with the various counters surrounding the chamber, provide the input for the logic circuitry. The outputs of the chamber photomultipliers corresponding to the desired events are photographed on an oscilloscope. These photographs together with the intensifier system output are used to provide spatial and temporal information about the events.

We are using this instrument for studying various rare meson decay processes. In the design of such an experiment it is necessary to define the incoming beam and to select the desired decay from the large number of unwanted processes. The beam telescope consists of a series of scintillation and Cerenkov counters, the stopping counter

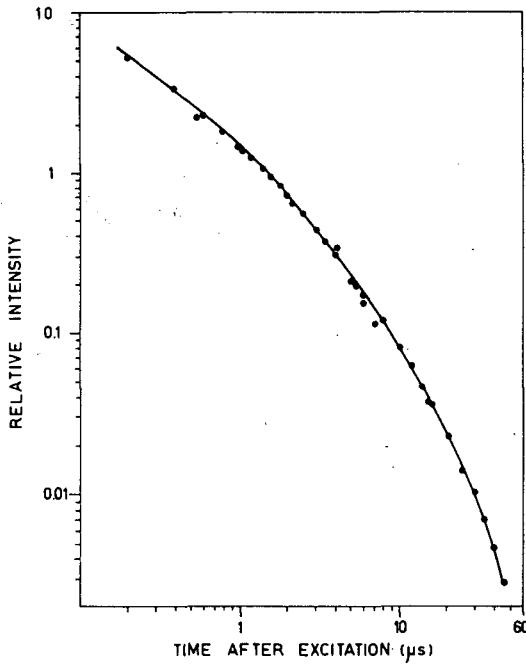


Fig. 2
Differential plot of P 15 output

of which is a region of the chamber. The stopping of a particle in the chamber initiates a gate which stays open for several particle lifetimes. Various other regions of the chamber and surrounding counters are so arranged that appropriate directional correlations between the charged and photon secondaries and range-requirements of the charged decay product are met before the system is triggered. The unwanted decay modes are eliminated by appropriate anti-coincidence counters. When the system is triggered, the appropriate intensifier stages are pulsed on, the oscilloscope display is triggered, the cameras are advanced and both register and reticules are imprinted on the film. An inhibit circuit prevents the system from triggering again until all the above processes have been completed. This prevents the recording of more than one event on any frame.

In autumn, 1960, an experiment was carried out at the Nevis Synchrocyclotron of Columbia University. This experiment was designed to test the filamentary chamber at a high-energy particle accelerator, provide a test of the selection system by making a background free measurement of the π^+ lifetime and be a preliminary run of a series of experiments designed to look for the radiative pion decay modes ($\pi^+ \rightarrow \mu^+ + \nu + \gamma$ and $\pi^+ \rightarrow e^+ + \nu + \gamma$) and the pion beta decay ($\pi^+ \rightarrow \pi^0 + e^+ + \nu$).

A chamber 2 in square, Fig. 3, was used. The upper half of the chamber, which was filled with filaments, served as the stopping counter, while the bottom half, in which 8 gold plates were inserted, served as the electron detector and photon converter. 100 π^+ /s stopped in the chamber. Because of the duty cycle of the accelerator, this

corresponded to an instantaneous intensity of at least 3000 particles per second and probably considerably more. This beam intensity was limited only by the output of the accelerator and not by the capability of the system.

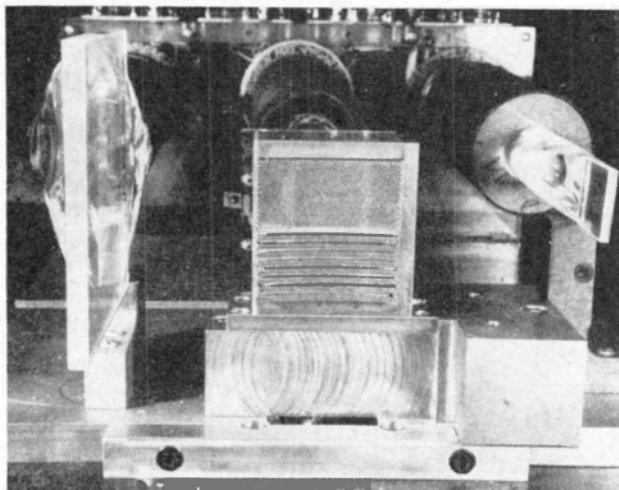


Fig. 3

The filamentary chamber and counter array used in the π^+ decay experiment

Each stopping pion initiated a gate, Fig. 4, which, during various times throughout the experiment, was 51 ns or 160 ns. During this gate it was required that a coincidence between the stopping region and the decay region occur. Since the μ^+ from π^+ decay only had a range of two or three filaments, they could not reach the decay region. The positrons from the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain were suppressed in the ratio of the μ^+ lifetime to the gate length. Since the most prominent of the rare pion decay modes only occurs 10^{-4} times as frequently as the normal mode, the normal mode, Fig. 5, was still recorded 10^2 times as often as the rare modes.

Using the oscilloscope photographs of the stopping region and accepting only traces that correspond to a clean and clear pion decay-image intensifier picture, a pion lifetime measurement was made. In addition, a number of events corresponding to $\pi^+ \rightarrow e^+ + \nu$ were observed, consistent with measured branching ratios. The number of photographs taken during this run was not sufficient to permit the unambiguous identification of any of the other pion decay modes. This work is continuing.

We are now attempting an experiment on the three-body decay modes of the K^+ meson. Here we hope to study the $K_{\mu 2}^+$ and $K_{e 2}^+$ decay modes and in particular measure the energy spectrum of the charged secondary as well as measure the lifetime of each of the modes. In this case the chamber is divided into three regions, the K mesons being stopped in the centre region. One of the arms acts as a range telescope, while both arms serve as photon converters. The $K_{\mu 2}^+$ mode is eliminated by anti-counters, but the $K_{\pi 2}^+$ mode is retained both to calibrate the range telescope and to aid in the search for other K^+ decay modes involving π^- mesons. This experiment is being done with a chamber $6\frac{1}{2}$ in high and 3 in wide.

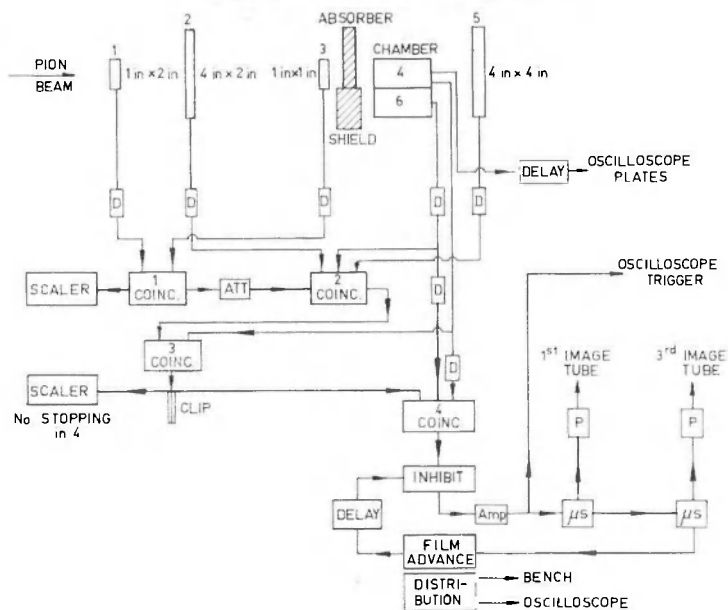


Fig. 4
A block diagram of the circuitry used in the π^+ decay experiment

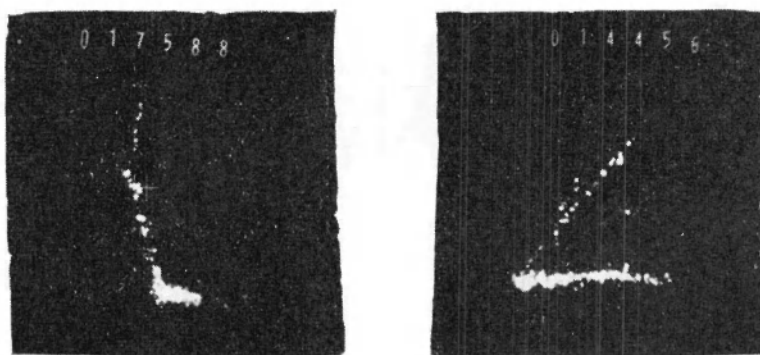


Fig. 5
Samples of π^+ decay pictures

The techniques described above can be applied to various other decay processes, in particular the hyperon beta decay processes.

As our description has indicated this system is capable of selecting particular processes in a high beam flux, and providing a spatial-resolution of about a millimeter and a time-resolution of several nanoseconds.

ACKNOWLEDGEMENTS

It is with great pleasure that we acknowledge the valuable assistance of Messrs. John Dobbs, Edward Mayer, Frank Sciulli, Hiroaki Uto and Kenneth Young.

REFERENCE

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AN IMAGE INTENSIFIER SYSTEM

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Abstract — Résumé — Аннотация — Resumen

An image intensifier system. On the basis of experience in operating large scintillation chambers at the Cosmotron, relative advantages of the plastic fibre and NaI types are discussed. The plastic chamber is $5 \times 5 \times 10$ in and is made up of $\frac{1}{2}$ mm fibres, whereas the homogeneous chamber is a $4 \times 6 \times 6$ in block of NaI. The chambers could be viewed stereoscopically with two chains of light amplifiers, ending in intensifier orthicon cameras. Comparisons are also made between operating with light amplifiers only and using light amplifiers with a television system. The unique method employed of reading the subsequent track pictures into a computer is also described briefly.

Dispositif renforceur d'images. En se fondant sur l'expérience acquise dans l'utilisation de chambres à scintillation de grandes dimensions au Cosmotron, les auteurs étudient les mérites respectifs des chambres à fibres en matière plastique et à NaI. La chambre en matière plastique mesure $5 \times 5 \times 10$ pouces et elle est composée de fibres de $\frac{1}{2}$ mm; la chambre homogène est un bloc de NaI de $4 \times 6 \times 6$ pouces. Les chambres sont observées par stéréoscopie avec deux chaînes de renforceurs de lumière se terminant par des caméras renforceuses à orthicon. Les auteurs comparent également les résultats obtenus en utilisant des renforceurs de lumière simples et des renforceurs pourvus d'un appareillage de télévision. Les auteurs décrivent aussi brièvement une méthode tout à fait particulière utilisée pour transmettre les images des trajectoires à une calculatrice.

Система усилителей яркости изображений. В докладе рассматриваются относительные преимущества пластической фибры и виды больших сцинтилляционных камер NaI на основе опыта применения больших сцинтилляционных камер в космотроне. Размер пластической камеры $5 \times 5 \times 10$ дюймов, и она сделана из $\frac{1}{2}$ мм фибры, тогда как гомогенная камера имеет размер $4 \times 6 \times 6$ в блоке NaI. За камерами можно наблюдать через стереоскоп с двумя цепями световых усилителей, которые заканчиваются усилительными ортikonными камерами. Проводится также сравнение между использованием только световых усилителей и световых усилителей с телевизионной системой. Дается также краткое описание уникального метода получения последующих следовых изображений со счетно-решающего устройства.

Sistema intensificador de imágenes. Basándose en la experiencia adquirida en el manejo de cámaras de centelleo de grandes dimensiones en el Cosmotron, los autores comparan las ventajas de los tipos a base de fibras de material plástico y de NaI. La cámara de material plástico mide $5 \times 5 \times 10$ pulgadas ($12,7 \times 12,7 \times 25,4$ cm) y está hecha de fibras de 0,5 mm, mientras que la cámara homogénea consiste en un bloque de NaI de $4 \times 6 \times 6$ pulgadas ($10,1 \times 15,2 \times 15,2$ cm). Las cámaras pueden ser observadas estereoscópicamente con dos cadenas de amplificadores de luz que terminan en orticonoscopios intensificadores. Los autores comparan también las ventajas de utilizar amplificadores de luz exclusivamente, o de emplearlos en combinación con un sistema de televisión. Describen someramente un método de trabajo especial que han empleado, consistente en transmitir directamente a una calculadora las imágenes de trazos obtenidas.

I. Introduction

At the Cosmotron the MIT group has tested large scintillation chambers of both the plastic $\frac{1}{2}$ -mm fibre and homogeneous (NaI) type, using cascaded image tubes and an orthicon camera. The fibre chamber is 5 in $\times$ 5 in $\times$ 10 in and the NaI block, 4 in $\times$ 6 in $\times$ 6 in. These could be viewed stereoscopically by two chains of light amplifiers, each consisting of a one-stage, 5-in Westinghouse tube, followed by a doubly-gated, 3-stage, 1-in RCA tube, and finally by an RCA intensifier orthicon and a modified 1029-line Bendix television system. The video information is displayed on four kinescopes, two for visual viewing and two for recording by fast (30 ms) cameras (Flight Research, Model IVC). The resulting pictures could be read directly into MIT's TX-O computer for measurement and analysis. The system using chamber 2 upon organic fibres is shown in Fig. 1, and some typical tracks in the subsequent Figures. Fig. 2 is a fast meson, Fig. 3 a stopping proton, and Fig. 4 an interaction. Differences in ionization are clearly apparent in these pictures made with NaI.

In the present state of the image tube art, it is much simpler to get into operation a large NaI chamber than a similar-sized fibre chamber. The main difference lies in the optical coupling between the chamber and the first photocathode. While simple commercial lens systems can be used to transfer the image from the NaI to the first photocathode, fibre chambers require (1) a coupling bundle of clad-glass fibres (see Fig. 1) to transfer the image from the plastic fibres to the image tube; and (2) a faceplate on the first image tube made either of very thin glass or of vacuum-tight, clad-glass fibres. Because of the necessity for high-efficiency photocathodes for either type of chamber, we initiated a programme with Westinghouse over two years ago to put trialkali cathodes on their 5-in tubes. At present, some good thick faceplate tubes are available, thin

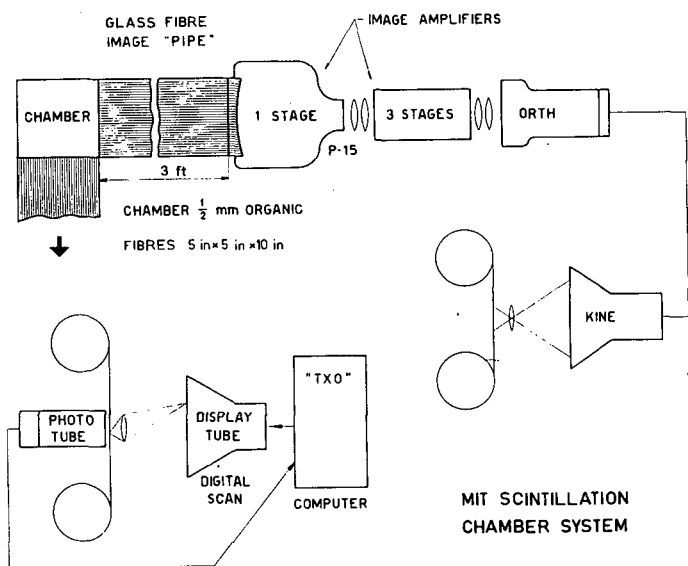


Fig. 1
MIT scintillation chamber system

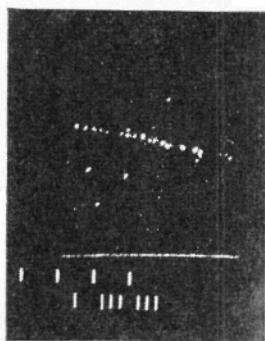


Fig. 2
Fast meson

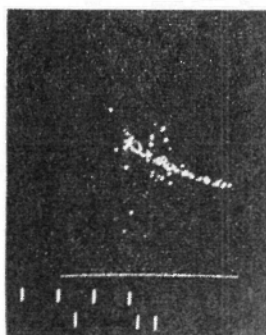


Fig. 3
Stopping proton

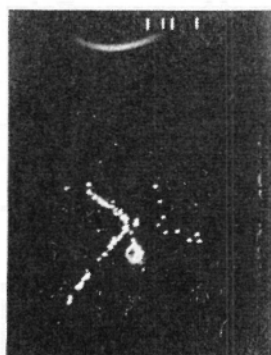


Fig. 4
Interaction

faceplate ones are just coming into use, and suitable fibre faceplate tubes are yet to be made, giving the NaI chambers a temporary advantage.

Other comparative advantages of the two types of chambers can be mentioned briefly. Fundamentally NaI chambers are limited in size by the depth of focus of the coupling lens, but with the multi-alkali Westinghouse tubes, that depth is about the same as the largest fibre chamber that can be used at present, 5 in $\times$ 5 in $\times$ 10 in. The 10-in length which is available, and whose fibres run in alternate directions and whose image in one dimension can be collapsed, is advantageous when one is dealing with particle decays. On the other hand, the greater stopping power of NaI may be more important for some uses, or the presence of hydrogen in the plastic fibres could be crucial for some experiments. For almost any experiment ionization information is very important and while the amount of light from a track is almost independent of depth in NaI, it may vary a factor of 3 in 5 inches of fibres and unfortunately may not have a uniform variation over the chamber. We have been developing low-index coating for fibres and this should improve the fibre-transmission properties.

There is little choice between NaI and fibres in regard to background light from a track, particularly since the largest source of such background is in the light amplifiers, presumably from gas scattering. For most purposes a far more important source of background is the build-up of light from old tracks because of the long tail on the decay of the P-15 storage phosphor. Here the slow decay of the NaI light, which will eventually be a disadvantage, is now an advantage because it provides a slower build-up of light at the P-15 phosphor, enabling one to gate on the following light amplifier nearer the peak of the P-15 light output and hence improve the signal-to-background ratio. Roughly a NaI chamber can stand about 10^5 particles per second, but this number depends greatly on the type of tracks one is looking for and the apparatus used. While a fibre chamber can stand perhaps a factor of two or three less than this, in some situations it may perform better than NaI because it will give fewer neutron stars and gamma conversions.

The NaI and fibre chambers each have particular advantages when one considers designing a triggering system for a given experiment. On the one hand, a single photomultiplier viewing one-face of the NaI block, to measure total energy-release, can be a powerful selection tool. On the other hand, the fibre chamber can be used as a hodoscope by having many photomultipliers view groups of fibres and one can in this way require selected numbers of tracks to appear in designated positions in the chamber.

An obvious advantage of NaI, which is available commercially (e.g. from Harshaw Chemical Company) and sealed in glass, over the fibre chamber is the ease of construction. While selecting, aligning, and polishing fibres pose interesting problems, our greatest challenge was to provide good optical coupling between the plastic and the glass fibres. While any stereoscopically-viewed chamber requires a glass-fibre coupling-bundle, in our case we had to have coupling bundles 3 ft long, since the chamber was to be in a magnetic field. The chamber was made of $\frac{1}{2}$ -mm fibres and for reasons of economy and light-coupling efficiency, we chose to couple each plastic fibre to a $\frac{1}{4}$ -mm clad-glass fibre (made by Mosaic Fabrications, Inc.). To provide the alignment of the fibres, matching photo-etched plates were made (by Buckbee-Meers Company) with holes for each fibre, every other hole being off-set, since the fibres are densely packed along a layer, but only every other layer goes in a given direction. The plastic fibres, being easily bent, had to be inserted individually (after dipping in a low-index polyvinyl acetate glue to protect the fibre surface) but the glass fibres were pre-spaced in a comb-

like form and could be inserted in groups and epoxied in place. Since the plastic fibres were glued into the holes and the glass fibres epoxied, both could then be polished and the two plates butted together. The optical contact was quite good, but there were other troubles with the chamber which almost surely could have been corrected in another attempt. Instead, a rather different approach was tried in which the photo-etched plates were made with slots instead of holes and both the plastic and glass fibres were prefabricated in layers. This type of construction is more expensive, because the glass fibres (not being in registration) must be much smaller than the plastic fibres and the optical coupling is not quite as efficient, but the chamber is far easier to make, and the problem of registering the two ends of the glass fibres is not so formidable.

III. Light amplifiers

Both the fibre chamber and the NaI block were tested at the Cosmotron with the same light-amplifying system, which featured intensifier orthicon cameras. Since the MIT group was the first to use a television system with a scintillation chamber, it may be useful to compare such a system with one having only image intensifiers. When this work was started nearly three years ago, even intensifier orthicons had better resolution than the then available multi-stage light amplifiers. Now, however, the reverse is the case by about a factor of two. Magnetic-light amplifiers will be even better, but magnetic-intensifier orthicons are also being developed. A second advantage the television system appeared to have a few years ago was that, with the information in video form, it appeared feasible to reduce that information between proton-synchrotron machine pulses and to record on magnetic tape the co-ordinates of "lit" spots. Such a system was worked out but not constructed, since we found a cheaper solution in reading pictures directly into a computer. A third advantage of the television system still proves useful, namely, that one has more control over the appearance of the track information, since one can easily change the signal level, the background discrimination, and even the uniformity of gain across the picture. The fourth advantage has been particularly important in this early testing phase and in the operating of a machine: that one has an immediate and simply available presentation of what is going on in the chamber or in the light amplifier. Thus the operation can be monitored while photographing data, without waiting for the development of test strips. As an adjunct to this rapid diagnostic capability, we installed small projectors on the inter-stage coupling lenses to put resolution patterns on the first photocathode of each light amplifier when it was necessary to find a fault. Despite these advantages of the television system, the rapid improvement in image-intensifier resolution, distortion, noise, and gain probably makes a straight-image intensifier-chain the better choice for future work.

In addition to using multi-alkali Westinghouse tubes and an intensifier orthicon, some other features of our system should be mentioned. Because the 3-stage RCA tube and the orthicon have curved faceplates and because fast optical coupling is necessary, we had the Farrand Optical Company design an $f/0.87$ lens system to match that curvature. These lenses have proved quite satisfactory, but they do introduce vignetting. However, because we had an order of magnitude in light-gain to spare in our system, we were able to put neutral density-filters at the output of the 3-stage tube to more or less compensate for this vignetting. Cathode non-uniformities could also be compensated for in this way, and a "creeping-spot" cathode-scanning system was built to measure such non-uniformities in the system.

The gating system used was a fast (rise time $\sim 0.1 \mu\text{s}$) gate on the first photocathode of the 3-stage tube, which follows the P-15 storage phosphor on the Westinghouse, and a slow gate on the third photocathode of that tube, following two slower P-11 phosphors. This double gate, plus the gate on the kinescope which allowed the film to see only one non-interlaced frame, made tube background-noise negligible. The double gate had another purpose, however. To optimize signal to background, one should turn on the light-amplifying stage following the P-15 storage phosphor, as soon as possible after the desired event has occurred. Delays in the triggering electronics, if the triggering system is refined, make it desirable to use a relatively simple but rapid trigger on the slow gate. One loses a few events because of system deadtimes when the incomplete fast trigger is vetoed by the complete slow trigger, but for most experiments this is not important. It should be emphasized that a major source of trigger delay is provided by photomultipliers and improvements in photomultiplier delay-time would be very advantageous.

IV. Data reduction

As has already been mentioned, the pictures taken by photographing the kinescope could be read directly into a computer, the TX-O at MIT. In Fig. 1 this system is shown schematically. Since we were the first physics group to use a computer in this way, perhaps some discussion of the present system would be worthwhile. The basic idea is a simple one, resembling the use of a flying-spot scanner. The flying spot is provided by a cathode-ray tube-display which has a programmed spot controlled by the computer. As this spot is moved across its 512 positions in 512 lines, it is imaged on a 35-mm negative containing the track information of interest. A photomultiplier behind the film detects whether the position on which the spot is imaged is dark or light and signals the computer accordingly. Should the spot be on a position corresponding to a bright point in the chamber, the computer will store the location of that position. Using the full resolution of the scope (512×512), a picture can be scanned in about 10 s, although for present pictures as 256×256 scan taking about 3 s is sufficient. After the picture is in the TX-O's memory, the computer displays the picture on the programmed CRT. The operator then holds a "light pen", containing a phototransistor connected to the computer in the same way as the photomultiplier is, at the positions of the end points of the tracks of interest as they are seen on the CRT. The computer then locates these approximate end-points more accurately and proceeds to find representative intermediate points along the track for the purpose of fitting third-order equations to the tracks. To save machine time, the point locating is actually done using the film as the storage medium rather than the track locations already in the machine memory. Thus, because the TX-O is rather slow at doing arithmetic, the original film read-in is done only so that the operator may approximately locate the appropriate end-points. Naturally it would be desirable to eliminate both this step and the operator. To this end, pattern-recognition procedures have been studied, but so far they consume too much machine time, primarily because of the limitations of the TX-O.

The simplicity of scintillation-chamber pictures, plus the pre-selection afforded by the time-resolution of this device, makes the automatic processing of pictures both feasible and desirable. Such a system should have a remarkable capability for experiments involving large numbers of events, as well as for those involving rare events in large numbers of unwanted ones.

INTENSIFIER TUBE DEVELOPMENT

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Abstract — Résumé — Аннотация — Resumen

Intensifier tube development. Butslov *et al.* (Proceedings of IV Congress on High-Speed Photography, Cologne, 1958) have published an account of their work on an Image Intensifier Chronograph useful in connection with spark counters. Comments are made on extensions of this technique with respect to different kinds of output, deflection and shuttering. In particular some of the problems connected with multi-stage intensifiers will be considered.

As a result of some experience in experiments of this type an attempt has been made to make small-diameter fibre scintillators for both detectors and output screens.

Perfectionnements du tube renforceur. Butslov *et al.* (Actes du quatrième congrès sur la photographie ultrarapide, Cologne, 1958) ont publié un compte rendu de leurs travaux de mise au point d'un chronographe renforceur d'images jouant un rôle utile dans les compteurs à étincelles. Des observations sont faites sur les applications de cette technique aux différents types de sortie, de déflexion et d'obturation. On étudie notamment certains des problèmes relatifs aux renforceurs à plusieurs étages.

Grâce à l'expérience que les recherches dans ce domaine ont permis d'acquérir, on a essayé de réaliser des scintillateurs à fibre, de petit diamètre, à la fois pour des détecteurs et pour des écrans de sortie.

Разработка конструкции усилительной электронной лампы. Бутслов и другие опубликовали отчет о своей работе по созданию хронографа для усиления яркости изображений, который полезно применять в связи сосчетчиком искр (труды IV конгресса по высокоскоростной фотографии, Кельн, 1958 г.). Делаются замечания относительно возможностей распространения этого метода в связи с различными видами выходящих импульсов и устройствами отклонения и прерывания. В частности, рассматриваются некоторые проблемы в связи с многокаскадными усилителями.

В результате накопленного при экспериментах этого рода опыта была сделана попытка сконструировать волокнистые сцинтилляторы малого диаметра как для детекторов, так и для экранирования выходящих импульсов.

Desarrollo de válvulas intensificadoras. Butslov y otros (Actas del IV Congreso de Fotografía Ultraveloz, Colonia, 1958) han publicado una memoria sobre sus estudios acerca de un cronógrafo intensificador de imágenes que tiene utilidad en el caso de los contadores de chispa. El autor estudia la posibilidad de extender la aplicación de este procedimiento a distintas clases de salida, deflexión y obturación. En particular trata algunos problemas relacionados con los intensificadores de etapas múltiples.

Como aplicación de la experiencia adquirida en ensayos de este tipo, se ha intentado preparar centelleadores de fibra de diámetro pequeño, tanto para detectores como para pantallas de salida.

Some image tubes with time resolution

As an introduction it would be well to repeat some of the comments made in a previous paper [1] concerning the general philosophy of instrument design as these have a considerable bearing on the devices to be described.

Because one part of an experiment reacts in design on every other part, a fundamental limit on one part will be a limit on the total experiment. An experiment in physics is

a measurement carried out by a chain of information-handling devices. Improvements in these measurements can be obtained by a process akin to the mathematical process of "iteration". One part of the chain may be developed further if certain other developments can be carried out on another part, these developments in turn react on further parts of the chain so that one can almost consider that a "solution" is being approached, the solution being an experiment of optimum efficiency. This tends to be the normal approach in modern times because of the availability of a wide range of commercial instruments, but because of this it tends to be forgotten that there are other ways of improving measurements. The iterative process itself does not ensure that any solution is unique, nor does it give any information concerning the number of other solutions.

The design of an experiment should be approached more fundamentally than a search for developments in components and should be based on physical principles. A useful approach to a design principle can be expressed as follows: the number of transformations of the information should be a minimum. A corollary of this would be that any type of information carrier should not be used in more than one position in the chain.

A few examples will help to clarify these statements and will lead on to the new work we wish to describe. Let us consider the case of a typical nuclear experiment, the detection of a particle flux by a scintillator. The block diagram can be set out as is shown in Fig. 1 below.

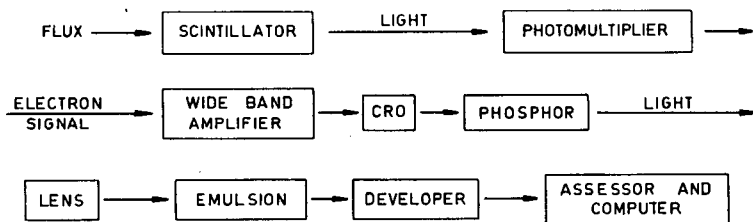


Fig. 1

Block diagram of typical nuclear experiment

As a first example of the method, a very simple and easy one, the phosphor-assessor group of stages may be considered. Here an electron beam hits the phosphor, light is emitted and some of it is collected by the lens which absorbs a proportion depending on the wavelength and focusses the remainder. The light falling on the emulsion affects the grains and the picture is formed. Now the efficiency of these processes is very low. The phosphor efficiency is something like 10%, the collecting efficiency at the most 10%, the lens transmission in the blue-violet will be 50% maximum and only one grain of the emulsion is activated for every thousand quanta that fall on it. Whether this loss is important or not depends on whether compensation has had to be made in the adjacent stages: is there any limit set by this inefficiency? In recent years with such tubes as the travelling-wave deflection tubes limitations have appeared; it is not possible to record the fastest traces and the minimum-spot sizes by known optical methods. The use of reflecting-lens systems is difficult because of the inherent diameter excess and the further extension of refracting systems will not improve the situation very much because any gain in aperture is almost cancelled by the absorption of the extra

axial thickness. The two approaches which best illustrate the point are, on the one hand, the working on higher transmission glasses, on the other hand dispensing with the lens altogether and using, say, fibre tube-ends, xerographic plates with wire conductors or even methods involving thin end-windows.

No doubt experts in these matters can point out further small-scale rationalizations but the above examples are almost trivial compared with what follows. Attention is drawn again to the block diagram. What are the physical actions carried out? The scintillator transforms a particle flux into a light flux which is again transformed into a particle flux but the particles are electrons. Amplification is then obtained by accelerating the electrons and multiplying their number by secondary multiplication followed by normal electronic amplification. It is not until the signal deflects the beam of electrons in the 'scope that any time-resolution takes place, but from this stage onwards the time-response is unimportant. The information required exists successively in the following forms: particle flux, light flux, particle flux, field-changes, position of particles, position of light-emitting points and finally, position of light-absorbing points. Against this the only necessary physical actions may be written down as follows:

- (1) Transformation;
- (2) Time-resolution;
- (3) Amplification for storage;
- (4) Storage.

The transformation stage is required to get the maximum information from the input. It is difficult to describe this without bringing in the qualities of known receptors, but the purpose is to change the given radiation or flux at high efficiency into the one most suitable for time-resolution. The most suitable type of signal known at present for time-resolution is the position of the focussed spot of a beam of electrons.

This can be utilized not only as in the case of the 'scope, where the signal to be resolved is represented by one co-ordinate, but also by taking the beam-flux as the signal to be resolved. This latter is more fundamental, because it requires one less physical transformation of the information-carrying signal. Hence it will be chosen here.

So far a sweeping beam of electrons has been obtained, with the flux carrying the signal. This now requires, first, sufficient amplification for storage, then efficient storage. In the standard arrangement, amplification has to be provided so that the signal can deflect a beam of quite high energy. The beam is of high energy because of the inefficiency of the next process, but the real criticism is that all this goes on before the time-resolving takes place. Thus every previous stage has to have a response time which is small compared to the time-resolution required. This makes the problem of instrument design quite difficult in all these previous stages and is not logically sound.

Another minor criticism is that a tendency exists of paying too much attention to monitoring requirements. For fast transient recording the 'scope is not a visual instrument as it is for continuous signals, and it is encouraging that sometimes the phosphor has been chosen in a region of the spectrum that is fairly easy to record photographically. However, in principle it is not good that monitoring requirements should affect the basic design and, if the signal is kept in a form not detectable by our senses, only a small proportion of it should pass through the monitor.

The philosophy of taking the experiment as a whole is exemplified in the excellent paper by BUTSLOV *et al.* [2] given at the Cologne congress. This paper stresses the examination of the properties of all the information channels and their fundamental physical limitations.

The position of the time-resolving stage in the chain and the physics of that stage have been previously considered in work on Image Converters. Here the time-resolution takes place by interrupting or deflecting the electron beam within the tube. In the case of the Butslov *et al.* tube there is a novel capping shutter but the main time-resolution is given by a circular sweep. This is possible in a simple fashion because the beam is very small in diameter, hence electrostatic deflection can be used with elementary electrodes. The objections to this type of tube relate to the stages after the time-resolving has taken place. The final output is still a phosphor screen which has to be photographed, thus extra stages are necessary to overcome the inefficiency. In addition this transformation into light is of no experimental advantage and in the first one or two multipliers it is possible that serious disadvantages may exist because of phosphor inefficiency at low levels of excitation [3]. Once the signal is in the form of the variation of electron density in two dimensions efforts should be made to obtain storage without changing the form of the information carrier. LALLEMAND [4] has shown that it is efficient to use the direct effect of electrons on photographic emulsions but this is a very awkward technique to use.

Transformations from electrons to light can be avoided both in the multipliers and in the output. Many tubes have been made now both to the design of WILCOCK *et al.* [5] and to that of WACHTEL *et al.* [6] (the Astracon) using thin-film electron multipliers but they all have phosphor outputs. A tube being made for the Atomic Energy Authority, which may need one stage of such intensification, consists of a photocathode, a deflection system, a bombardment-induced conductivity screen and a reading-out gun. This tube has been described by CHIPPENDALE and FOULKES [7] and has led to some interesting work in the Atomic Energy Authority on the form of scanning which is optimum for any form of image. The scanning can be made slow enough for tape-recording and information can be put on the tape which relates to the type of scan. This enables monitoring to be carried out and also the calling-up of relevant individual scans of the picture.

Another tube has been built which is a complete streak-camera for the ultra-violet region of the spectrum. The design is quite straightforward and is aimed particularly at the region below 1200 Å where no known materials transmit. In these circumstances the system must be built into the chamber containing the experiment. Two variations are illustrated (see Figs. 1 and 2). The first has the slit in the image plane and is used where the pressure in the event chamber is less than the greatest pressure tolerable for the electron tube. The second requires the slit to be in the object plane and is used

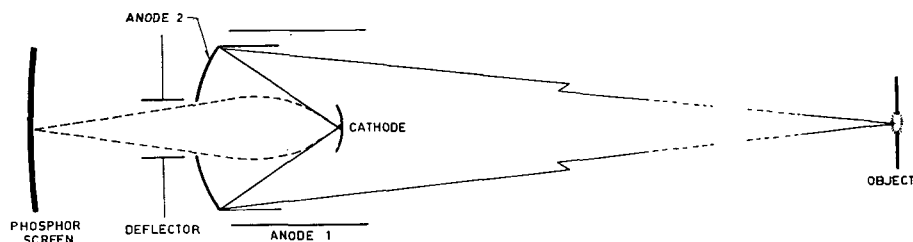


Fig. 2

Structure of streak camera for vacuum ultra-violet

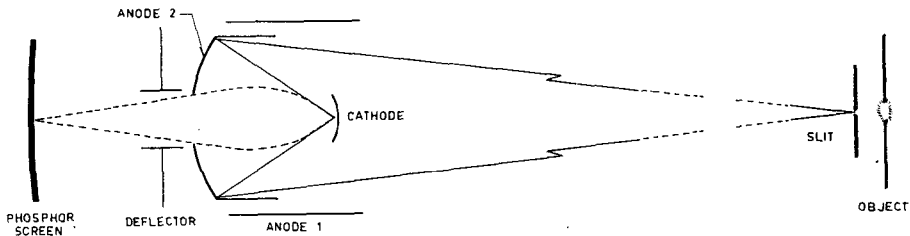


Fig. 3

Structure of streak camera for vacuum ultra-violet, (where event pressure is greater than 10^{-7} Torr)

where the pressure in the event-chamber is so high that the mean free path of electrons is too short for the electron tube part and differential pumping is required.

A gold photocathode is used at present but much work needs to be done on the best choice of material. Many measurements have still to be made on quantum efficiency and this is quite a difficult region of the spectrum in which to work. It was decided that as reflectivities are very low in this region only one mirror surface would be allowed. As with the photocathode much more work is necessary before the final choice is made of the most suitable material for the mirror surface.

There are several further possibilities for complete camera tubes but they are still in the early design stage.

An important problem in many of these tubes is the deflection of a large-diameter beam and this is best carried out with multiple plates as described by NAKAMURA and KASAI [8].

Recently experiments have been carried out by the author on phosphor fibres for tube-ends. KAPANY [9] has pointed out the difficulty produced by the very high refractive index of most efficient phosphor substances. However if the fibre were the phosphor itself, the high index would be an advantage. Unfortunately the chemical and physical character of the most efficient phosphors is such that a straightforward "drawing" process cannot be applied and complicated fibre cross-sections have to be attempted.

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THE LUMINESCENT CHAMBER AND ITS USE IN HIGH-ENERGY PHYSICS EXPERIMENTS

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Abstract — Résumé — Аннотация — Resumen

The luminescent chamber and its use in high-energy physics experiments. A luminescent chamber has been employed for the first time in experiments in high-energy particle physics. At the Bevatron of the Lawrence Radiation Laboratory, particle tracks in activated sodium-iodide crystals were photographed using a cascade system of three-image intensifier tubes. In one experiment, elastic pion-proton scattering was studied using two arrays of scintillator, each 20 cm long, one to observe the scattered pion and the other the recoil proton from a liquid hydrogen target. Scintillation counters selected only nearly-coplanar events to be recorded; however the final criteria for elastic scattering were the kinematics of the recorded tracks. About 1000 elastic events were photographed at each of three incident pion moments up to 2.5 MeV/c. In a second experiment a single-scintillator array $10 \times 10 \times 20$ cm³ was used to observe stopping recoil protons from inelastic pion scattering (single pion production) at three incident pion momenta. Again several thousand events were recorded. The range and angle of the recoil proton uniquely determined the momentum transfer and the centre-of-mass energy of the di-pion system which were the relevant kinematical parameters in this problem. In these experiments post-event triggering and five-microsecond time-resolution were achieved by gating the second image tube on a signal from the scintillation-counter electronics. The design and successful execution of these experiments are discussed in this paper, with particular reference to the relevant details of the image tubes, the scintillation counters and the electronic systems. Experience has also been gained in the analysis of the track photographs, particularly regarding the accuracy obtainable and reliability of the physics thus obtained. In conclusion, the future evolution of the luminescent chamber is explored, considering the image intensifier tubes and scintillators under current development. The role of the luminescent chamber in future high-energy experiments is analysed in relation to the spark chamber and other detectors.

La chambre à luminescence: son emploi dans les expériences de physique des hautes énergies. Pour la première fois, une chambre à luminescence a été utilisée dans des expériences sur la physique des particules de haute énergie. Au bévatron du Lawrence Radiation Laboratory, des trajectoires de particules dans des cristaux d'iodure de sodium activé ont été photographiées à l'aide d'un système composé de trois tubes renforceurs d'image disposés en cascade. Au cours d'une première expérience, les auteurs ont étudié la diffusion élastique pion-proton au moyen de deux dispositifs de 20 cm de long vus chacun par un scintillateur et servant à observer l'un le pion diffusé, l'autre, le proton de recul d'une cible d'hydrogène liquide. Les compteurs à scintillations ne sélectionnaient, aux fins d'enregistrement, que les événements quasi coplanaires; cependant, les critères de diffusion élastique étaient les données cinématiques des trajectoires enregistrées. Pres de 1000 événements élastiques ont été photographiés pour chacune des trois valeurs de la quantité de mouvement des mésons incidents, jusqu'à 2,5 MeV/c.

Au cours d'une seconde expérience, on n'a utilisé qu'un seul dispositif de $10 \times 10 \times 20$ cm vu par un scintillateur, pour observer les protons de recul qui s'arrêtent lors de la diffusion inélastique des pions (production d'un pion unique) pour trois quantités de mouvements différents du pion incident. On a, ici encore, enregistré plusieurs milliers d'événements. Le parcours et l'angle du proton de recul ont permis de déterminer le transfert de la quantité de mouvement et l'énergie dans le centre de masse du système pion-pion, qui constituaient dans ce cas les deux paramètres cinématiques déterminants. Dans ces expériences, on a pu réaliser le déclenchement

conditionné par la production de l'événement et obtenir un temps de résolution de 5 microsecondes, en faisant en sorte que le second tube à rayons cathodiques se déclenche lorsqu'un signal est donné par la partie électronique du compteur à scintillations.

Les auteurs exposent les travaux de préparation et d'exécution qui ont été nécessaires pour mener ces expériences à bonne fin; ils donnent, en particulier, les détails voulus sur les tubes à rayons cathodiques, les compteurs à scintillations et les systèmes électroniques utilisés. L'analyse de photographies de trajectoires leur a permis d'étudier, notamment, le degré de précision qui peut être atteint et la valeur des résultats physiques qui peuvent être obtenus. Enfin, ils explorent les possibilités de développement qui s'offrent à la chambre à luminescence, compte tenu des tubes renforceurs d'image et des scintillateurs actuellement à l'étude. Ils analysent le rôle que la chambre à luminescence est appelée à jouer à l'avenir dans les expériences du domaine des grandes énergies en comparaison avec la chambre à étincelles et les autres détecteurs.

Люминесцентная камера и ее использование в экспериментах, проводимых в физике высоких энергий. Впервые в экспериментах в области физики частиц высоких энергий была использована люминесцентная камера. На беватроне радиационной лаборатории им. Лоуренса с помощью каскадной системы трех усилителей яркости изображения были сфотографированы следы частиц в активированных йодисто-натриевых кристаллах. При одном эксперименте упругое рассеяние пи-мезонов на протонах изучалось с помощью двух блоков сцинтилляторов, каждый из которых имел длину 20 см, причем один использовался для наблюдения рассеянного пи-мезона, а другой — для наблюдения протона отдачи, полученного в результате бомбардирования мишени, покрытой жидким водородом. Сцинтилляционные счетчики отбирали для записи лишь почти копланарные явления, однако окончательными критериями упругого рассеяния были кинематические данные записываемых следов. В каждом из трех случайных пи-мезонных моментов мощностью до 2,5 мэв/с было сфотографировано до 1000 случаев упругого рассеяния. Во втором эксперименте для наблюдения остановки протонов отдачи, возникающих в результате неупругого рассеяния пи-мезона (получение одного пи-мезона) в трех случайных моментах движения пи-мезона, использовался один блок сцинтилляторов размером $10 \times 10 \times 20$ кубических сантиметров. И здесь было записано несколько тысяч явлений. Диапазон и угол рассеяния протона отдачи позволили определить момент передачи и центр массы энергии системы ди-пи-мезона, которые в данном случае представляли соответствующие кинематические параметры. При проведении этих экспериментов за счет пропуска сигнала через вторую трубку с переносом изображения сигнала, исходящего из электронного сцинтилляционного счетчика, были достигнуты пуск после явления и временная разрешающая способность в течении пяти микросекунд. В данном докладе обсуждаются идея и успешное выполнение этих экспериментов, причем особое внимание уделяется соответствующим деталям трубок с переносом изображения, сцинтилляционным счетчикам и электронным системам. Накоплен также опыт по анализу фотографий следов и, особенно, опыт в отношении возможной точности и надежности получаемых таким образом физических данных. В заключение рассматривается дальнейшее развитие люминесцентной камеры с учетом текущей работы, которая проводится с усилителями яркости изображения и сцинтилляторами. Анализируется роль люминесцентной камеры в будущих экспериментах с высокими энергиями по сравнению с искровой камерой и другими детекторами.

La cámara luminiscente y su empleo en experimentos de física de elevada energía. Por primera vez se ha empleado una cámara luminiscente en experimentos de física con partículas de elevada energía. En el Bevatron del Lawrence Radiation Laboratory se fotografiaron trazas de partículas en cristales de yoduro sódico activado por medio de un sistema en cascada de tres tubos intensificadores de imagen. En un experimento se estudió la dispersión elástica pión-protón utilizando dos conjuntos de centelleadores, cada uno de 20 cm de longitud. Uno para observar el pión dispersado y, el otro, el protón de retroceso procedente de un blanco de hidrógeno líquido. Los contadores de centelleo seleccionaban únicamente los sucesos casi coplanares que habían de ser registrados; no obstante, respecto de la dispersión inelástica, el criterio

definitivo era la cinemática de las trazas registradas. Se fotografiaron alrededor de 1000 sucesos elásticos correspondientes cada uno a tres cantidades de movimiento del pión incidente hasta 2,5 MeV/c. En un segundo experimento se utilizó únicamente un conjunto de centelleadores de $10 \times 10 \times 20 \text{ cm}^3$ para observar el frenado de los protones de retroceso procedentes de la dispersión inelástica de piones (producción de piones aislados) en tres cantidades de movimiento correspondientes a piones incidentes. En este caso se registraron también varios millares de sucesos. El alcance y el ángulo del protón de retroceso determinaron exclusivamente la transferencia de cantidad de movimiento y la energía del centro de masa del sistema di-piόν, que fueron los parámetros cinemáticos de interés en este problema. En estos experimentos se logró un disparo después de cada suceso y un tiempo de resolución de $5 \mu\text{s}$, desbloqueando el segundo tubo de imágenes al recibir una señal del circuito electrónico del contador de centelleo. Los autores estudian la preparación y la ejecución con éxito de estos experimentos, sobre todo las características más interesantes de los tubos de imágenes de los contadores de centelleo y de los sistemas electrónicos. Se ha adquirido también experiencia en el análisis de fotografías de trazas, en particular respecto de la precisión alcanzable y la exactitud de los datos físicos obtenidos. Por último examinan la evolución futura de las cámaras luminiscentes, en especial de los tubos intensificadores de imágenes y los centelleadores en desarrollo actualmente. También analizan el papel que la cámara luminiscente podrá desempeñar en los futuros experimentos con partículas de elevada energía, en comparación con las cámaras de chispa y otros detectores.

I. Introduction

The luminescent chamber and its newer companion, the spark chamber, permit experiments in high-energy physics employing a fast time-resolution of about $1 \mu\text{s}$, moderate space-resolution of about 1 mm and the ability to select the event to be recorded. Thus the one event of interest in 10^4 or 10^5 incident particles per pulse may be photographed with a time-resolution adequate to reject other events from the same picture.

The luminescent chamber has been discussed extensively in the literature. However only recently has a serious high-energy physics experiment been published [1] employing this technique. ZAVOISKII first published particle-tracks employing an alkali halide crystal viewed by a single-stage image-intensifier tube [2]; subsequently a multi-stage, magnetically-focused image-tube was employed by his group for recording single photo-electrons from particle tracks [3]. In 1958 the authors' group at the University of Michigan used a system of cascaded image-tubes to record cosmic-ray tracks in larger sodium-iodide crystals [4] and later other groups in the United States also successfully photographed tracks of cosmic rays using plastic scintillator filaments [5], and sodium iodide crystals [6]. More recently a group in the USSR has extended Zavoisii's earlier work [7]. The properties of image tubes and scintillators used in these various activities have been reviewed in numerous papers presented by the authors and others at various symposia and congresses [8]. During 1959 the authors operated a luminescent chamber in parasitic particle beams at the Bevatron of the Lawrence Radiation Laboratory and during 1960 major runs on experiments in high-energy pion physics were successfully carried out. Earlier Bevatron tests and some details of them are discussed in papers by the authors in 1960.

It is the purpose of this paper to report details of the execution of these experiments and comment on the luminescent-chamber technique in this context. No further details of the general technique will be reviewed. It is probably relevant to note that all the authors' work has involved large, solid crystals of thallium-activated sodium iodide rather than filaments of plastic scintillator. While the light-piping character of the

filaments relieves the depth-of-field problem inherent in the single-crystal technique, the sodium-iodide crystals, lens-coupled to the cathode of an image tube permits a large crystal area to be presented on the available image-tube cathodes. Thus the single crystals exchange field area for field depth. Perhaps more important, the coupling to the cathode with a lens from the scintillator is considerably simpler than the coupling required for high-quality filamentary scintillator images. While such coupling will surely be feasible this problem has retarded the filament technique in the past.

II. Luminescent chamber-system

In the two experiments described below, a system of three image-intensifier tubes was used viewing a configuration of thallium-activated sodium-iodide crystals. In each case the total crystal area was about 10×20 cm imaged on to the central 10 cm diam. portion of the WX4171 cathode, so that the crystal-viewing optics used demagnified the crystal image by about 2:1. The crystals were in the form of $5 \times 5 \times 10$ cm "bricks", each encased on all six sides by glass, so that they could be stacked together in configurations appropriate for particular experiments. Six such bricks were employed as described in the next section.

The configuration of image tubes is schematically illustrated in Fig. 1. The first tube, the WX4171, serves as an image-demagnifying stage and short-time image storage. The second tube, a three-stage image tube, type C73491, provides high gain with unity magnification. In addition, the 5- μ s gate on the first stage of this tube provides the essential fast time resolution of the system. The third image tube, also a C73491, further intensifies the light image and is gated by a slow pulse of about 10 ms to reduce the background light on the film. The image tubes are coupled together by lenses as indicated in Fig. 1. The coupling between the first two tubes employs the fastest lenses readily available, a pair of Farrand $f/0.87$, 76-mm "Super-Farrons". Since the efficiency of the P15 phosphor of the first image tube is rather low, it is important to have a highly efficient coupling such that a single photoelectron in the WX4171 will produce at least one photoelectron in the second tube. The multi-alkali cathode of the WX4171 is about 15% efficient in converting blue light quanta (near the peak of the NaI emission) to photoelectrons; and, as the tube has a gain of about 30, each photoelectron gives rise to about 200 quanta from the P15 phosphor. The "Super-Farron" lens pair transmits about 15% of this light to the C73491 cathode where again about 15% of the quanta convert to photoelectrons. As a result these 200 quanta should produce on the average 4.5 photoelectrons in this tube. However, the 5- μ s gate turned on 0.3 to 0.4 μ s after the beginning of the P15 decay passes only about 40% of the light from the P15 phosphor, due to the "hyperbolic" decay characteristics of this phosphor. As a result barely 2 photoelectrons are expected in the second-image tube for each one in the first, as far as subsequent image-amplification requirements are concerned.

In order to produce a detectable image on the fastest film, about 2×10^8 quanta/cm² are required and the final image size of a single photoelectron is about 0.1 mm diam. However, the film is developed automatically under conditions not optimized for the greatest sensitivity and the developed film must be scanned efficiently by non-technical workers, so that much more than this minimal exposure is actually desirable. While accurate numbers are not available on the gains of the C73491 tubes as operated, the total system gain from the first C73491 cathode to the film is approximately 10^6 (10^4 for each image tube and 10^{-2} for the two lens pairs). The relevant fact is that single photoelectrons from the first cathode of the system do show up readily on the film.

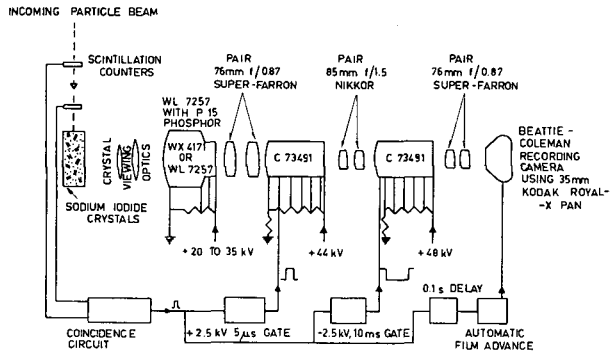


Fig. 1

Schematic diagram of luminescent chamber system

A block diagram of the triggering electronics system is given in Fig. 2. The first C73491 was triggered by applying a + 2500-V pulse to the focusing electrode of the

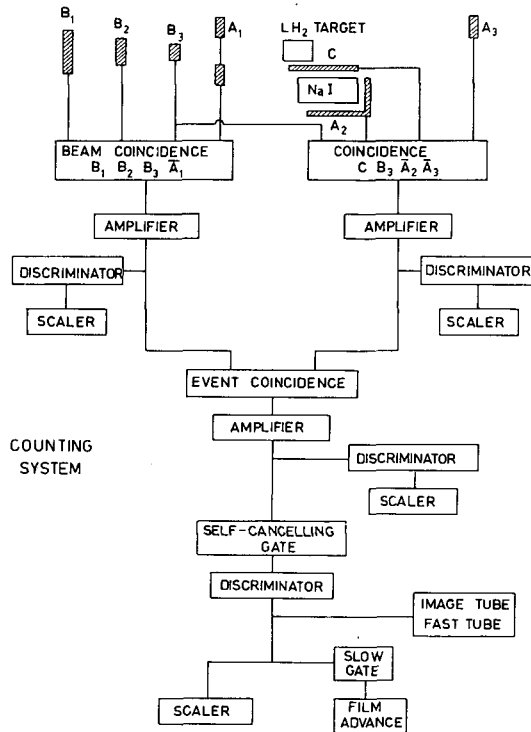


Fig. 2

Block diagram of electronics system used in luminescent chamber experiments. It is necessary to provide a self-cancelling gate circuit to prevent the system from recording more than one event per beam pulse

first stage. The total time-delay between the passage of the particle and the opening of this gate determines the fraction of the light from the P15 first phosphor collected. As the initial decay of the P15 phosphor corresponds to a decay constant much less than a microsecond it is important to make this gate-firing delay as short as possible. In addition the gate pulse must be flat to 2% and have a sharp rise and fall for best focus. The circuit used is given in Fig. 3. The total delay between the passage of the particle through the scintillator and the voltage pulse on this gate is about $350 \text{ m}\mu\text{s}$. Of this, about $100 \text{ m}\mu\text{s}$ is in cable length and photomultiplier delay, $100 \text{ m}\mu\text{s}$ in the thyatron firing delay and the remainder in the various other circuits.

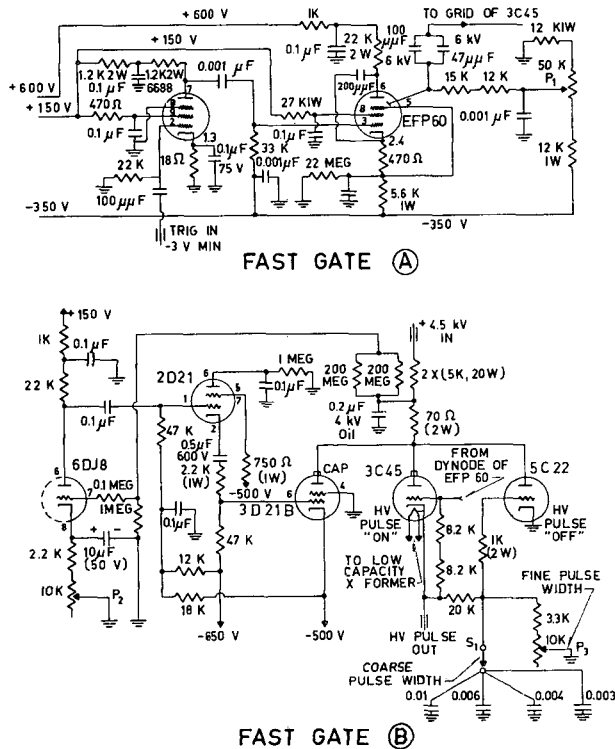


Fig. 3

Circuit diagram of fast positive gate used on the first focusing electrode of the second image tube. The output pulse is fed by $125\text{-}\Omega$ cable to the image tube and terminated at the image tube with a 125 resistor

The gate circuit for the slow gate used on the second three-stage tube is reproduced in Fig. 4. The pulse from this circuit is applied to the image tube cathode. With the cathode at $+2000$ to $+2500$ volts the tube is cut off by the lower voltage on the grid. The pulse grounds the cathode so that the tube passes images for the duration of the pulse. Modifications of this circuit can be used for gating times as short as a microsecond,

however on some tubes the resistivity of the cathode reduced the effectiveness of this technique for fast pulses.

The camera used is a commercial unit for 100-ft rolls of 35-mm film.

SLOW GATE

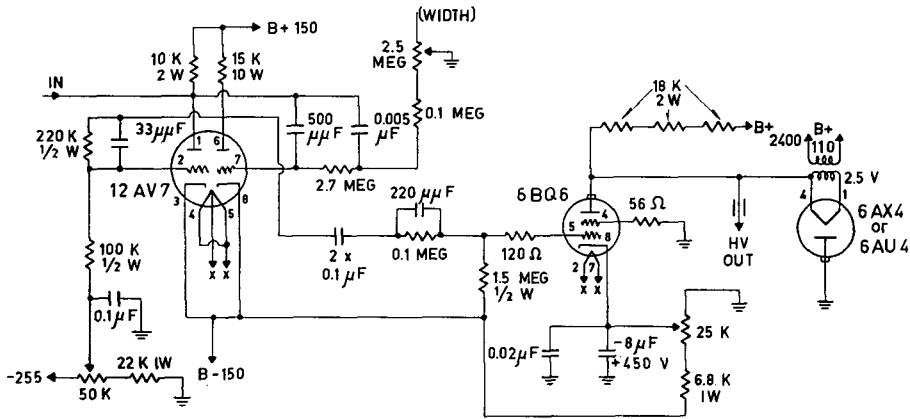


Fig. 4

Circuit diagram of negative gate circuit used on cathode of the third image tube

III. Experiments

A. π^- -p ELASTIC SCATTERING

Details of this and the following experiment are given as illustrations of the technique, not for the experimental results in themselves. To study π^- -p elastic scattering at 1.5, 2.0, and 2.5 GeV/c incident pion momentum at angles behind the diffraction peak, a three-inch long liquid hydrogen target flanked vertically by two sets of scintillators, $5 \times 5 \times 20$ cm each, was employed as shown in Fig. 5. Outside the sodium-iodide luminescent chamber scintillators, two scintillation counters subtending $\pm 7^\circ$ from the vertical plane defined probable scattering events. When three beam-defining scintillation counters and these coplanarity counters indicated an elastic-scattering event and the various anti-coincidence counters did not fire, the image tubes were pulsed on as described above. Examination of the film confirms that only one in every six or seven such photographs actually shows an elastic scattering. A large number of extraneous processes can trigger the counters and resemble an elastic scattering. However, the track photographs clearly discriminate between these other processes and true elastic scatterings. Fig. 6 is a correlation graph giving the deviation from the kinematically-predicted elastic-scattering angles and the angles actually observed. This indicates the low contamination of the data by inelastic events as well as giving a measure of the track-angle accuracy.

The crystal viewing optics in this experiment consisted of two sets of lenses, each an f/5, 15-in f. l. achromat together with an f/1.9, 5-in f. l. lens as a 2.5:1 demagnifying combination. Each lens-set images one $5 \times 5 \times 20$ cm crystal array on to a part of the

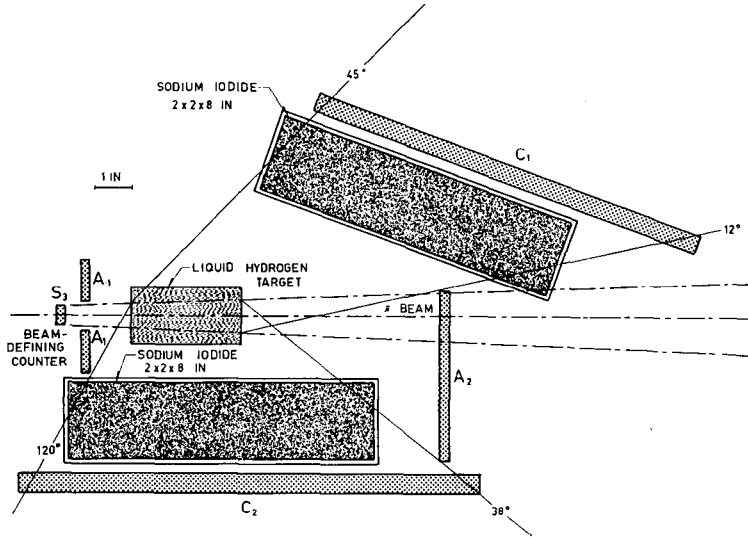
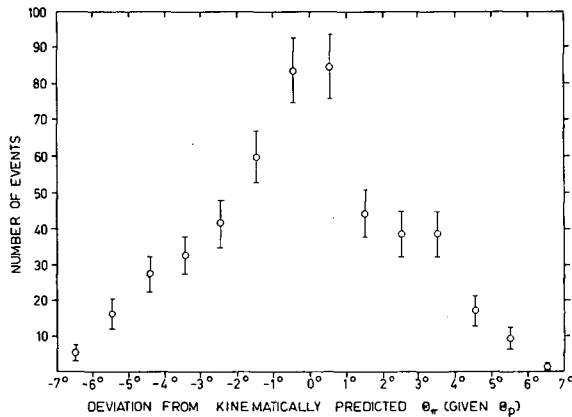
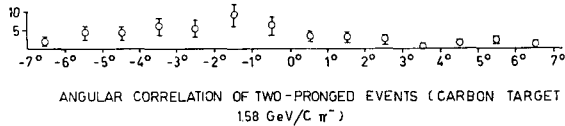


Fig. 5

Experimental set-up for π^- -p elastic scattering experiments—1.5—2.5 GeV/c



ANGULAR CORRELATION FOR π^- -P ELASTIC SCATTERING (1.5 GeV/c)



ANGULAR CORRELATION OF TWO-PRONGED EVENTS (CARBON TARGET
1.50 GeV/c π^-)

Fig. 6

Deviation of π^- -p elastic scattering data points from the kinematically predicted correlation angle. The deviations recorded are measured perpendicular to the graph of θ_π (lab) versus θ_p (lab) calculated for pions incident at 1.50 GeV/c. For comparison, a small sample of data from a graphite target is included

WX4171 cathode so that the two images are closely adjacent on the image tube. The aperture used was large, so that minimum-ionizing tracks appeared as a row of scattered dots, each an image of a single photoelectron. The large lens-aperture gave broad track images as a result of the finite depth of field and off-axis aberrations, as noted in the Figure. However it was felt that the angle of such tracks could be ascertained as accurately as better-resolved tracks containing a smaller number of photon images, and that the dense tracks would make the film scanning simpler and more reliable.

A sample angular-distribution of π^- -p elastic scattering is included in Fig. 7. These data are illustrative only; certain systematic corrections have not been included. For example, the nuclear mean free path in sodium iodide is about 40 cm, so that there is a 10% to 15% probability of an interaction of the scattered pion or proton interacting in the detecting crystal.

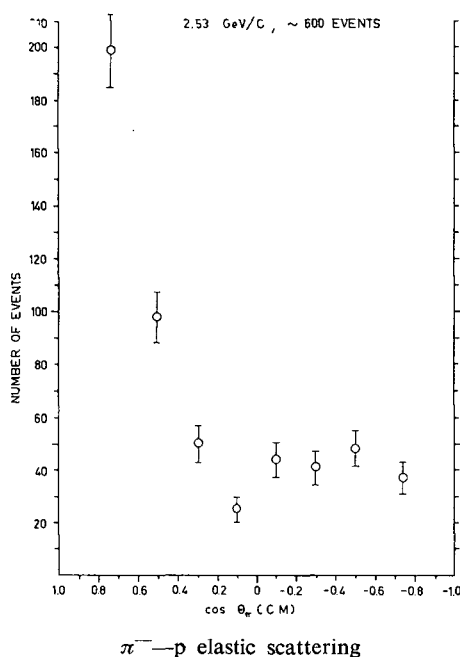


Fig. 7

Angular distribution of π^- -p elastic scattering at 2.53 GeV/c incident pion momentum as determined from a part of the data taken in the experiment described in the text. This data is preliminary, as certain systematic corrections have not yet been included

B. INELASTIC PION SCATTERING

As one of many experiments designed to study the pion-pion interaction, the same incident pion beam geometry and hydrogen target were used to study the reaction $\pi^- + P \rightarrow \pi^- + \pi^0 + P$. As shown in Fig. 8, the luminescent chamber, in the form of six $5 \times 5 \times 10$ -cm bricks of sodium iodide, was placed below and ahead of the hydrogen target, with a small coincidence counter over it and a large anti-coincidence

counter below. With pions of 800, 900, and 1000 MeV/c incident on the target, events were sought where a proton recoiled from the target into the sodium iodide and came to rest in the visible volume. The range of protons thus detected corresponded to momenta of from 450 MeV/c to 700 MeV/c. The range and angle of the recoiling proton, together with the incident pion energy, uniquely determine the proton momentum transfer and the centre-of-mass energy of the pion-pion system which are the relevant kinematical parameters in this problem.

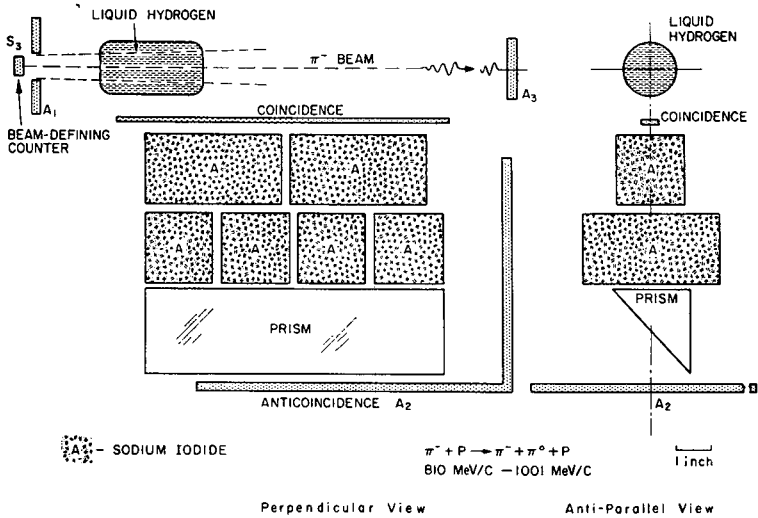


Fig. 8

Experimental set-up for inelastic $\pi^- \rightarrow p$ scattering experiment. Stopping protons are photographed in the scintillator volume

A major requirement of the luminescent chamber in this experiment is the problem of distinguishing between stopping protons and other stopping tracks. In Fig. 9, chamber photographs of different stopping particles are shown, in which the qualitative difference between pions and protons from ionization and scattering is apparent. From the dynamics of the interaction, it is probable that most of the stopping particles in the crystal are protons and the film scanning bears this out. However, only one scintillation counter out of the pion beam was required to fire for a picture to be recorded and most of the photographs show no tracks at all. Scanning of these empty frames of course is not time consuming; more serious is the identification of stopping-tracks as protons in instances where the ionization criterion is less clear. Two criteria are employed here: the reaction kinematics define an area of the range-angle space where no protons may lie and the distributions of the questionable protons should resemble (statistically) those of the more certain protons. Both criteria were applied and give confidence in the interpretation of the observed tracks.

As stopping tracks were viewed in this experiment, the crystal-viewing lens was less critical than before (the ionization of a proton near the end of its range makes it readily visible). An $f/2.5$, 12-in $f.1.$ lens together with an $f/5$, 24-in $f.1.$ achromat were used to image the crystal area onto the WX4171 cathode with an appropriate demagnification.

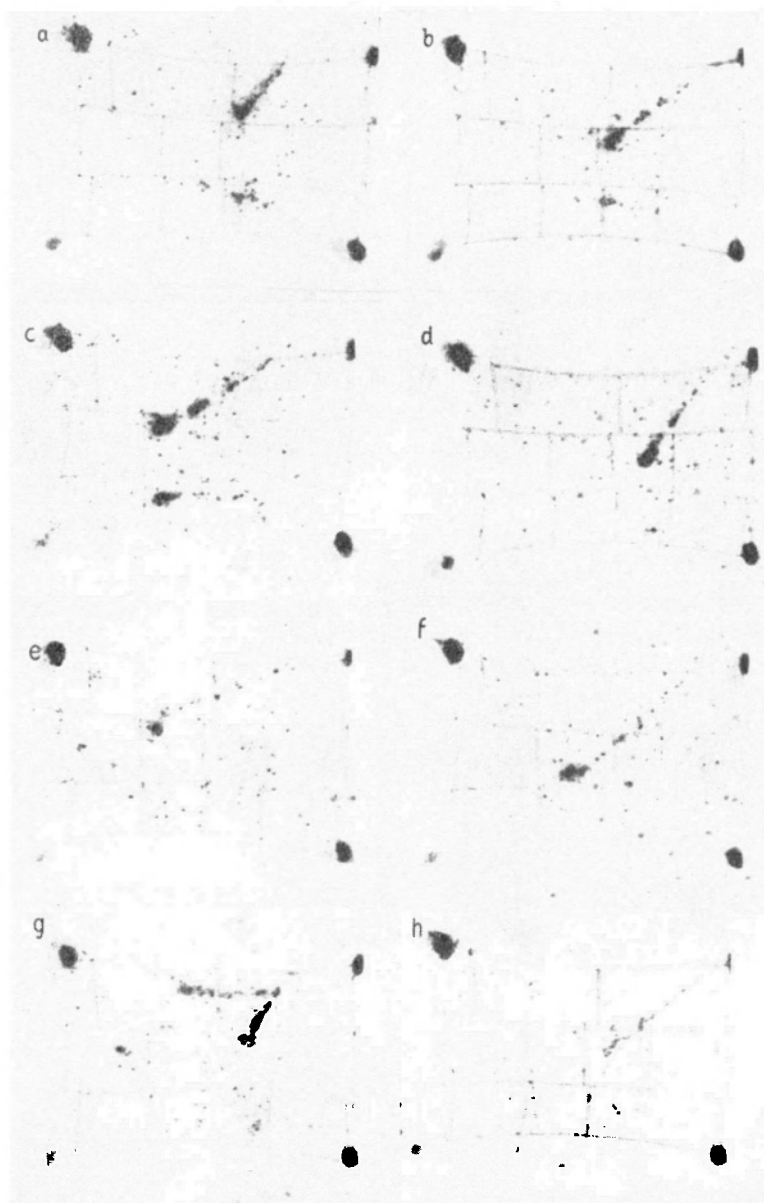


Fig. 9

Stopping protons photographed in the configuration of Fig. 8. Beam direction is from the right

In both experiments a set of fiducial lights by the crystal was pulsed every time a picture was taken to assist in orienting the crystal image on the film, as the image-tube

field was slightly displaced and rotated during the beam pulse by the Bevatron stray magnetic field. From the track photographs it is also apparent that the image tubes contain considerable distortion, so that it was necessary to correct angles and lengths taken off the film for this distortion. To aid this, grids and angle patterns were photographed through the image tubes so that exact corrections could be made.

IV. Commentary on the method

The usefulness and practicality of the luminescent chamber in experiments in high-energy physics where fast time-resolution and post-event selection are desired has been proven by these experiments. While experiments on elastic and inelastic pion-nucleon scattering are also being done with bubble chambers and conventional scintillation counters, in these experiments the particular data can be more rapidly collected by fast chambers such as the luminescent chamber. The track quality in these experiments, while adequate, shows room for considerable improvement. In this experiment about 150 image elements are resolved across the useful field and the depth of field used gives tracks somewhat broader than the images of single photoelectrons. Better image tubes will reduce the image size of single photoelectrons, and more efficient cathodes, lenses of higher transmission and better scintillators will improve the track resolution. Tubes are now commercially available which can amplify single photoelectrons to a brightness sufficient for photography and incorporation of such tubes permits luminescent chamber systems of one or two tubes with all the flexibility of the system described above. Characteristics of some image tubes and coupling lenses are shown in Tables I and II.

TABLE I

TYPICAL PROPERTIES OF LENS SYSTEMS; EACH SYSTEM CONSISTS OF A PAIR OF IDENTICAL UNITS COMBINED FOR UNITY MAGNIFICATION

Manufacturer	Focal (a) length (mm)	Rated (a) Aperture	Theoretical (b) Collection Efficiency	Transmission (c)		60% Vignetting Radius (mm) (d)
				P 11	P 20	
Farrand	76	f/0.85	0.26	0.50		10
Taylor-Taylor-Hobson	50	f/0.80	0.28			5.5
Canon	50	f/1.2	0.16	0.61	0.73	8
Zeiss	75	f/1.5	0.10			8.5
Nikkor	85	f/1.5	0.10			10
Carl Meyer	60	f/1.6	0.09	0.47	0.72	7.2
Bausch and Lomb	127	f/1.9	0.07	0.45	0.67	25
Kodak (Aeroektar)	178	f/2.5	0.04	0.28	0.38	25

(a) focal length and aperture for each element of the pair.

(b) theoretical collection efficiency from a Lambertian surface given by $\sin^2\theta$ where θ is the half-angle subtended by the lens: $\tan \theta = 1/2f$.

(c) transmission is ratio of actual transmission of the lens to the theoretical transmission, recorded for light from P 11 and P 20 phosphors.

(d) the recorded values are the radii in millimeters at which the transmission falls to 60% of its value on axis.

TABLE II
IMAGE TUBE PARAMETERS

Tube Mfr.	Tube Type	Focus	Cath. Diam. (in)	Anode Diam. (in)	Axial (a) Anode Resol.	No. of Stages	Total Volt. (kV)	Quantum Gain (b)	Phos. Type	Noise (c)	Cathode Efficiency at 4400 Å	Cath. Type	Approx. Price \$
West.	WL7257	ES	5	1	15	1	25—35	10—20 80—120	P15 P11	10 ⁷ —10 ⁸ 10 ⁸ —10 ⁹	8%	S11	3000
	WX4171	ES	5	1	15	1	25—35	20—40	P15	—	15%	S20	5000
	C73458	ES	1	1	18(d)	2	20—25	300— 2000	P11 P20	10 ⁷ —10 ⁹	15%— 20%	S20	3000— 5000
RCA	C73459	ES	1 or 2 (e)	1	—	2	20—30	~ 1000	P11 P20	—	—	S20	6000
	C73491	ES	1	1	12	3	30—45	5000 (h) 20000	P11 P20	10 ⁸ —10 ⁹	15%— 20%	S20	10 000
RCA	— (g) C70012	EM	1.5 3	1.5 3	15	2	20—30	1000	P11 P20	—	—	S20	—
IT-T	FW113 (f)	EM	1.5	1.5	15	2	—	—	P11 P20	—	—	S11	—
West.	WX4342	EM	1	1	10—12	4 (g)	25—36	> 5000	P11	—	5%— 7%	S11	—
20th Century England	Wilcock- Emberson- Intensifier	EM	0.8	0.8	15	5 (g)	35	20000— 30000 (h)	P11	—	—	S11	—

(a) Resolution in line pairs per millimeter.

(b) Quantum gain defined as light power out divided by light power in.

(c) Noise in units of quanta per second from anode with no cathode illumination.

(d) Resolution and distortion very poor at edge of field.

(e) Available with 1 or 2-in first cathode, P11 or P15 first phosphor.

(f) Developmental types. No working tubes yet available.

(g) Transmission secondary electron emission dynodes.

(h) With the best tubes of these types, single photo-electrons from the first cathode may be visually observed using a 10X eye-piece.

The recent advent of the spark chamber has given high-energy physicists a second technique with many features in common with the luminescent chamber. The spark chamber can record tracks of particles with resolution in two dimensions of a millimeter and time-resolution of less than a microsecond. Spark chambers may be made with plates of thick lead or iron or of 0.025 mm aluminium. They may be made quite large, or smaller chambers may be combined into a variety of configurations.

The luminescent chamber has the advantage of homogeneity; a track in any direction may be detected with equal certainty and resolution and measurements of range, multiple scattering and ionization may be made (as in experiment B above). On the other hand, the spark chamber can be made with so little material in it that there is only a very small probability for nuclear interaction within its volume, making it ideal for studies of decay in flight of neutral particles. In experiments such as that of the elastic scattering described above no correction for chamber interactions would be necessary. Also larger hydrogen targets are practical to use with large spark chambers.

The authors recently extended the elastic pion-proton scattering experiments to $\pi^+ + \text{P}$ using a spark chamber system built by MURPHY *et al.*, for another experiment at the Bevatron. Operation and picture analysis of data with both techniques emphasizes the close practical similarity of the two.

In closing, it may be of interest to note a possible area of overlap between the two fast-chamber techniques. In a spark chamber each ion pair is "amplified" (by the discharge) to give off more than 10^{10} quanta, while in the scintillation chamber all amplification occurs in the image tubes. It may be possible to pulse a noble gas volume in such a way that an avalanche only begins, e.g., progressing only a millimeter, before the voltage falls. If, say, 10^5 quanta result from this proto-discharge, the event could be recorded using image tubes with small-aperture optics. This would permit an isotropic gas-volume detector with many of the desirable properties of both techniques.

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DISCUSSION

H. L. Anderson (United States of America): I should like to ask Dr. Lande a question about his paper. In his experiment on the decay of the π -mesons into electrons what did he measure besides the branching ratio? He made some mention about lifetime.

K. Lande (United States of America): We measured the π -meson lifetime. There were some 1500 events. We measured branching ratios into the two modes I indicated and we are now measuring the lifetime of the events which were associated with π going to electron plus neutrino.

H. L. Anderson: But that lifetime cannot differ from the lifetime of the π decay.

K. Lande: I agree. This is one way of making sure that these are actually π -mesons.

H. E. Wegner (United States of America): It appears that one would like to use the luminescent chamber, in the same way that a hydrogen bubble chamber is employed, to study detailed track dimensions and trajectories. It also appears from the paper of Professor Jones that there are severe distortion problems in the image intensifier system. Would Professor Caldwell or Professor Jones care to comment on the control of distortion and the long-term stability in a two-dimensional photographic array, and how good are these systems for quantitative evaluation of track trajectories in the study of high-energy events?

D. O. Caldwell (United States of America): The distortion apparent in the scintillation chamber pictures is caused by the characteristics of the electrostatic imaging in the light amplifiers. Recent tubes have about 5% pincushion distortion, but this is constant in time and correction can be made for it. Magnetic image tubes which are just coming into use, have essentially no pincushion distortion and have perhaps 0.5% S-type distortion, also constant in time.

R. J. Griffiths (United Kingdom): Professor Jones has stated that his electronics limited the recording of events to one per bevatron beam-burst. I would like to ask him what was the actual dead-time of the system, and what was the limiting factor.

L. W. Jones (United States of America): The limiting factor in our experiment was the camera film advance time, which was about one second. Professor Caldwell, I think, states in his paper that he used a camera with 30-ms film advance time. This factor need not be a limitation: one can evolve sweeping techniques, and image tubes are available which will displace an image by one frame diameter in one micro-second. However, for the experiments that we did—the π -scattering experiments—the repetition rate of events was about one every two pulses so that little data was lost by recording only once per pulse. If we had had no dead-time limitation, we would have recorded the same data in only 20 or 30% less time. It was not a serious limitation.

I should like to comment on Mr. Wegner's question. We corrected for distortion by photographing accurately drawn grids in the course of our experiment and we were then able—using the fiducial lights—to orient our tracks in real space to $\pm 1^\circ$ of angle, regardless of where the track occurred on the picture. We had other uncertainties: the beam divergence within the target was also about 1° , so that the total uncertainty in pion scattering in the elastic scattering experiment was about $\pm 2^\circ$. This, however, was more than sufficient for accurately identifying an event as elastic rather than inelastic and in fact we could even determine approximately the momentum of the incoming pion beam from the kinematics of the recorded tracks.

A. Roberts (United States of America): Professor Jones has brought up the comparison between luminescent chambers, or scintillation chambers, and spark chambers; he made a number of statements that I should like to comment on, and my meaning may become clearer after the papers on spark chambers have been given later. He mentioned, for example, that a disadvantage of the spark chamber is that it is not isotropic. I should like to make the following five points in comparing the two chambers:

1. It is possible in spark chambers to record the tracks of particles going in all directions, although perhaps not with the same accuracy.

2. Notwithstanding the inhomogeneity of the spark chamber, it can be made so thin that the amount of material is not a serious matter even for the scattering of low-energy protons.

3. It is considerably easier to make spark chambers work in a magnetic field than luminescent chambers. The spark chamber is not very sensitive to magnetic fields and any system of image intensifiers must be very carefully used, either in a zero field, for electrostatic intensifiers, or in a carefully controlled field in the case of the magnetic intensifiers. Further, with the relatively small volume associated with the luminescent chamber, events in which particles go some distance before decaying may be harder to handle.

4. The resolution is of course still considerably better in the luminescent chamber than it is in the spark chamber.

5. Finally, there is the problem of data handling. Mr. Jones remarked that in analysing pictures manually, by scanners, it is approximately just as hard to do one type of picture as the other. I do not think, however, that automatic methods of data handling could be as readily applied to the luminescent chamber as to the spark chamber.

L. W. Jones: Professor Roberts has amplified my very brief comparisons in a way which is certainly most appropriate. I could add still further to what he has said but perhaps it would be as well to leave most of the discussion until later. I think the ease of analysing spark-chamber photographs is in fact just a function of their smaller image content, namely the fact that the image really only has a number of information channels equal to the number of gaps in the spark chamber. Regarding the size of the devices, it is true that the spark chambers can be made larger than scintillation chambers, but some idea of the possible size of luminescent chambers is given by Dr. Reines' reference to the 17 or 21-in diameter phototubes which he hopes to use in his experiment. The resolution of the scintillation chamber is perhaps ultimately limited only by the wave-guide light cut-off effects in filaments of scintillator. This stage is a long way off, but it is certainly feasible to consider hyper-fragment physics with a glass filament scintillation chamber. Regarding isotopic properties, as Professor Roberts says, thin-foil spark chambers may be nearly homogeneous, but for chambers of large stopping power the spark chamber has problems comparable to those of a multiplate cloud chamber, whereas the homogeneous luminescent chamber has not. Perhaps we could continue this comparison after further discussion of spark chambers.

H. L. Anderson: I wish to put another question to Dr. Lande, namely to ask him how well he was able to measure the energy of the electrons which he sees in his decay processes.

K. Lande: Very poorly. I do not think one can really measure electron energies in this fashion and I did not mean, in any way, that we were measuring electron energies. The plates I indicated were there mainly to convert gamma rays originating from the various bremsstrahlung processes that I referred to. On the other hand, I think the

plates are very good energy-measuring devices for heavier particles, namely for π - and μ -mesons, and in that case I think the resolution will be comparable to the measuring accuracy of the device, which will probably be in the vicinity of several per cent. I think, therefore, that this will be a very good way of measuring particle ranges and hence particle energies.

I hope we may get some electron energy information, not simply from their range, but from the shower phenomena: for example with high-energy electrons at several hundred mego-electron volts originating from, say, K-mesons ($K \rightarrow e + \pi^0 + \mu$), one can take advantage of the showering of electrons in order to tell something about their energy.

H. L. Anderson: It was not clear to me how you could distinguish in your experiment between the proper decay, $\pi \rightarrow e$, as compared with π rapidly going to μ and then rapidly going to e , of which a sizeable fraction is always present.

K. Lande: There is a special process by which we did this. It is a little too complicated to go into now, but I could describe it to you later.

M. Parlier (France): I would like to know whether Dr. Lande or Professor Caldwell could tell us something about the present stage of development of glass-fibre optics in the United States, and whether they have been able to deposit photocathodes on these optics.

D. O. Caldwell: As far as getting reasonable photocathodes on the glass-fibre optics is concerned the present position is that S-11 (Cs-Sb) photocathodes can apparently be more easily made than S-20 (tri-alkali) cathodes, although the latter have even been made up to 5 in in diam. One problem is that the heavy metal in the core glass is attacked by the alkalis and hence a protective barrier must be used over the fibre optics before depositing the cathode. The most successful protective barrier so far, on glass-fibre optics up to 5 in in diam., is a thin layer of lime glass, a few thousandths of an inch thick, which does not spoil the image qualities. There have also been problems of sealing the faceplates into tubes, especially that of keeping the faceplates vacuum-tight, but successful tubes have been provided, even with 5-in diam. faceplates.

RECENT WORK ON CERENKOV IMAGE DETECTORS

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Abstract — Résumé — Аннотация — Resumen

Recent work on Cerenkov image detectors. The Cerenkov image-detector (CID) consists of a Cerenkov radiator, an optical objective that gives a ring-image of the Cerenkov light cone and a system of cascaded image-intensifiers that provide an electronically amplified ring image at the output phosphor, bright enough to photograph. The detector has the advantages of not requiring a highly collimated beam, of allowing the simultaneous observation of several particles and of providing highly accurate data on the direction and velocity of these particles. The theoretical performance of the device has been previously described.

Some preliminary observations on the performance of the CID were made with an external pion beam from the Brookhaven cosmotron, using an intensifying system consisting of one WX-4047 (a single-stage intensifier with a 5-in diam. cathode), a 3-stage RCA C-73491 and an RCA C-73477 image-intensifier orthicon, with a television output that was amplified and photographed from the kinescope. In the brief time available it was shown that the system performance was of the order expected with regard to intensity; we photographed satisfactory images of single photo-electrons. However, the resolution was considerably poorer than that anticipated from known properties of system components. The tests had to be discontinued because the intensifier system was needed for another experiment. A completely re-engineered and re-designed system is now in construction and it is expected that photographs of images from this system will be presented and an analysis of the performance obtained will be given.

Additional optical design work on objectives for CID systems now indicates that it should be possible to design radiator-objective mirror combinations covering different velocity ranges, and adapted to different purposes, including both survey work and precision measurements.

Travaux récents sur les détecteurs d'images de Cerenkov. Le détecteur de Cerenkov d'images se compose d'un milieu radiatif de Cerenkov, d'un objectif optique donnant une image annulaire du cône lumineux de Cerenkov et d'une série de renforceurs d'images en cascade qui produisent, sur le phosphore de sortie, une image annulaire amplifiée électroniquement, assez lumineuse pour être photographiée. Ce détecteur présente l'avantage de ne pas exiger une collimation trop élevée du faisceau, de permettre l'observation simultanée de plusieurs particules et de fournir des renseignements extrêmement précis sur la direction et la vitesse des particules. Le comportement théorique de ce dispositif a déjà été décrit.

On a fait certaines observations préliminaires sur le comportement du détecteur, à l'aide d'un faisceau extérieur de mésons émis par le cosmotron de Brookhaven; on a utilisé un dispositif intensificateur composé d'un WX-4047 (renforceur à un étage muni d'une cathode de cinq pouces de diamètre), d'un RCA C-73491 à trois étages et d'un tube orthicon renforceur d'image RCA C-73477 dont le signal de sortie a été amplifié et photographié au cinéscope. Pendant le court laps de temps dont on disposait on a constaté que, du point de vue de l'intensité, le comportement du dispositif était, dans une large mesure, conforme à ce qu'on en attendait; on a pris des photographies satisfaisantes de photoélectrons uniques. Cependant, la résolution obtenue a été de loin inférieure à celle que l'on avait escomptée d'après les propriétés connues des éléments du dispositif. Les essais ont dû être interrompus, le dispositif intensificateur ayant dû être affecté à d'autres expériences.

Un autre dispositif entièrement nouveau est actuellement en construction. Les auteurs espèrent être en mesure de présenter des photographies d'images prises avec ce dispositif ainsi qu'une analyse des performances obtenues.

Les travaux de perfectionnement optique des objectifs destinés au détecteur révèlent la possibilité de mettre au point des combinaisons milieu radiatif-miroir satisfaisant aux exigences des différentes gammes de vitesse et répondant à diverses fins: recherche générale et mesures de précision.

Новейшие работы с детекторами изображений Черенкова. Детектор изображений Черенкова (CID) состоит из излучателя Черенкова, оптического объектива, дающего кольцевое изображение черенковского светового конуса, и системы каскадных усилителей контрастности изображения, дающей электронно-усиленное кольцевое изображение на выходном люминофоре достаточно яркое, чтобы его можно было сфотографировать. Преимуществом детектора является то, что он не требует слишком сильной коллимации пучка, делает возможным одновременное наблюдение за несколькими частицами и дает чрезвычайно точные данные относительно направления и скорости этих частиц. Ранее была описана теоретическая характеристика работы этого устройства.

Некоторые предварительные наблюдения над результатами работы детектора изображений Черенкова (CID) были проделаны при помощи вырабатываемых брукхейвенским космотроном внешнего пучка пи-мезонов с использованием усилительной системы, состоящей из одного усилителя WX-4047 (однокаскадный усилитель с катодом диаметром 5 дм), трехкаскадного RCA C-73491 и одного RCA C-73477 усиливающего контрастность изображения ортикаона с телевизионным выходом, который был усилен и сфотографирован с кинескопа. За короткое время было установлено, что в отношении интенсивности работа системы соответствовала тому порядку величины, который от нее ожидался; удалось удовлетворительным образом сфотографировать изображения отдельных фотоэлектронов. Однако разрешающая способность оказалась значительно меньшей, чем этого можно было ожидать на основании известных свойств составных частей системы. Испытания должны были быть приостановлены, так как усилительная система понадобилась для другого эксперимента. В настоящее время создается совершенно заново переделанная и сконструированная система, а поэтому считают возможным представить изображения, полученные при помощи этой системы, а также анализ достигнутых результатов.

Проводимая в настоящее время дополнительная работа по конструкции оптических объективов для системы детекторов изображений Черенкова показывает, что можно будет сконструировать зеркальные комбинации излучателя и объектива для различных интервалов скоростей и для различных целей, включая как исследовательскую работу, так и точные измерения.

Nuevos estudios de los detectores de imagen de Cerenkov. El detector de imagen de Cerenkov (DIC) consiste en un radiador de Cerenkov, un objetivo óptico que da una imagen anular del cono de luz de Cerenkov, y un sistema de intensificadores de imagen en cascada que producen en la pantalla de salida una imagen anular amplificada electrónicamente, tan luminosa que puede ser fotografiada. Las ventajas del detector son que no requiere un haz altamente colimado, que permite observar varias partículas simultáneamente, y que con él se obtienen datos muy exactos sobre la dirección y la velocidad de las partículas. Previamente fue ya descrito el comportamiento teórico del dispositivo.

Los ensayos preliminares del DIC se realizaron con un haz externo de piones del cosmotrón de Brookhaven empleando un sistema intensificador que consiste en un WX-4047, un intensificador de una sola etapa con cátodo de 5 pulgadas (12,7 cm) de diámetro, un RCA C-73491 de tres etapas y un orticonoscopio RCA C-73477 intensificador de imagen con una salida de televisión que fue amplificada y fotografiada en el kinescopio. A pesar del poco tiempo disponible, los autores comprobaron que el rendimiento del sistema en cuanto a intensidad era del orden de magnitud esperado, habiendo fotografiado satisfactoriamente imágenes de fotoelectrones aislados. En cambio, el poder de resolución resultó ser muy inferior al que permitían prever las propiedades conocidas de las partes componentes del sistema. Los autores tuvieron que interrumpir los ensayos porque el sistema intensificador se necesitó para otro experimento. Actualmente se está construyendo otro sistema según diseños y técnicas nuevas, y los autores

esperan poder presentar fotografías de imágenes obtenidas con él y dar un análisis de su rendimiento.

Las últimas investigaciones ópticas de los objetivos para sistemas DIC indican la posibilidad de diseñar combinaciones de reflectores radiador-objetivo que cubran diversos intervalos de velocidad y se adapten a diversos fines, incluyendo el uso como monitores y la realización de medidas de precisión.

I. Introduction

The Cerenkov image-detector (CID) consists of a Cerenkov radiator, an optical objective that gives a ring image of the Cerenkov light cone and a system of cascaded image-intensifiers that provide an electronically amplified ring image at the output phosphor, bright enough to photograph [1]. The detector has the advantages that it does not require a highly collimated beam, allows the simultaneous observation of several particles and provides highly accurate data on the direction and velocity of these particles. The theoretical performance of the device has been previously described [2].

Some preliminary observations on the performance of the CID were made with an external pion beam from the Brookhaven cosmotron, using an intensifying system consisting of one WX-4047 (a single-stage intensifier with a 5-in diam. cathode made by Westinghouse Co.), a 3-stage RCA C-73491 and an RCA C-73477 image-intensifier orthicon, with a television output that was amplified and photographed from the kinescope [3]. In the brief time available it was shown that the system performance was of the order expected with regard to intensity; we photographed satisfactory images of single photoelectrons. However, the resolution was considerably poorer than that anticipated from known properties of system components.

II. Construction and performance

Fig. 1 shows the mechanical design of the image intensifier system. It consists of a camera D and three independent units A, B, C. Each contains two lenses with an image-

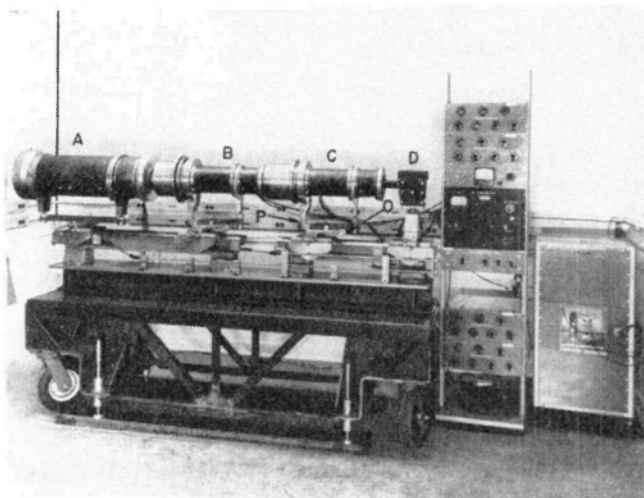


Fig. 1
The image-intensifier system

intensifier tube between them. The units are individually focused using a resolution pattern and a parallel light source. Then they are mounted in line on compounds of two lathes. The units can be moved along the lathe beds by means of controls located near the camera mount D.

The details of unit A are shown in Fig. 2. The $f/1.5$ lens (1), which has a 5-in field, focuses the ring-image of the Cerenkov radiation on the photocathode of the WX-4047 image-intensifier tube (3). Rings (2) are used to support the lens and the tube in the steel housing A, and are positioned by means of nylon screws. To provide magnetic shielding, a cylinder of conetic material is inserted in the housing.

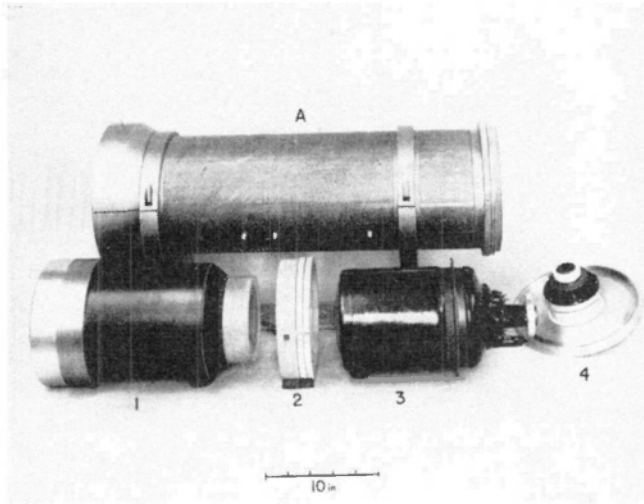


Fig. 2
Unit A containing the WX-4047 tube

The optical coupling between the units is obtained by means of two $f/0.87$ lenses. One lens (4) of Fig. 2 has a flat field and is focused on the phosphor of the WX-4047 image-intensifier tube. The other lens (1) has a backward curving field and focuses light on the photocathode of the RCA-73491 tube. It is a part of unit B. Fig. 3 shows details of that unit. The lens (1) and the housing (2) form an assembly which is screwed on to the threads (T). The steel housing B accommodates the RCA-73491 tube (3) and the magnetic shield [4]. The conetic shield is lined with $\frac{1}{4}$ -in thick teflon to provide electrostatic insulation. The image-intensifier tube is held inside the housing by a set of rings which are positioned by nylon screws visible in the picture. The lens [5] couples the image to the next unit C.

A ball joint between the housing B and the lens assembly (2), as shown in Fig. 3, allows the housing to be pivoted about the point P by means of a screw (see Fig. 1). Such an adjustment can be necessary to obtain the best focus if the geometrical, optical and electronic axis of the image intensifier tube do not coincide. Unit C is identical with unit B, except that the RCA tube has no coupling lens at the phosphor end. The image at this point is photographed by a camera mounted on unit D.

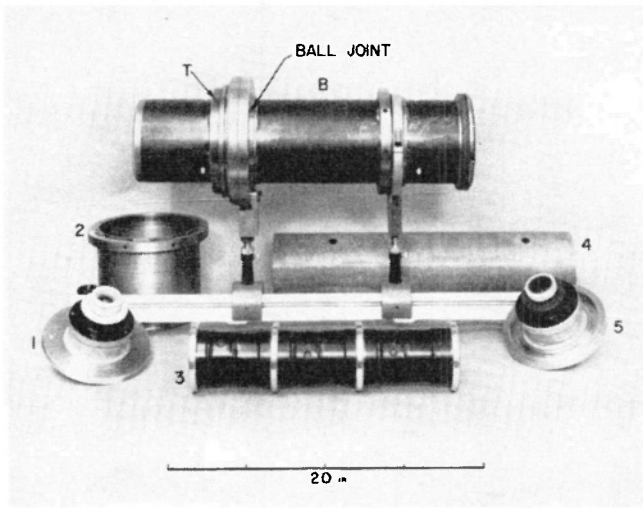


Fig. 3
Unit B containing the RCA-73491

The lens mounts have stops which prevent the image tubes from being damaged during the focusing procedure. The units have height adjustments and locking screws. The lathe beds are mounted on a steel cart equipped with steel jacks and wheels, which is designed to take 10000 pounds of shielding. The overall length of the system is about 9 ft.

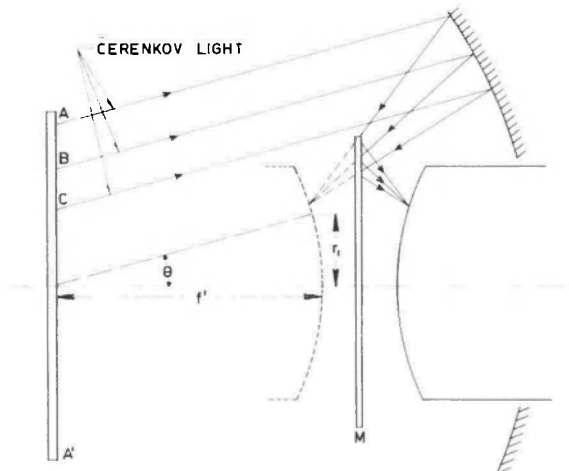


Fig. 4
Proposed optical design to focus a 15° Cerenkov cone on the photocathode with an effective diameter of 5 in.

The present system is designed to accept a Cerenkov light cone of about 12° . An optical design is now under consideration which would permit the observation of 15° and possibly 20° cones [6]. Fig. 4 shows such a design. The Cerenkov rays A, B, C etc. fall on a spherical mirror of 41.5 cm radius and are reflected by a plane mirror into a photocathode with a 5-in effective radius. Spherical aberration in the system is corrected by the plate A.

The performance of the system will be tested with a circular image produced by an axicone lens. Another test will be made with cosmic rays. The radiator shown in Fig. 5 will be oriented vertically to detect the Cerenkov lights from cosmic rays which will be reflected by a 45° mirror into the image-intensifier system. These tests are in progress and photographs of images for this system will be presented.

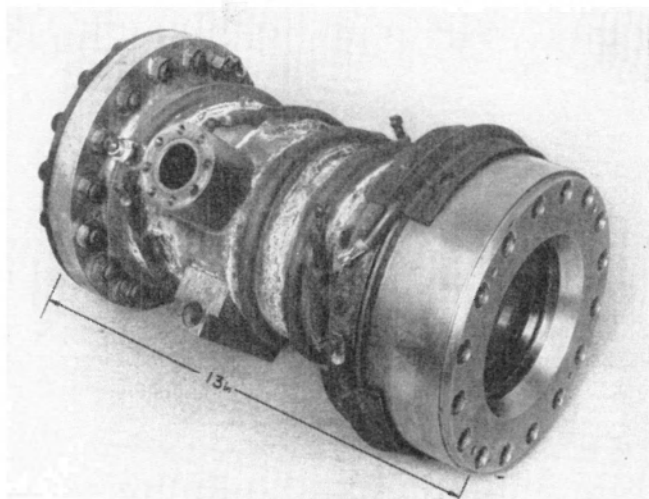


Fig. 5
Gas Cerenkov radiator

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PHOTOMULTIPLICATEURS SANS FENÊTRE RÉALISATION — ÉTUDE DES PROPRIÉTÉS

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Abstract — Résumé — Аннотация — Resumen

Windowless photomultipliers: realization, study of the properties. This study was undertaken in order to make measurements of radiations emitted by plasmas.

The photomultipliers can be utilized for the detection of photons of the far ultraviolet ($100 \leq \lambda \leq 1500 \text{ \AA}$), electrons (50 eV to 10 keV), and low-energy ions (a few keV).

The photomultipliers studied (14, 15 and 17 stages) are preceded by a target or by a photocathode adapted for the purpose, and can easily be connected to a vacuum chamber (operating pressure, 10^{-5} mm Hg). The total voltage is 4000 to 5000.

A good gain stability is obtained with dynodes of Ag-Mg or Cu-Be alloys. The total gain as a function of voltage depends on the way in which the material is treated and seems to depend closely on the oxidation state.

The authors determined the coefficient of secondary emission as a function of the energy of the electrons (50 eV to 20 keV) for Cu-Be and Ag-Mg alloys, oxidized and non-oxidized.

In the area of the ultraviolet under vacuum, the windowless photomultiplier has several advantages over a detector with a light converter (sodium salicylate): better time resolution, photoelectron/UV photon yield five times higher, insensitivity to visible light and the near UV, thermal background negligible, signal-to-noise ratio considerably higher.

Photomultiplicateurs sans fenêtre: réalisation, étude des propriétés. Les auteurs ont entrepris cette étude afin d'effectuer des mesures de rayonnements émis par les plasmas.

Les photomultiplicateurs étudiés sont utilisables pour la détection des photons de l'ultraviolet lointain ($100 \leq \lambda \leq 1500 \text{ \AA}$), des électrons (50 eV à 10 keV) et des ions de faible énergie (quelques keV).

Ces photomultiplicateurs (14, 15 et 17 étages) sont précédés d'une cible ou d'une photocathode adaptée à l'utilisation. Ils peuvent se raccorder simplement à une enceinte à vide (pression de fonctionnement 10^{-5} mm Hg). La tension d'alimentation totale est de 4000 à 5000 V.

Une bonne stabilité du gain est obtenue avec des dynodes en alliage d'Ag-Mg ou de Cu-Be. Le gain total en fonction de la tension d'alimentation dépend du traitement appliqué au matériau et semble lié étroitement à l'état d'oxydation.

Les auteurs ont déterminé le coefficient d'émission secondaire en fonction de l'énergie des électrons (50 eV à 20 keV) pour les alliages de Cu-Be et Ag-Mg oxydés ou non.

Dans le domaine de l'ultraviolet du vide, le photomultiplicateur sans fenêtre présente plusieurs avantages sur un détecteur avec convertisseur de lumière (salicylate de sodium): meilleure résolution en temps, rendement photoélectron/photon UV cinq fois plus élevé, insensibilité à la lumière visible et au proche UV, bruit de fond thermique négligeable, rapport signal sur bruit considérablement plus grand.

Фотоумножители без окошка для отдаленного ультрафиолетового света. Авторы проводили эту работу с целью измерения излучений, испускаемых плазмой.

Эти фотоумножители используются для обнаружения фотонов отдаленного ультрафиолетового света ($100 \leq \lambda \leq 1500 \text{ \AA}$), электронов (50 эв - 10 кэв) и ионов низкой энергии (несколько кэв).

Перед изучаемыми фотоумножителями (14, 15 и 17 каскадов) стоит мишень или фотокатод, приспособленный к данному случаю. Они могут просто присоединяться к вакуум-

ному сосуду (давление при функционировании 10^{-5} мм ртутного столба). Общее напряжение питания равняется от 4000 до 5000 вольт.

Хорошая стабильность усиления достигается диодами из серебрено-магниевого или медно-бериллиевого сплава. Общее усиление напряжения питания зависит от обработки материалов и, как кажется, тесно связано с состоянием окисления.

Авторы определили коэффициент вторичного излучения в зависимости от энергии электронов (50 эв до 20 кэВ) для окислившихся или неокислившихся медно-бериллиевых и серебрено-магниевых сплавов.

В области ультрафиолетового света в вакууме фотоумножитель без окошка имеет ряд преимуществ по сравнению с детектором со световым преобразователем (салициловокислый натрий): лучшая разрешающая способность по времени, К.П.Д. фотоэлектрон/ фотон ультрафиолетового света в пять раз выше, нечувствительность к видимому свету и свету, близкому к ультрафиолетовому, незначительный тепловой фон, значительно большее отношение сигнал-фон.

Fotomultiplicadores sin ventana para el ultravioleta lejano: realización, estudio de sus propiedades.

Los autores han llevado a cabo el presente estudio a fin de efectuar mediciones de las radiaciones emitidas por los plasmas.

Esos fotomultiplicadores pueden utilizarse para detectar fotones del ultravioleta lejano ($100 \leq \lambda \leq 1500 \text{ \AA}$), de electrones (50 eV a 10 keV) y de iones de baja energía (varios keV).

Los fotomultiplicadores estudiados (de 14, 15 y 17 etapas) van precedidos de un blanco o de un fotocátodo adaptado para esta utilización. Pueden acoplarse sencillamente a un recipiente al vacío (presión de trabajo: 10^{-5} mm Hg). La tensión de alimentación total es de 4000 a 5000 V.

Se obtiene una buena estabilidad de ganancia con diodos de aleación Ag-Mg o de Cu-Be. La ganancia total en función de la tensión de alimentación depende del tratamiento aplicado a los materiales y parece estar relacionada estrechamente con el estado de oxidación.

Los autores han determinado el coeficiente de emisión secundaria en función de la energía de los electrones (50 eV a 20 keV) para las aleaciones de Cu-Be y de Ag-Mg oxidadas o no.

En el campo de los rayos ultravioleta en el vacío, el fotomultiplicador sin ventana presenta varias ventajas respecto de un detector con convertidor luminoso (salicilato de sodio): mejor resolución en el tiempo, rendimiento fotoelectrón/fotón UV cinco veces más elevado, insensibilidad a la luz visible y al UV cercano, ruido de fondo térmico despreciable, relación señal/ruido considerablemente más elevada.

Introduction

Les recherches intensives dans deux domaines de la physique — étude des plasmas, physique de la haute atmosphère — ont donné encore plus d'intérêt à la mesure de certains rayonnements et flux de particules: rayonnement ultraviolet lointain et rayons X mous d'une part, ions et électrons de faible énergie d'autre part.

La mesure de l'intensité de ces rayonnements et surtout l'étude de l'évolution de cette intensité au cours du temps sont très difficiles à effectuer à l'aide de détecteurs courants tels que compteurs G. M., compteurs proportionnels, détecteurs à scintillations, en raison de l'absorption par la fenêtre du détecteur, ou de l'existence d'un bruit de fond élevé.

Pour remédier à ces difficultés, il a été nécessaire de reprendre la mise au point de photomultiplicateurs sans fenêtre [1] [2], qui avaient déjà fait, par le passé, l'objet de quelques études [3]. En particulier, le multiplicateur de J. S. ALLEN [3] a été utilisé par certains chercheurs [4] [5].

Notre travail a porté sur les points suivants: mise au point du multiplicateur et définition de ses caractéristiques; étude, pour différents traitements, de l'émission secondaire du matériau utilisé pour sa construction; mesure de l'efficacité de détection

des multiplicateurs pour des électrons d'énergie variable; mesure du rendement photo-électrique des cathodes métalliques.

Description

Le détecteur comprend (fig. 1):

Un multiplicateur d'électrons identique d'aspect au multiplicateur d'un photo-multiplicateur classique;

Une photocathode ou cible adaptée à l'utilisation;

Une enveloppe se raccordant à une enceinte à vide.

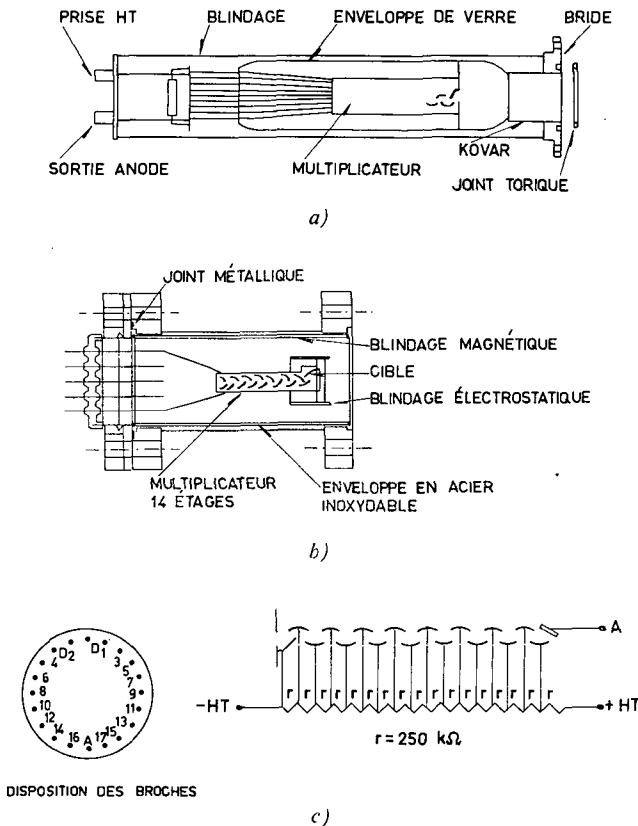


Fig. 1

- a) Photomultiplicateur dans fenêtre. b) Photomultiplicateur sans fenêtre pour ultra-vide.
c) Câblage du photomultiplicateur.

Le matériau des dynodes doit être tel que le coefficient d'émission secondaire ne soit pas modifié à la suite de rentrées d'air. Les multiplicateurs courants, activés au césium, ne conviennent pas. Dans la plupart des cas, il semble que le Cu-Be, après activation, donne les meilleurs résultats [1] [3].

On sait que les dynodes des multiplicateurs d'électrons sont constituées par un support métallique recouvert d'un film d'une substance complexe (semi-conducteur ou isolant, de quelques centaines d'angströms d'épaisseur). Dans le cas du Cu-Be et de l'Ag-Mg, ce sont respectivement des films de Be O et de Mg O, corps qui appartiennent à la catégorie des cristaux ioniques [5] [6] [7].

Nous avons adopté le Cu-Be (2% de Be), et effectué quelques essais avec l'Ag-Mg.

Mesure du gain

Nous avons utilisé deux dispositifs expérimentaux.

Le premier est représenté sur la figure 2. Une lampe à décharge, du type Chalonges, éclaire la photocathode du photomultiplicateur qui n'est sensible qu'à l'ultraviolet lointain. La pression de fonctionnement de la source étant de 1 mm Hg, un dispositif de pompage différentiel s'impose (pression dans le photomultiplicateur de l'ordre de 10^{-5} mm Hg).

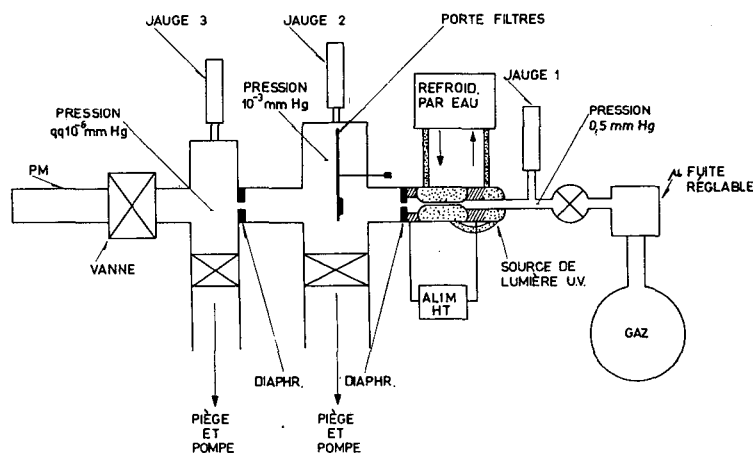


Fig. 2

Montage pour la mesure du gain de photomultiplicateurs sans fenêtre.

Dans le second montage, la source est constituée par un canon à électrons qui permet de tester le multiplicateur seul (fig. 3B). Avec ce dispositif on peut faire varier le courant d'entrée dans de grandes proportions (10^{-14} à 10^{-8} A).

RÉSULTATS

Les mesures ont été faites sur plusieurs structures:

Multiplicateur à 16 étages* (première dynode utilisée comme photocathode), dynodes en Cu-Be oxydé (fig. 4);

* Fourni par le laboratoire d'applications de l'Institut de physique de Zürich (A.F.I.F.).

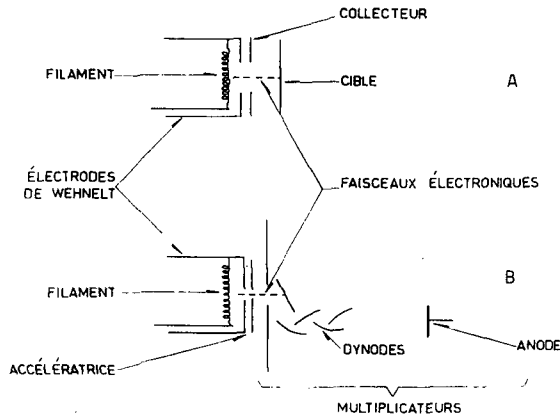


Fig. 3

Canons à électrons pour étude de l'émission secondaire.

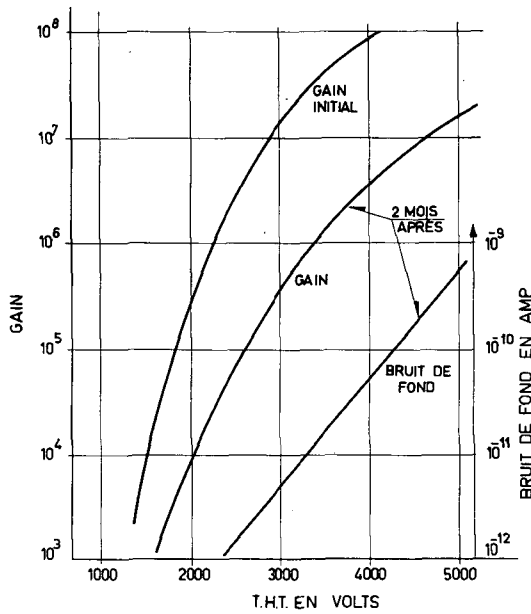


Fig. 4

Gain et courant de bruit de fond pour photomultiplicateur sans fenêtre (16 étages).

Multiplicateurs à 14 étages (modèle 55 AVP Radiotechnique), avec dynodes soit en Cu-Be oxydé ou non, soit en Ag-Mg oxydé ou non (fig. 5).

Les structures non oxydées ont un gain faible (fig. 5), le coefficient d'émission secondaire moyen du Cu-Be non oxydé étant de l'ordre de 2,4 pour 300 V par étage.

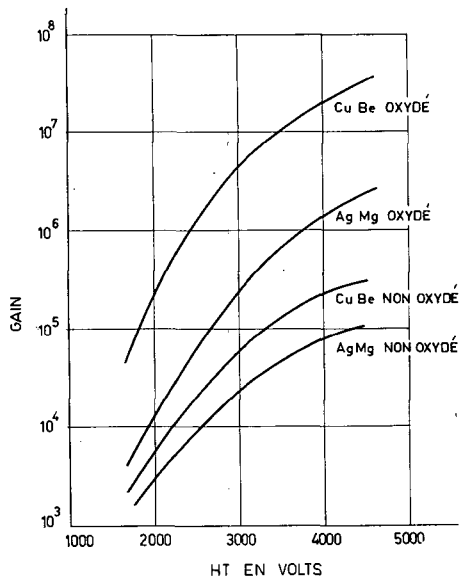


Fig. 5

Gain de photomultiplicateur sans fenêtre (14 étages).

Avec les multiplicateurs activés on obtient des coefficients d'émission secondaire de 3,5 pour 300 V par étage, mais on note une décroissance du gain en fonction du temps, décroissance d'autant plus rapide que le courant débité par la structure est plus intense (fig. 6).

Des remises à l'air de quelques heures ne modifient pas le gain.

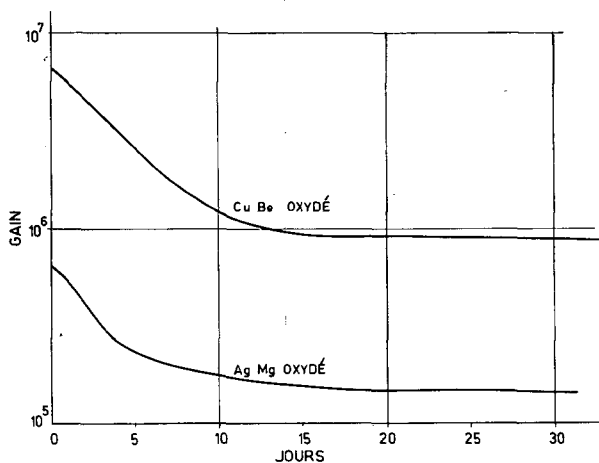


Fig. 6

Décroissance du gain avec le temps pour deux photomultiplicateurs de 14 étages.
HT = 3400 V

Caractéristiques d'emploi

Les courbes de la figure 7 concernent l'influence de la *pression* sur le gain du multiplicateur; à 10^{-4} mm Hg le fonctionnement est encore possible, mais pour éviter les claquages, surtout aux tensions élevées, une pression de 10^{-5} mm Hg est préférable.

L'utilisation de *pièges* à azote liquide sur les pompes s'impose pour éviter la pollution des dynodes par le fluide de pompage.

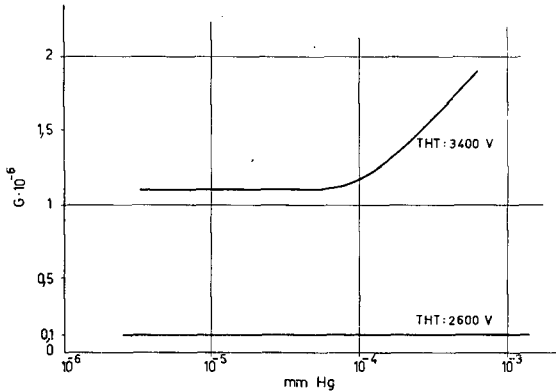


Fig. 7

Gain en fonction de la pression.

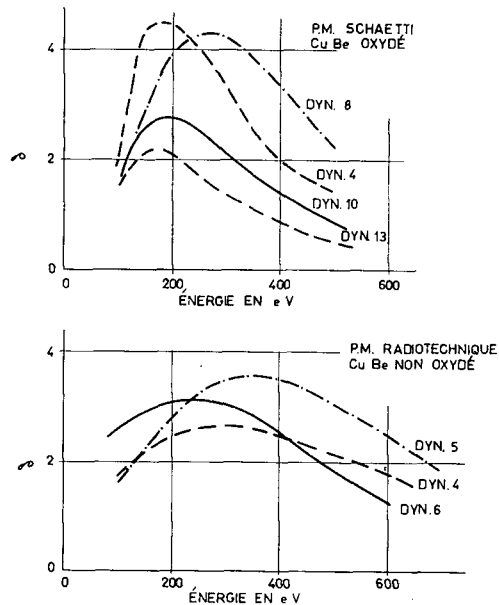


Fig. 8

Coefficients d'émission secondaire: mesure sur différentes dynodes de photomultiplicateur sans fenêtre.

Mesure du coefficient d'émission secondaire, influence de l'oxydation

La mesure du coefficient d'émission secondaire de chaque dynode a été effectuée en fonction de la tension interétages des dynodes. Les résultats sont représentés sur la figure 8. D'une manière générale, les coefficients d'émission secondaire sont plus élevés dans les premiers étages, où les courants sont plus faibles.

Pour une mesure précise du coefficient d'émission secondaire, il est préférable d'utiliser des cibles. Ces mesures ont été faites avec le montage schématisé sur la figure 3A. Les résultats sont représentés sur la figure 9.

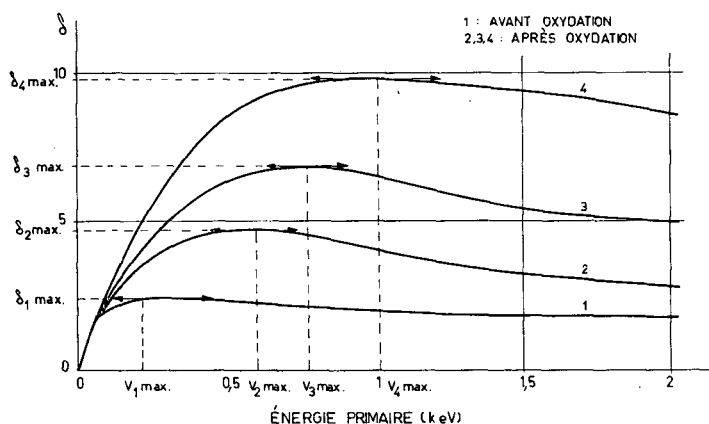


Fig. 9

Coefficient d'émission secondaire pour des cibles en Cu-Be en fonction de l'énergie des électrons primaires.

Le Cu-Be poli a un coefficient maximum δ de 2,3 pour 300 V environ. Après oxydation on a obtenu des δ_{max} voisins de 10. On constate sur les courbes que plus le coefficient d'émission secondaire maximum δ_{max} est élevé plus la tension V_{max} correspondante est grande, ceci étant lié à l'épaisseur du film de Be O [8] [9].

Au cours des essais, le courant primaire était de l'ordre de 10^{-7} A. Des courants dépassant 10^{-6} A produisent une diminution du coefficient d'émission secondaire.

Détection des électrons, spectre des impulsions

Nous avons tracé le spectre d'amplitudes des impulsions de sortie du photomultiplicateur avec le montage de la figure 3B, où le flux d'électrons primaires, mono-énergétiques, était réduit à quelque 10^4 e/s.

On utilisait pour cela un ensemble électronique classique, avec amplificateur et sélecteur d'amplitudes à un canal.

Les résultats sont représentés, pour plusieurs énergies, sur la figure 10. La différence des surfaces est due au fait que les courants primaires sont différents. En réalité le rapport du nombre d'impulsions de sortie au nombre d'électrons primaires varie peu pour ces trois énergies; il est de l'ordre de 0,6.

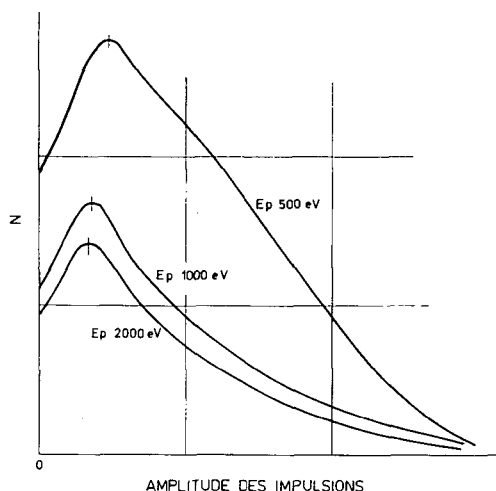


Fig. 10

Spectre des impulsions à l'anode du photomultiplicateur pour des électrons primaires mono-énergétiques.

Effet photoélectrique pour l'ultraviolet lointain

Les mesures dans l'ultraviolet à vide présentent de nombreuses difficultés du fait que peu de matériaux y sont transparents: CaF_2 l'est jusqu'à $1250 \text{ \AA}$ et LiF jusqu'à $1050 \text{ \AA}$; le coefficient d'absorption des gaz est très important: pour O_2 , $k > 100 \text{ cm}^{-1}$ à la pression atmosphérique pour $\lambda < 1000 \text{ \AA}$, et pour N_2 , $k > 100 \text{ cm}^{-1}$ pour $\lambda < 800 \text{ \AA}$ [10] [11].

Plusieurs auteurs [10] [12] [13] [14] [15] ont trouvé un rendement photoélectrique très élevé pour différents métaux dans l'ultraviolet à vide. Pour le platine, l'or, le nickel, etc., il est voisin de 10% et comparable à celui des photocathodes complexes dans le visible et le proche ultraviolet (Cs^3Sb , Cs^2O , CsTe) [10] [16]. Ce rendement est supérieur de plusieurs ordres de grandeur à celui au voisinage du seuil photoélectrique, qui se situe entre 4,6 et 6 eV, soit entre 2700 et $2000 \text{ \AA}$.

Il n'existe pas actuellement de théorie bien établie justifiant cette augmentation rapide de l'effet photoélectrique pour des photons de longueur d'onde inférieure à $1500 \text{ \AA}$.

MÉTHODE DE MESURE, APPAREILLAGE

L'appareillage utilisé comprend (fig. 11):

La source de lumière: lampe du type Chalonges, les gaz excités étant He, Ne et A;

Un monochromateur* à réseau fonctionnant en incidence normale, dans le vide, entre 500 et $3000 \text{ \AA}$ [17];

* Nous exprimons nos sincères remerciements à MM. Romand et Vodar (CNRS, Bellevue), promoteurs et réalisateurs de cet appareil, pour l'aide qu'ils nous ont apportée dans ce domaine.

Un récepteur, qui peut être, au choix, une cellule photoélectrique (possédant un dispositif de dégazage de la photocathode), un photomultiplicateur sans fenêtre ou un photomultiplicateur classique avec sa fenêtre recouverte d'une couche de salicylate de Na;

Un dispositif d'enregistrement du courant de sortie (10^{-13} A à 10^{-6} A).

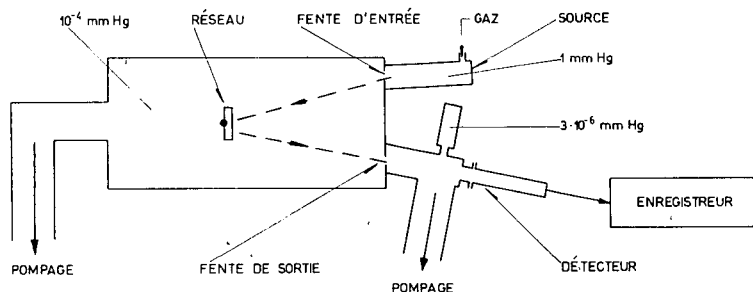


Fig. 11

Montage pour l'étude de l'effet photoélectrique.

Le rendement photoélectrique relatif est évalué en comparant, pour un même flux UV incident, le courant débité par la cathode du photomultiplicateur sans fenêtre ou de la cellule à celui délivré par la photocathode d'un photomultiplicateur classique (51 AVP) dont la fenêtre a été recouverte d'une mince couche de salicylate de sodium. Ce convertisseur, couramment utilisé dans l'ultraviolet à vide est connu pour avoir un rendement quantique de fluorescence constant entre 500 et 2000 Å [18].

RÉSULTATS

Nous avons porté sur la figure 13 les courbes de rendement concernant le nickel, le Cu-Be et l'or; des relevés analogues ont été faits pour le molybdène et le platine. Les valeurs portées en ordonnées sont celles du rendement photoélectrique par rapport à celui de l'ensemble «salicylate + photocathode classique».

L'examen des résultats met en lumière les faits suivants:

Augmentation rapide du rendement pour $h\nu > 8$ eV, soit $\lambda < 1500$ Å;

Similitude des courbes pour tous les métaux utilisés;

Influence du dégazage (chauffage au rouge sous vide pendant quelques minutes), qui entraîne une baisse importante du rendement, montrant ainsi le rôle joué par les gaz occlus. Le rendement de l'or étant le moins affecté, ce métal a été choisi pour constituer les photocathodes de nos détecteurs.

L'un des buts de notre étude était de comparer le détecteur à scintillations «salicylate de Na + PM classique» au photomultiplicateur sans fenêtre. Ce dernier possède un rendement plus élevé, ainsi qu'une sensibilité beaucoup plus faible à la lumière parasite, constituée en grande partie par la lumière visible ou le proche ultraviolet diffusé dans le monochromateur. La figure 12 le met en évidence. On y a juxtaposé la même partie du spectre relevée au moyen du détecteur avec salicylate de sodium, puis au moyen d'un P.M. sans fenêtre. Il apparaît que le rapport signal/bruit de ce dernier est incomparablement meilleur.

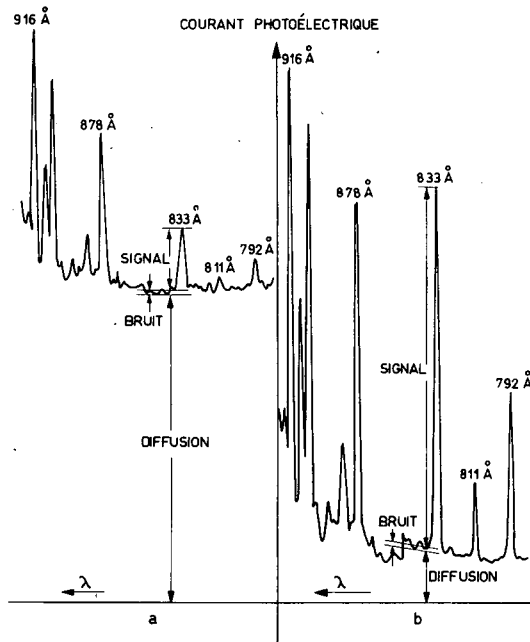


Fig. 12

Extraits de spectres dans l'ultraviolet lointain. *a*) Photomultiplicateur 51 AVP avec salicylate de sodium. *b*) Photomultiplicateur sans fenêtre, photocathode en nickel.

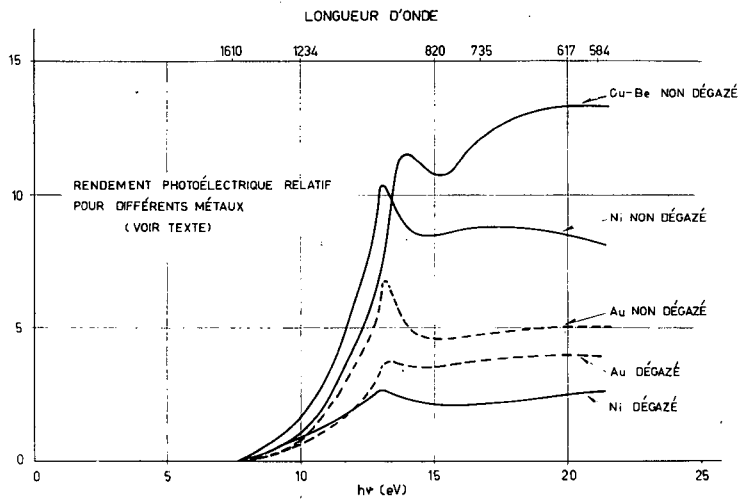


Fig. 13

Rendement photoélectrique relatif pour différents métaux.

Conclusion

Quelques-uns de ces détecteurs mis au point par nos soins sont actuellement utilisés au Département de recherches physiques du C.E.A., notamment pour les études suivantes: spectrométrie des ions et des électrons, essais d'une décharge, mise au point de canons à plasma, spectrographie du rayonnement UV à vide.

Ce travail a abouti non seulement à la mise au point d'un détecteur nécessaire pour les études énumérées ci-dessus, mais aussi à des résultats concernant l'effet photo-électrique et l'émission secondaire. Des travaux ultérieurs devraient nous permettre de préciser et de compléter ces résultats, notamment du point de vue quantitatif.

REMERCIEMENTS

Nous mentionnerons pour terminer la précieuse collaboration que nous ont apportée MM. Cantin et Tarrius au cours de cette étude.

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ÉTUDE DES CARACTÉRISTIQUES DU PHOTOMULTIPLICATEUR 56 AVP DANS LE DOMAINE DE TEMPS INFÉRIEUR A LA NANOSECONDE

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Abstract — Résumé — Аннотация — Resumen

Study of the characteristics of the 56 AVP photomultiplier in the time region inferior to one nanosecond. In order to determine the response characteristics of type 56 AVP photomultipliers to ultra-short light pulses, the authors used the C.L.A.R.E. mercury relay as light source and introduced a time-amplitude converter of very high resolving power.

A description is given of the electronic circuit, the intrinsic resolving power of which is 2.5×10^{-11} s. Used with two 56 AVP photomultipliers receiving the light pulses of the C.L.A.R.E. relay, its resolving power is 1.5×10^{-10} s. The transit time of the photomultipliers has thus been measured and also its variation from the centre to the edge of the photocathode, together with its variations as a function of the potential of the focusing electrode. On reducing the light flux on one of the photomultipliers in such a way that it only receives one photon per spark of the C.L.A.R.E. relay, the fluctuations of the transit times of the photoelectrons in the structure between the photocathode and the first dynode can be measured. These fluctuations can be reduced to less than 5×10^{-10} s.

An explanation of the influence of the electrode potentials is proposed. It is shown, in short, that the association of the 56 AVP photomultiplier with the electronic device described permits a definition of the form of all light pulses, the duration of which can be less than one nanosecond.

Étude des caractéristiques du photomultiplicateur 56 AVP dans le domaine de temps inférieur à la nanoseconde. Pour préciser les caractéristiques de réponse aux impulsions lumineuses ultra-brèves des photomultiplicateurs type 56 AVP, les auteurs ont été amenés à employer le relais à mercure C.L.A.R.E. comme source lumineuse et à réaliser un convertisseur temps-amplitude à très haut pouvoir de résolution.

Le circuit électronique est décrit. Son pouvoir de résolution intrinsèque est de $2,5 \cdot 10^{-11}$ s. Utilisé avec deux photomultiplicateurs 56 AVP recevant les impulsions lumineuses du relais C.L.A.R.E., son pouvoir de résolution est de $1,5 \cdot 10^{-10}$ s. Les auteurs ont ainsi mesuré le temps de transit des photomultiplicateurs, ses variations du centre au bord de la photocathode et ses variations en fonction du potentiel de l'électrode focalisatrice. En réduisant le flux lumineux sur un des photomultiplicateurs de façon qu'il ne reçoive qu'un photon par étincelle du relais Clare, ils ont pu mesurer les fluctuations des temps de transit des photoélectrons dans l'étage «optique d'entrée». Ces fluctuations peuvent être rendues inférieures à $5 \cdot 10^{-10}$ s.

Une explication de l'influence des potentiels des électrodes sur ces fluctuations est proposée. On montre enfin que l'association du photomultiplicateur 56 AVP avec le dispositif électronique décrit permet de préciser la forme de toute impulsion lumineuse dont la durée peut être inférieure à la nanoseconde.

Изучение особенностей фотоумножителя 56 AVP в области времени ниже наносекунды. Чтобы уточнить особенности реакции фотоумножителей типа 56 AVP на ультракороткие световые импульсы, авторы были вынуждены использовать ртутное реле КЛАРА в качестве светового источника и сконструировать время-амплитудный преобразователь с очень высокой разрешающей способностью.

В работе описывается электронное устройство. Его внутренняя разрешающая способность равняется $2,5 \times 10^{-11}$ С. Если оно используется с двумя фотоумножителями 56 AVP,

получающими световые импульсы от реле КЛАРА, то его разрешающая способность равняется $1,5 \times 10^{-10}$ с. Таким образом, при помощи этого устройства было измерено время пролета в фотоумножителях, его колебания от центра к краю фотокатода и его колебания в зависимости от потенциала фокусирующего электрода. Уменьшив световой поток на одном из фотоумножителей таким образом, что он получает лишь один фотон на искру реле КЛАРА, удалось измерить колебания времени пролета фотоэлектронов в „оптическом входном“ каскаде. Эти колебания можно сделать ниже чем 5×10^{-10} с.

В работе предлагается объяснение влияния потенциалов электродов на эти колебания. В заключение показывается, что присоединение фотоумножителя 56 AVP к описанному электронному устройству позволяет уточнить форму любого светового импульса, длительность которого может быть ниже наносекунды.

Estudio de las características del fotomultiplicador 56 AVP en el campo de los tiempos inferiores al nanosegundo. A fin de determinar las características de respuesta, frente a impulsos luminosos ultrabreves, de los fotomultiplicadores tipo 56 AVP, los autores decidieron emplear el relevador de mercurio C.L.A.R.E. como fuente luminosa y montar un convertidor tiempo-amplitud con un poder de resolución sumamente elevado.

Se describe en el trabajo el respectivo circuito electrónico. Su poder de resolución intrínseco es de $2,5 \cdot 10^{-11}$ s. Utilizado juntamente con dos fotomultiplicadores 56 AVP que reciben impulsos luminosos del relevador C.L.A.R.E., alcanza un poder de resolución de $1,5 \cdot 10^{-10}$ s. Así, se ha medido el tiempo de tránsito de los fotomultiplicadores, sus variaciones desde el centro hasta el borde del fotocátodo y sus variaciones en función del potencial del electrodo de enfoque. Reduciendo el flujo luminoso incidente sobre uno de los fotomultiplicadores, de modo que no reciba más que un fotón por cada chispa del relevador Clare, fue posible medir las fluctuaciones de los tiempos de tránsito de los fotoelectrones en la etapa «óptica de entrada». Estas fluctuaciones se pueden reducir a menos de $5 \cdot 10^{-10}$ s.

Los autores proponen una hipótesis que explica cómo influyen sobre tales fluctuaciones los potenciales de los electrodos. Por fin, señalan que la combinación del fotomultiplicador 56 AVP con el dispositivo electrónico descrito permite determinar la forma de cualquier impulso luminoso cuya duración pueda ser inferior a un nanosegundo.

Introduction

La détermination de l'instant d'émission d'un photon du domaine visible, proche UV ou IR, est utilisée dans certaines expériences de physique atomique [1] ou d'astrophysique [2].

Dans notre laboratoire, les expériences projetées sur la mesure des durées de scintillation [3] nécessitaient la mesure de la précision en temps des photomultiplicateurs rapides de développement récents type 56 AVP [4] lorsque l'événement initial est réduit à un seul photon atteignant la photocathode.

La mesure des fluctuations de temps de transit apportées par le photomultiplicateur implique d'une part la connaissance de l'instant d'émission du photon, et d'autre part un dispositif capable de mesurer le temps écoulé entre cet instant origine et l'impulsion électrique apparaissant à l'anode du photomultiplicateur avec une très bonne précision.

Evaluation des fluctuations de temps de transit pour un photoélectron dans le photomultiplicateur 56 AVP

D'après E. GATTI et V. SVELTO [5], dont nous emploierons les notations, l'impulsion électrique à l'anode du photomultiplicateur due à un photoélectron peut être représentée par :

$$U(t) = Af(t, \lambda, h)$$

A est le gain du photomultiplicateur

$f(t, \lambda, h)$ caractérise le SER («single electron response») avec $\int_0^{\infty} f(t, \lambda, h) dt = 1$

λ est la largeur de l'impulsion anodique définie par:

$$\lambda^2 = \int_0^{\infty} (t - b)^2 f(t, \lambda, h) dt$$

(b : centroïde de l'impulsion de valeur moyenne $\bar{b}$ — voir figure 1)

h est une variable statistique ayant la dimension d'un temps de valeur moyenne nulle (c'est-à-dire $h = b - \bar{b}$).

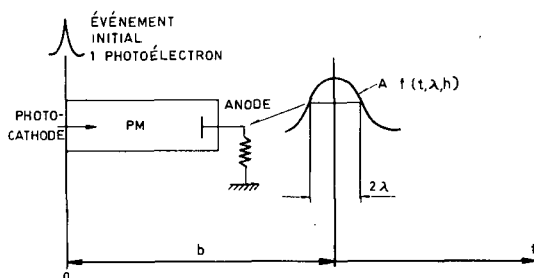


Fig. 1

Forme d'impulsion d'anode de photomultiplicateur.

Dans notre cas (un seul photoélectron), le temps à mesurer («machine time») est b , et les fluctuations apportées par le photomultiplicateur seront celles sur b dont la variance est:

$$\varepsilon_{ph}^2 = \varepsilon_{cd}^2 + \frac{\varepsilon_{dd}^2}{g-1} \left(1 + \frac{2}{g} \right) \quad [5]$$

où ε_{cd}^2 = variance du temps de transit entre photocathode et première dynode

ε_{dd}^2 = variance du temps de transit interdynode

$$\varepsilon_{dd}^2 = \frac{\lambda^2}{n-1} \quad (\lambda \text{ mesuré } \sim 10^{-9} \text{ s}) \quad [6]$$

g : rendement moyen d'émission secondaire

$n-1$: nombre de dynode.

Dans le photomultiplicateur 56 AVP on peut prendre $g = 3$, $n = 15$, $\varepsilon_{cd} = 3 \cdot 10^{-10}$ s d'après G. PIÉTRI [4] [7]. On trouve $\varepsilon_{ph} = 4 \cdot 10^{-10}$ s.

Vérification Expérimentale

Nous nous sommes proposés de vérifier expérimentalement cette précision.

1° Il nous fallait tout d'abord une *source de photons* dont l'instant origine soit connue avec une précision inférieure ou égale au temps à mesurer. Notre choix s'est porté sur un générateur d'impulsions électriques et lumineuses du type bien connu utilisant l'établissement du contact dans un relais CLARE [8].

La mise en forme est aussi courte que possible. Les impulsions électriques (fig. 2), observées à l'aide du tube 5XP11 d'un oscilloscope Tektronix 517, présentent une

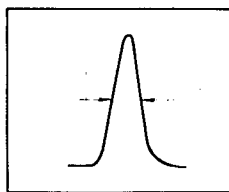


Fig. 2
Résolution.

largeur à mi-hauteur de $1,2 \cdot 10^{-9}$ s, mais sont certainement plus étroites si l'on tient compte du temps de montée des plaques de déflexion du tube 5XP11 et des câbles coaxiaux; c'est donc sur une largeur à mi-hauteur de quelque 10^{-10} s qu'il faut compter.

2° Il nous fallait ensuite un *appareillage* capable de mesurer le temps écoulé entre l'impulsion électrique du relais et l'impulsion d'anode du photomultiplicateur avec une très bonne précision. Le dispositif expérimental est représenté schématiquement sur la figure 3. L'étincelle est focalisée au centre de la photocathode du photomultiplicateur et son intensité réduite de telle sorte qu'un seul photoélectron au maximum parvienne à être émis.

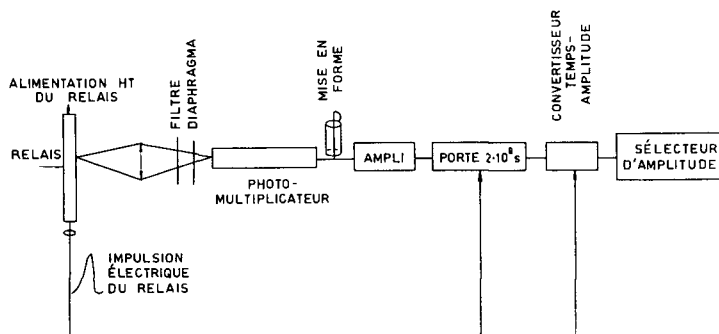


Fig. 3
Dispositif de mesure du retard de l'impulsion du photomultiplicateur.

La mesure de l'intervalle de temps entre l'impulsion électrique du relai et le centroïde de l'impulsion anodique du photomultiplicateur est réalisée par un circuit convertisseur temps-amplitude à grande résolution du type de J. CHRISTIANSEN *et al.* [9] utilisant la lampe E80T. La résolution de ce circuit essayé au générateur d'impulsion était de $2,5 \cdot 10^{-11}$ s.

L'impulsion due au photoélectron de l'étincelle est extraite de celles dues au bruit de fond par l'intermédiaire d'une «porte» de $2 \cdot 10^{-8}$ s de large ouverte par l'impulsion électrique du relai.

L'impulsion d'anode du P.M. est mise en forme par une ligne à retard court-circuitée de façon à obtenir un temps mesuré correspondant à son centroïde.

Les fluctuations de la largeur 2λ de l'impulsion (SER) étant négligeables: $\varepsilon\lambda \sim 6 \cdot 10^{-11}$ s, d'après la formule de E. GATTI *et al.* [5] le temps de passage au zéro: t_i est indépendant

de l'amplitude, donc des fluctuations de gain du photomultiplicateur, et est, à une constante près, celui du centroïde (fig. 4). C'est ce temps t_i qui est pris en considération par l'appareillage.

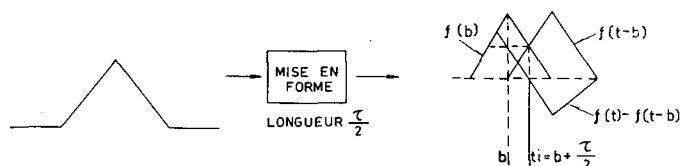


Fig. 4
Mise en forme.

3° *Résultats obtenus.* Les impulsions issues du convertisseur temps - amplitude sont envoyées sur un sélecteur d'amplitude. Les courbes obtenues sont données figure 5.

D'après les évaluations ci-dessus de ε_λ et ε_{ph} , on doit s'attendre à des fluctuations de l'ordre de ε_{ph} qui est prédominant, soit $\sim 4 \cdot 10^{-10}$ s. Or les résultats enregistrés (voir fig. 5) montrent que ε_{ph} est en réalité plus faible. En effet si $\ell(t)$ est la forme vraie de l'impulsion lumineuse (voir plus haut) et $h(t)$ la loi des écarts du temps de transit dans le P.M. de variance ε_{ph}^2 (nous négligeons la contribution de ε_λ), la forme d'impulsion donnée par l'appareillage sera le produit de convolution:

$$\int_{-\infty}^{+\infty} \ell(t-z) h(z) dz.$$

Si on admet que les formes de $\ell(t)$ et $h(t)$ sont gaussiennes, avec les écarts σ et ε_{ph} on trouverait pour l'écart σ de $\ell(t)$, ε étant l'écart de la courbe expérimentale:

$$\sigma = \sqrt{\varepsilon^2 - \varepsilon_{ph}^2} \quad \sigma \leq \sqrt{(5^2 - 4^2) \cdot 10^{-10} \text{ s}} = 3 \cdot 10^{-10} \text{ s}.$$

Or on trouve des écarts ε de l'ordre ou même inférieurs à ε_{ph} (calculé) (voir fig. 6); on obtient en effet une courbe donnant:

$$2\varepsilon = 5 \cdot 10^{-10} \text{ s} < 2\varepsilon_{ph} = 8 \cdot 10^{-10} \text{ s}.$$

Si on prend en considération cette dernière valeur, on voit que, l'impulsion lumineuse ne pouvant avoir une largeur négligeable, les évaluations de ε_{ph} sont exagérées. En reprenant la formule donnant ε_{ph} :

$$\varepsilon_{ph}^2 = \varepsilon_{cd}^2 + \frac{\varepsilon_{dd}^2}{g-1} \left(1 + \frac{2}{g} \right).$$

On voit l'importance de la contribution de l'étage d'entrée (étage cathode-première dynode) par le terme ε_{cd}^2 , et également celle de la statistique de l'émission secondaire par le terme $\frac{2}{g}$, qui provient en fait de $2\varepsilon_g^2/g^2$ où l'on fait $\varepsilon_g^2 = g$ (statistique de Poisson) [5, appendice II].

Ceci nous a amenés à mesurer l'influence des tensions des électrodes de l'étage d'entrée sur la forme de l'impulsion donnée par l'appareillage; en effet, ces tensions influent

sur les trajectoires électroniques, donc sur ε_{cd} et l'émission secondaire de la première dynode.

La figure 5 donne l'influence des potentiels de la focalisatrice et de la déflectrice (voir figure 8), influence résumée sur la figure 6. Le résultat le plus surprenant est celui de l'influence de la tension totale cathode-première dynode (voir fig. 5 et fig. 7).

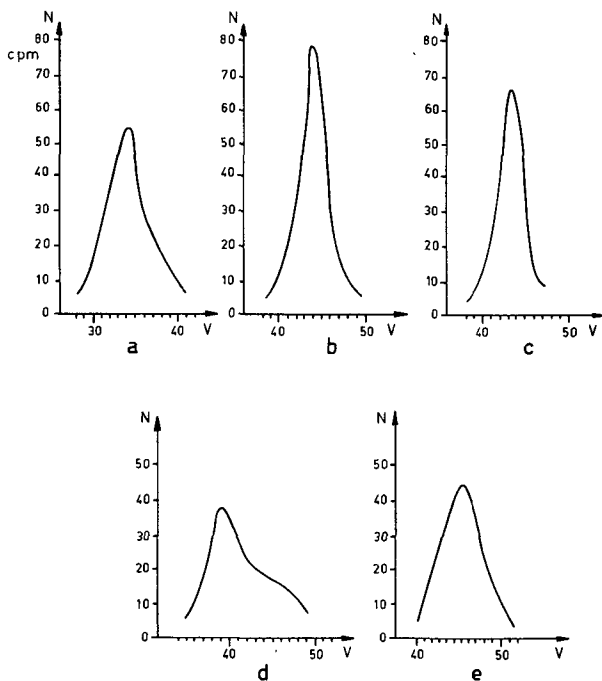


Fig. 5

Courbe donnée par le sélecteur d'amplitude.

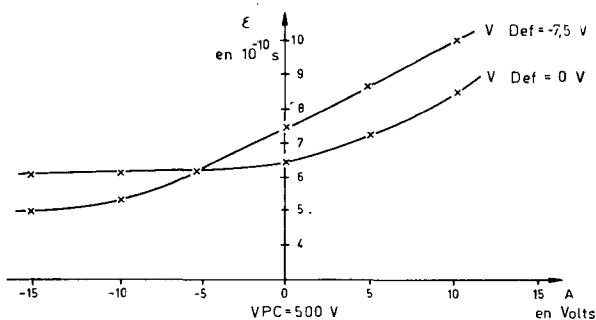


Fig. 6

Valeur expérimentale des écarts ε en fonction de la tension de la déflectrice et de la focalisatrice.

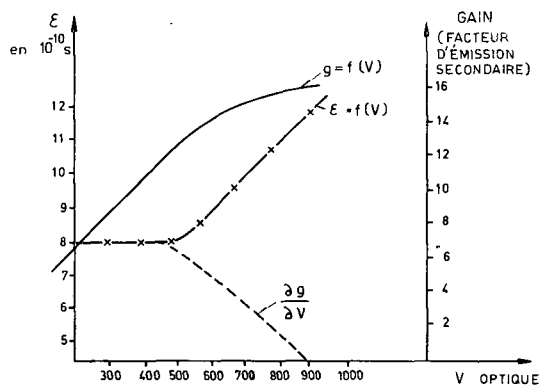


Fig. 7

Valeur expérimentale des écarts ε en fonction de la tension totale cathode — première dynode.

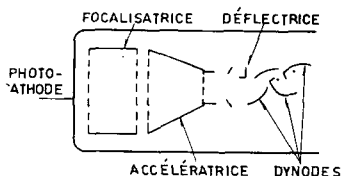


Fig. 8

Schéma de l'optique du photomultiplicateur.

Comme nous le montre ce graphique, la largeur ε augmente avec $V_{PC} - V_{1re\ dyn.}$ et ceci à partir de 500 V. A cette augmentation de potentiel doivent pourtant correspondre des champs plus intenses à la surface de la photocathode, ainsi que des temps de transit plus faibles dans l'optique. Il semblerait que l'apport que donne ce potentiel à ε_{ph} se fasse surtout sentir par les variations du facteur d'émission secondaire g surtout dans la première dynode.

Il est curieux en effet de constater que la pente de la courbe $g = f(V)$ donnée par PIÉTRI [4] [7] pour des surfaces en alliage Ag-Mg affecte la même allure que la variation $\varepsilon = f(V)$ (fig. 7), ce qui semblerait en accord avec un effet cité par G. T. WRIGHT [10], selon lequel la variance ε_g^2 de g ne suivrait plus la loi de Poisson ($\varepsilon_g^2 = g$) lorsqu'on approche du maximum de la courbe $g = f(V)$ où l'on aurait $\varepsilon_g^2 > g$.

Une courbe $f(V)$ ayant un maximum vers 550 V [11] expliquerait également très bien le phénomène (fig. 9), car alors $\varepsilon_{ph}^2 = \varepsilon_{cd}^2 + \frac{\varepsilon_{dd}^2}{g-1} \left(1 + \frac{2}{g}\right)$ est susceptible de croître avec V au delà de 500 V. Mais la courbe donnée par PIÉTRI [7] a son maximum pour 800 V, ce qui nous fait envisager une autre explication.

L'énergie des électrons secondaires de la première dynode influe sur le temps de transit première-deuxième dynodes.

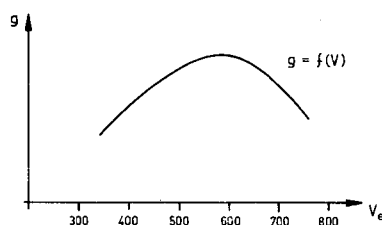


Fig. 9

Emission secondaire en fonction de la tension cathode — première dynode.

Or la répartition de cette énergie est variable avec l'énergie du photoélectron incident [12]. Au-delà de 500 V, l'électron incident extrait des électrons secondaires dans des couches plus profondes, ce qui entraîne d'une part des instants d'origines quelque peu différents et, d'autre part, des énergies de sortie différentes.

On peut montrer par un calcul simple basé sur la courbe de la figure 10 [12] que les effets du spectre d'énergie des électrons secondaires sur les fluctuations de temps de transit sont de l'ordre de celles mesurées, par exemple, pour la courbe de la figure 10 et la structure du 56 AVP $\Delta t = \pm 0,85 \cdot 10^{-10}$ s.

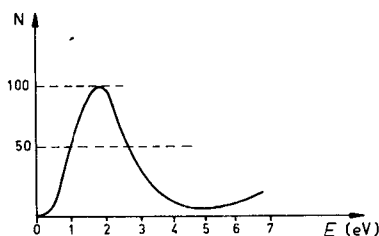


Fig. 10

Spectre d'énergie des électrons secondaires.

Donc, si la répartition en énergie des électrons secondaires est fonction de l'énergie de l'électron incident [10], c'est-à-dire s'il y a un élargissement de la distribution des énergies secondaires, nous obtenons facilement des fluctuations de l'ordre de 10^{-10} s, ce qui semble correspondre aux chiffres trouvés.

Conclusion

Ces mesures, bien que peu nombreuses quant aux performances du photomultiplicateur 56 AVP, donnent une idée de sa sensibilité pour les mesures d'instant d'émission de photons individuels, la précision atteinte étant de l'ordre de $3 \cdot 10^{-10}$ s. On peut donc l'employer à la mesure de forme d'impulsions lumineuses brèves [3], ainsi qu'à la mesure de vie moyenne de niveaux électroniques [1] dans le domaine de 10^{-9} s. Cette précision pourrait également être mise à profit dans des expériences de corrélations de faisceaux lumineux [2].

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DISCUSSION

J. V. Kane (United States of America): I should like to put a question on the paper introduced by Mr. Agrinier. Do you know of the measurements by Hayia-el-Hakim, which appeared in a University of California Report—I think in 1960. He measured the single photoelectron transit-time spread in this and in various other tubes, and his figure for this tube is in the region of $2-4 \times 10^{-9}$ s; this figure differs from the one you have given. Could you explain this?

B. Agrinier (France): I think the problem is the shaping of the pulse at the anode of the photomultiplier. Mr. Gatti has also carried out theoretical and experimental work of great interest in this field, and he says that one should use the centroid of the pulse, but we have found that when there are many photoelectrons, in the case of scintillation, we get space-charge phenomena in the last dynodes of the photomultipliers so that the time that is taken into account is not the centroid of the real event but perhaps corresponds to the very first photoelectron.

J. V. Kane: El Hakim analysed the pulses by a photographic method and he evaluated the time spread for the 50% point, the 10% point and the centre of gravity of the pulse. There was no apparent experimental difference between these three methods of analysis in his work. I have another question for Mr. Gatti. In his paper on time-spread, the parameter used to characterize the time-spread for a single photoelectron in the photo tube was also of an order of magnitude less than 10^{-9} s. Now, in the paper I presented this morning the time-spread figure we used is El Hakim's and its order of magnitude is several times 10^{-9} s. Moreover, our theoretical treatment unfortunately agrees with experiment, so it appears that both in the experiments and in the theory, there is a discrepancy in the figure for this time-spread. I personally feel that it is larger than 10^{-9} s.

E. Gatti (Italy): Some of the discrepancy could probably be accounted for by the effect of after-pulses. In measurements I have made on the size of the pulses, I have always found for conversion photomultipliers an order of magnitude of say, 4 or 5 ns for the single electron response. I have not made very accurate measurements of the centre of gravity, but I can say that I have always found less than 1 ns. I have also made measurements on artificial coincidence, using artificial light pulses, with a very low number of photons and hence, also of photoelectrons. The experimental results seemed to confirm a figure in the region of 5×10^{-10} for the standard deviation of the centroid of the single electron response.

J. V. Kane: I do not believe that El Hakim's results were influenced by after-pulses because he used a fast oscilloscope to look at the pulses themselves. I can only say that the comments that have been made have complicated the problem, and maybe we can clarify it in a later discussion.

EXPERIMENTS ON MULTI-STAGE LIGHT INTENSIFICATION BY ELECTRO-LUMINESCENCE

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JAPAN

Abstract — Résumé — Аннотация — Resumen

Experiments on multi-stage light intensification by electro-luminescence. In recent years, several papers on the solid-state image-intensifier by the use of electro-luminescent phosphor and photo-conductive materials have appeared as one of the important applications of solid-state electronics. It is convenient and important to use the solid-state intensifier for light amplification.

The purpose of this experimental work is to achieve more amplification by cascading the intensifier in multi-stage.

This paper first deals with the electrical and optical characteristics of a single-element light-intensifier, then points out briefly the advantage of employing parallel resistance with an electro-luminescent-panel to improve its characteristics.

Two types of photo-conductive cell were used, one was a sintered CdS cell and the other a CdS photo-sensitive powder, moulded with plastic binder.

According to the results obtained on a single-element light-intensifier, two-stage and three-stage light intensifiers were made and their characteristics were tested for various parallel resistances.

In the three-stage light intensifier, the amplification of about 400 was obtained at 0.3 rlx in-input radiation, and these results suggest the possibility of obtaining more amplification at lower input radiation.

The experimental results are believed to be applicable to a solid-state image-intensifier by devising a suitable construction.

Expériences sur l'intensification de la lumière en cascade par électroluminescence. Au cours des dernières années, on a publié plusieurs communications sur le renforceur d'images à cristal utilisant le phosphore électroluminescent et des matières photoconductrices; c'est là une des principales applications de l'électronique de l'état solide. Il est à la fois pratique et avantageux d'utiliser le renforceur d'images à cristal pour l'amplification de la lumière.

Ces expériences visent à accroître l'amplification en faisant cascader le renforceur en plusieurs phases.

Après avoir présenté les caractéristiques électriques et optiques d'un photomultiplicateur à un seul élément, les auteurs exposent succinctement l'intérêt qu'il y a à utiliser des résistances en parallèle avec panneau électroluminescent pour améliorer les caractéristiques de l'appareil.

Ils ont utilisé deux types de cellules photoconductrices: une cellule de sulfure de cadmium fritté et une poudre photosensible de sulfure de cadmium, agglomérée à l'aide d'un liant en matière plastique.

Compte tenu des résultats obtenus avec un photomultiplicateur à un seul élément, les auteurs ont construit des photomultiplicateurs à deux et à trois étages et fait des expériences destinées à déterminer leurs caractéristiques pour diverses résistances en parallèle.

Avec le photomultiplicateur à trois étages, on a obtenu une amplification d'environ 400 pour un rayonnement d'entrée de 0,3 rlx; ces résultats permettent de supposer qu'il serait possible d'obtenir une plus forte amplification pour un rayonnement d'entrée plus faible.

Les auteurs estiment que les résultats de leurs expériences seront applicables aux renforceurs d'images à cristal, lorsqu'on aura mis au point une construction appropriée.

Опыты по многокаскадному светомультипликации (фотоумножению) посредством электролюминесценции. За последние годы, в качестве одного из важных применений электроники твердых тел, был опубликован целый ряд докладов относительно повышения яркости

изображений с помощью кристаллического усилителя. Представляется удобным и важным использовать кристаллический усилитель для светоусиления (фотоумножения).

Целью настоящей экспериментальной работы является повышение степени усиления посредством многоступенчатого каскадирования усилителя.

В настоящем докладе сначала разбираются электрические и оптические характеристики монокаскадного усилителя, а затем с целью улучшения его параметров кратко излагаются преимущества использования параллельного сопротивления с электро-светящейся панелью.

Было использовано два типа фотопроводящей ячейки, одна из которых была уплотненная ячейка из Cds, а другая была сделана из фоточувствительного порошка Cds, сформованного вместе с пластическим связывающим веществом.

На основании результатов, полученных на монокаскадном усилителе, были построены двухкаскадные и трехкаскадные усилители, и их характеристики были проверены для различных параллельно включенных сопротивлений.

При помощи трехкаскадного усилителя было получено при входящей радиации в 0,3 радиолоксов, усиление почти в 400 раз; эти результаты указывают на возможность достижения более значительного усиления при понижении поступающей радиации.

Нужно думать, что путем осуществления надлежащей конструкции эти экспериментальные результаты могут быть применены для повышения яркости изображений посредством кристаллического усилителя.

Experimentos sobre intensificación en cascada de la luminosidad por electroluminiscencia. En los últimos años se han publicado varios trabajos sobre intensificación de la luminosidad de las imágenes mediante el empleo de intensificadores en estado sólido, usando fósforos electroluminiscentes y sustancias fotoconductoras, lo que constituye una aplicación importante de la electrónica del estado sólido. Es conveniente e importante el uso del intensificador de estado sólido para amplificación luminosa.

El objeto del presente trabajo experimental es obtener una mayor amplificación acoplando el intensificador en varias etapas en cascada.

Los autores comienzan describiendo las características eléctricas y ópticas de un elemento intensificador y examinan brevemente la ventaja de emplear una resistencia montada en paralelo con la pantalla electroluminiscente, para mejorar las características de ésta.

En los experimentos se utilizaron dos tipos de células fotoconductoras: una de CdS sinterizado y otra de CdS fotosensible en polvo, aglomerado con plástico y moldeado.

Basándose en los resultados obtenidos con un solo elemento intensificador, se construyeron intensificadores de dos y tres etapas y se efectuaron experimentos para estudiar sus características con diferentes resistencias montadas en paralelo.

Con el intensificador de tres etapas se obtuvo una amplificación del orden de 400, para una radiación de entrada igual a 0,3 rdlux. Estos resultados sugieren la posibilidad de obtener un mayor aumento para una radiación de entrada menor.

Los autores estiman posible aplicar estos resultados experimentales a los intensificadores sólidos de imágenes diseñando un dispositivo adecuado.

I. Introduction

Recent advances in the developments of the electro-luminescent phosphors have suggested a new method of light intensification.

This paper presents the experimental results of multi-stage light intensifiers using CdS photo-conductive powder and ZnS electro-luminescent powder to obtain the high-intensification gain.

The single-element light-intensifier has been constructed by a series of wiring with the photo-conductive cell (PC cell) and the electro-luminescent panel (EL panel) which were made separately, and they were laminated in two or three stages.

II. Experimental materials

A diagram showing the construction of the electro-luminescent panel appears in Fig. 1. A glass plate is coated with transparent conductive layer, consisting of Nesa. On top of the transparent electrode is applied a layer of electro-luminescent substance, consisting of an electro-luminescent powder (ZnS) suspended in Urea formadehyde resin, and the reflector layer of white lacquer (TiO_2 suspended in the same binder) is sandwiched between the ZnS layer and second electrode.

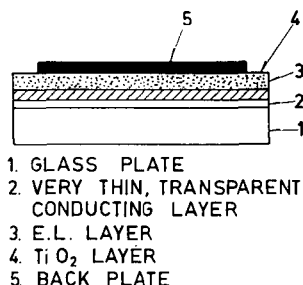


Fig. 1
Construction of a electro-luminescent panel

Two kinds of PC cell have been used. One is the sintered type CdS PC cell and the other is shown in Fig. 2.

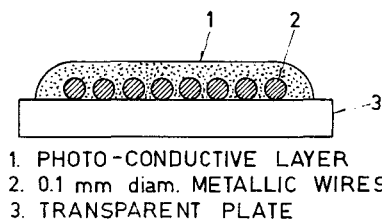


Fig. 2
Construction of parallel-electrodes type photo-conductive cell

The photo-conductive layer is a thin layer of CdS photo-conductive powder which is coated with transparent insulating lacquer. The electrode is gold-plated Mo wire, which is separated at 0.3 mm pitch and these wires are connected alternately to make a pair of electrodes.

The photo-conductive current and the dark current of both PC cells are shown in Table I. The parallel electrode type is more sensitive at high voltage than the sintered type, but the dark current is still more sensitive. Therefore, the sintered type was used in first stage and the parallel type was used in second and third stages.

TABLE I
CHARACTERISTICS OF A PHOTO-CONDUCTIVE CELL

Photo-conductive cell	D C Voltage	10	20	30	50	70	100
Sintered Type, useful area 19.5 cm ² }	photoconductive current mA	0.85	1.45	2.00	3.55	5.00	5.25
Input radiation 16rlx	dark current μ A	0.0007	0.0012	0.0017	0.0026	0.0037	0.0053
Parallel-electrodes Type, } useful area 25 cm ²	photoconductive current mA	0.014	0.012	0.40	5.2	12.0	20
Input radiation 20rlx	dark current μ A	0.046	0.063	0.083	0.11	0.15	0.20

III. Experimental results

To obtain the fundamental data of the multi-stage light intensifier, the characteristics of the single-element light-intensifier have been tested.

The sintered-type PC cell and the parallel-electrode type PC cell were used respectively. Then, 2-stage and 3-stage light-intensification have been experimented on utilizing these data.

1. SINGLE-ELEMENT LIGHT-INTENSIFIER

Luminous characteristics

Fig. 3 shows the schematic diagram of the light intensifier used in this experiment. (a) is an equivalent circuit using a sintered-type PC cell which is shown by resistance R_p . (b) is an equivalent circuit using the parallel-electrode type PC cell which is shown as the parallel circuit of C_p and R_p .

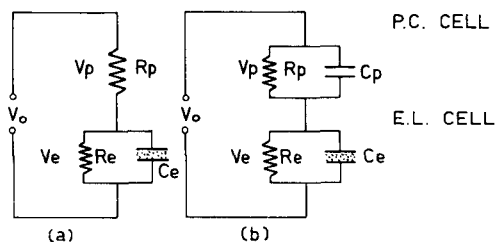


Fig. 3
Equivalent electrical circuits of a light-intensifier

The applied-voltage frequency vs. output-radiation characteristics of the (a) and (b)-type light-intensifiers have been tested. Fig. 4 shows the results obtained with the (a)-type. It shows that intensification gain increases linearly with the frequency and the relation between output radiation and frequency is the same as the EL panel characteristic.

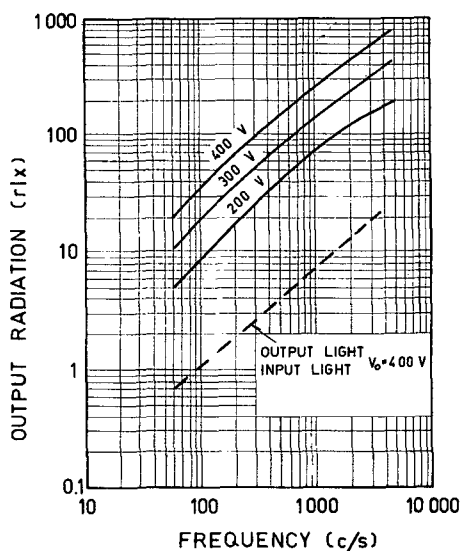


Fig. 4

Relations between output radiation and frequency for a one-stage light intensifier; the dotted line shows gain

The experimental results of type (b) are shown in Fig. 5. The output radiation increases with frequency up to about 1000 cycles, but at a higher frequency the radiation decreases strongly causing the variation of PC-cell impedance by parallel capacity.

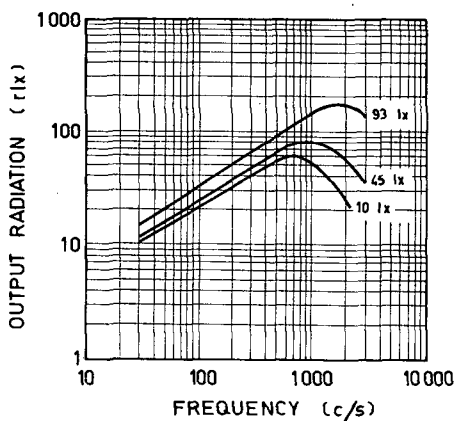


Fig. 5

Frequency characteristics of a one-stage light intensifier for various input radiations

The threshold frequencies are affected by both input radiation and the capacity of the EL panel and the PC cell. From the above results, it is desirable to use this light-intensifier in a lower frequency, under 1 kc/s.

2. INTENSIFICATION CHARACTERISTICS

Fig. 6 shows the light-intensification characteristics of the one-stage intensifier using the sintered-type PC cell.

As may be seen from the Figure, the saturation of output radiation occurs in the event of high-parallel resistance of the EL panel and by decreasing the parallel resistance the saturation characteristics are improved, which are termed the compensating resistance in this report.

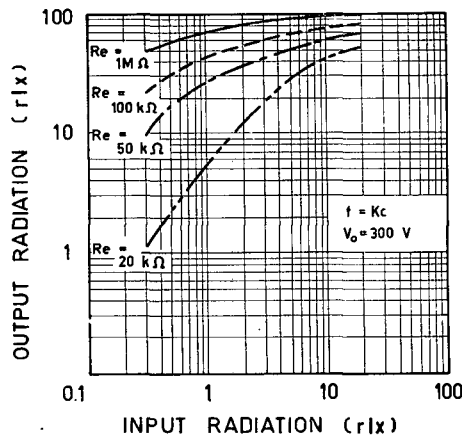


Fig. 6

Light-intensifier characteristics of one-stage intensifier using sintered-type PC cell. Effects of parallel resistance are shown

Fig. 7 shows the light-intensification characteristics of a one-stage intensifier using a parallel-electrodes type PC cell. With the reduction of compensating resistance, the intensification gain decreases and no improvements of the saturation are obtained, then this type must be used with the higher parallel resistance of the EL panel.

IV. Multi-stage light intensification

Utilizing the above-mentioned results, two-stage and three-stage light-intensifiers have been constructed, and the intensification characteristics have been tested.

1. TWO-STAGE LIGHT INTENSIFIER

The equivalent electrical circuit of a two-stage light-intensifier is shown Fig. 8. The parallel resistances $Re1$ and $Re2$ are used to improve the characteristics of intensification.

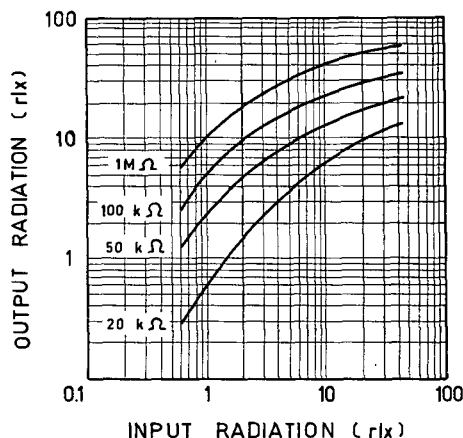
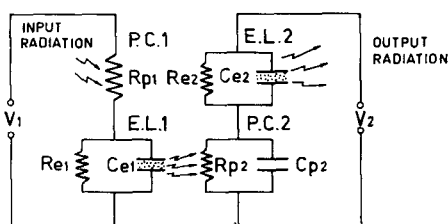


Fig. 7

Light-intensifier characteristics of a one-stage intensifier using the parallel-electrodes type PC cell. Effects of parallel resistance are shown



Re_2 : $1M\Omega$, $50k\Omega$
 Re_1 : $1M\Omega$, $100k\Omega$, $50k\Omega$, $20k\Omega$
 Ce_1, Ce_2 : $3000pF$,
 Cp_2 : $600pF$

Fig. 8

Equivalent electrical circuit of the two-stage light intensifier

Fig. 9 shows the experimental input-output relation characteristics of the two-stage light intensifier and the effects of the parallel resistances of EL panels.

From these results, we realize that the parallel resistance Re_1 of the first-stage is effective in improving the saturation, but the reduction Re_1 decreases the intensification gain; then, Re_1 must be properly selected to match the input radiation in order to operate.

To obtain a higher intensification gain, it is desirable that the selected parallel resistance Re is as large as possible.

2. THREE-STAGE LIGHT INTENSIFIER

To increase the intensification gain, a three-stage light intensifier has been tested, utilizing the results of two-stage light-intensifier experiments.

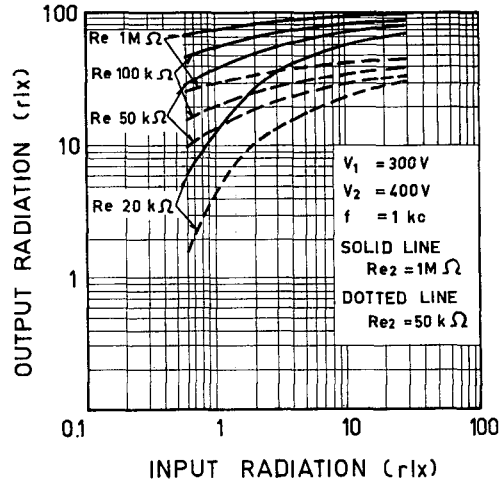


Fig. 9

Experimental B2—B1 characteristics for light intensifier shown in Fig. 8. Effects of parallel resistances of EL panel are shown

Fig. 10 shows the equivalent electrical circuit of a three-stage light intensifier. The sintered-type PC cell has been used in the first stage, and the parallel-electrodes type PC cell has been used in the other stages.

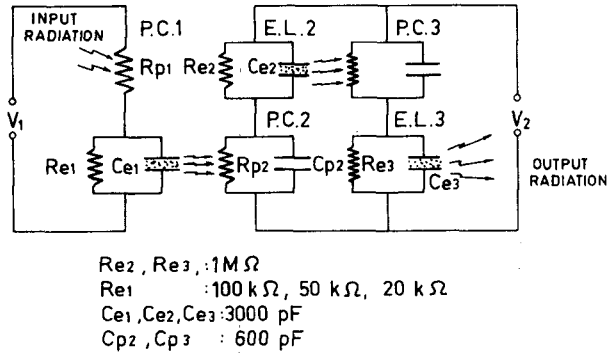


Fig. 10

Equivalent electrical circuit of a three-stage light intensifier

Re_1 is the compensating resistance as mentioned above, and Re_2 and Re_3 are the self-resistance of EL panel.

The input-output radiation characteristics with various Re_1 have been tested in the range of input radiation between 0.3 and 20 rlx. The results are shown in Fig. 11.

Compared with the two-stage type, the three-stage intensifier has a higher gain, and an amplification of about 400 is obtained at 0.3 rlx input-radiation. At lower input-radiation, these results suggest the possibility of obtaining further amplification.

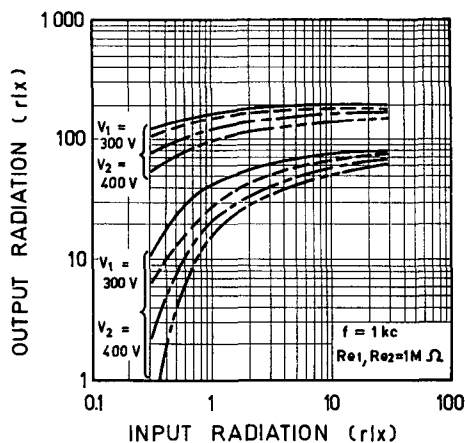


Fig. 11

Experimental B2—B1 characteristics for the light intensifier shown in Fig. 10. Effects of the parallel resistances of EL panel are shown

V. Conclusion

Multi-stage light intensification is effective for increasing the intensification gain but the gain changes according to the input radiation. The gain is low at large input-radiation.

To improve the intensification characteristics, the use of parallel resistance of the first-stage is especially effective at lower input-radiation.

The long building time and decay time are weak features of this device using a CdS photo-conductive powder and it is desirable that better photo-conductive materials should be developed.

DEVELOPMENT OF THE PHOTOMULTIPLIER FM 50 FOR STANDARD SCINTILLATION COUNTERS

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YUGOSLAVIA

Abstract — Résumé — Аннотация — Resumen

Development of the photomultiplier FM 50 for standard scintillation counters. The FM-50 is a tube with a plane, transparent Sb-Cs photocathode, 40 mm in diameter and an eleven-stage Ag-Mg multiplying system designed for standard scintillation counting. The special form of the first and second dynode allows electrons to be collected from large photocathodes in a Reichmann system. The optimal secondary emission coefficient of Ag-Mg alloy is attained when MgO layers, produced in the selective oxidation process, are very thin; therefore the dynode activation process can be simplified. The activation and sensibilization of the photocathode is discussed; a possibility of sensibilization with O₂ originating from a source incorporated in the tube is described. Some ways of stabilizing dark currents are discussed. The tube characteristics are given.

Mise au point du photomultiplicateur FM 50 pour compteurs à scintillations modèle courant. Le photomultiplicateur FM 50 est un tube comprenant une photocathode Sb-Cs, plane et transparente, de 40 mm de diamètre et un système multiplicateur Ag-Mg à onze étages conçu pour le comptage courant des scintillations. La forme particulière des première et deuxième dynodes permet de recueillir les électrons provenant de grandes photocathodes dans un système de Reichmann. Le coefficient optimum d'émission secondaire de l'alliage Ag-Mg est atteint quand les couches de MgO produites au cours du traitement par oxydation sélective sont très minces; on peut donc simplifier le processus d'activation des dynodes. L'auteur étudie l'activation et la sensibilisation de la photocathode; il décrit un moyen permettant d'effectuer une sensibilisation avec O₂ provenant d'une source incorporée dans le tube. Enfin il examine les moyens de stabiliser les courants d'obscurité, et donne les caractéristiques du tube.

Разработка конструкции фотоумножителя FM 50 для стандартных сцинтилляционных счетчиков. Фотоумножитель FM 50 является электронной лампой с плоским прозрачным сурьмово-цезиевым (Sb-Cs) фотокатодом диаметром 40 мм и с одинадцатью-каскадной серебряно-магниевого (Ag-Mg) умножительной системой, предназначенной для стандартного счета сцинтилляций. Специальная форма первого и второго динодов позволяет улавливать электроны с больших фотокатодов в системе Райхманна. Оптимальный коэффициент вторичной эмиссии серебряно-магниевого сплава достигается, когда слои окиси магния (MgO), образующиеся при процессе селективного окисления, чрезвычайно тонки; это позволяет упростить процесс активации динода. Обсуждается вопрос активации и сенсibilизации фотокатода; описывается возможность сенсibilизации при помощи O₂, вырабатываемого введенным в электронную лампу источником. Описываются некоторые способы стабилизации темновых токов. Приводятся характеристики электронной лампы.

Fotomultiplicador FM 50 para contadores de centelleo normales. El FM 50 es un tubo con un fotocátodo plano transparente de Sb-Cs, de 40 mm de diámetro, y un sistema multiplicador de Ag-Mg, de 11 etapas, que se usa como detector ordinario de centelleo. La forma especial del primer y segundo dinodos permite captar electrones provenientes de fotocátodos de grandes dimensiones en un sistema Reichmann. El coeficiente óptimo de emisión secundaria de una aleación Ag-Mg se obtiene cuando las capas de MgO que se forman en el proceso de oxidación selectiva son muy delgadas; por lo tanto, es factible simplificar el proceso de activación del dinodo. El autor analiza la activación y sensibilización del fotocátodo; describe una forma

posible de sensibilización mediante O_2 proveniente de una fuente incorporada a la válvula. Estudia algunos modos de estabilizar las corrientes de oscuridad. Se indican las características de la válvula.

I. Introduction

The photomultiplier FM 50 (Fig. 1) is a tube, developed on the initiative and with the help of the Yugoslav Atomic Energy Commission at the Ljubljana Institute for Electronics (Inštitut za elektroniko). The tube is designed for use in standard scintillation counters and has therefore a plane, semi-transparent cathode and an eleven-stage multiplying system. It is a result of the work done in a small laboratory, where the equipment is far from those used in specialized the tube manufacturers' laboratories. Several technological problems which arose during the work are discussed in this paper.

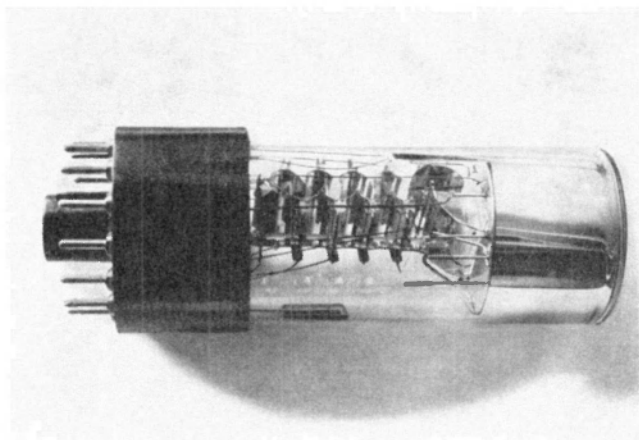


Fig. 1
Photomultiplier tube FM 50

II. Electron optics of the multiplying system

In our first experiments in 1951 with photomultiplier tubes, which unfortunately had to be abandoned, we used the Reichmann multiplying system. This was the reason that we decided to use the same system in the photomultiplier designed for scintillation counting. As it is impossible to collect the electrons originating from a large-plate photocathode on the first dynode of this multiplying system, we had to solve this electron-optic problem with a suitable design of the first, or both the first and second dynodes. During the experiment this necessity was followed by two others, specific for the conditions in which we worked: (1) the system must be insensitive to small deviations out of the axis of the tube, which may happen during the assembling and sealing of the tube; (2) the unchanged system must be applicable as well to multipliers with much larger photocathodes.

Facing the results obtained in the electrolytic tank and on the rubber membrane [1], we decided to shape the first two dynodes as is evident from Fig. 2. The electron beam reaches the large first dynode (having the potential of the shield) through a circular

15-mm opening in the shield. In front of the second dynode, a grid is placed. Finally a rod-shaped auxiliary electrode, parallel to the lower edge of the first dynode, having the potential of the third dynode, accelerates the electrons from the second dynode towards the third one. This and the following dynodes have the classic Reichmann form. The results obtained by this solution are satisfactory. It is notable that the dependence of the resolution R on the cathode—dynode 1, the potential V_{K-D1} , shown on Fig. 3, is very small.

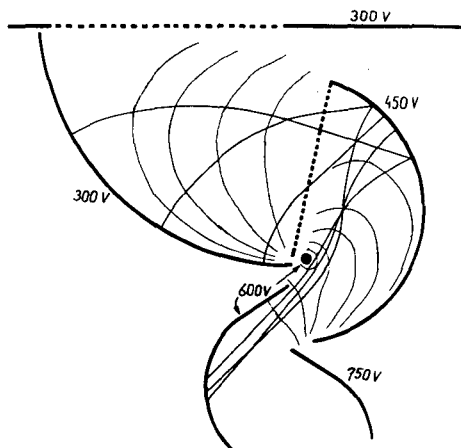


Fig. 2

Electrode arrangement and electron trajectories of the first three stages in FM 50 photomultiplier

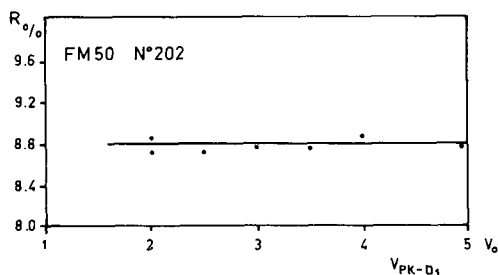


Fig. 3

Resolution R , as function of the cathode—dynode 1 accelerating voltage V_{K-D1} . V_0 is the interstage voltage

III. Dynode distance pieces

Our experience in using Macedonian mica distance-pieces was rather bad, as the caesium vapour caused large leakage currents. Being unable to obtain ceramic distance-pieces, we decided to fix the dynodes on glass-rod supports. For this purpose, we sealed in glass rods small pieces of steel wire, on which the dynodes are attached directly by spot-welding (Fig. 4). Of course the dynodes must be previously adjusted in a suitable

retainer. This solution satisfies mechanical as well as insulating requirements. It permitted various changes in the dynode system during the developing stage.

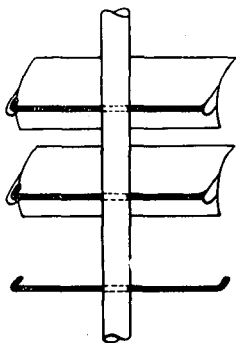


Fig. 4
Fixing of dynodes on supports

IV. Secondary emission surfaces

In choosing the dynode material we decided to use the Ag-Mg alloy (containing 2% Mg), which is very stable at heavy load. This alloy must be activated by a selective oxidation which, on its surface, produces a thin film of MgO, an excellent secondary emission substance. In this process we had to establish, with an appropriate temperature and concentration of oxidating medium, such conditions that the Mg diffuses toward the alloy surface, where the oxidation takes place. Several authors recommend the heating of the alloy in H_2O , CO_2 or O_2 atmosphere at low pressure (about 10^{-3} Tor) and temperature $450^\circ\text{--}550^\circ\text{C}$ [2] [3].

Measuring the secondary-emission coefficient σ during a staged oxidation JERİÇ [4] showed that the Ag-Mg emitter has the optimal σ at a definite thickness of the oxide layer. The maximum is sharp and σ drops quickly toward both the thinner and thicker layers. The optimal layers are very thin and far from having the so-often described yellowish colour. This discovery implied that such a thin oxide layer can already be formed during the tube-baking process; it was well known that during this period appreciable quantities of H_2O vapour and CO_2 were released from the glass envelope and other tube parts. After some experiments we succeeded and in this way obtained a satisfactory activation of previously untreated Ag-Mg dynodes. We have found that the following two conditions have to be fulfilled: the baking period has to be long enough (10—15 h), and the temperature must not be less than 360°C .

After the caesium-vapour treatment the secondary-emission coefficient of MgO improves. The thickness of the layer becomes less critical as well. It seems that the conductivity of the MgO layer becomes so much better and therefore the thicker layers are also good emitters.

V. Photocathode

Up to now the sensibilization is a barely understood problem in the manufacture of semi-transparent Cs_3Sb photocathodes. This procedure, the incorporation of minute amounts of oxygen in the Cs_3Sb layer, has been known since the Cs-Sb photocathodes

were discovered [5] [6]. Although the experimental manipulation for the production of high sensitive photocathodes are mostly well known, we do know little about the function of the oxygen in them. The oxygen-treated cathodes have a larger integral sensitivity than the unsensitized ones, because of their increased sensitivity to red light. Apart from that, we notice that the sensitized cathode is far less sensitive to excess caesium, which must in some way be bound to the oxide admixture. For this reason it is easier to manufacture these cathodes, which are, besides of their greater sensitivity, more uniform. This effect is very important for cathodes used in the scintillation counters and working in connection with different scintillators, especially in the blue part of the spectrum. The only deficiency is the fact that an excess of oxygen highly increases the thermionic emission of the cathode.

There are two ways of sensitization. The older method is in treating the cathode for a short period with oxygen at a pressure 10^{-4} to 10^{-6} Tor. In the second case, a thin oxide layer of MoO_2 , MnO , Cr_2O_3 or similar, is evaporated into the glass window, on which basis the cathode is manufactured. The caesium vapour treatment partially reduces the oxide and the Cs_2O formed, and causes the effect of sensitization in the cathode. Although this second process is very convenient, since the thermionic emission is not seriously increased, we use, in manufacturing our multipliers, the sensitization with oxygen. We have an oxygen source in the form of a resistance wire, covered with CuO and fixed in the cathode part of the tube, that results in a precise evolution of oxygen by heating the wire. In this way the sensitization can be effected without rising the thermionic emission and contaminating the dynodes with a larger amount of oxygen.

In this connection we should like to mention the presentation of the cathode sensibility. For multipliers used in scintillation counters, the sensitivity, expressed as quantum efficiency η at 400—450 m μ , is interesting. The traditional presentation in $\mu\text{A}/1\text{ m}$ units has no exact physical sense, since the relation between η and $\mu\text{A}/1\text{ m}$ units is not strictly determined. Fig. 5 gives this relationship in the form of lines, but nevertheless we may

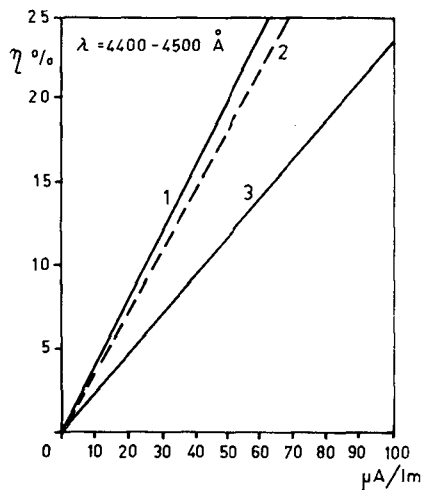


Fig. 5

Quantum efficiency vs. cathode sensitivity expressed in $\mu\text{A}/1\text{m}$ for Cs_3Sb photocathode

have deviations of at least $\pm 25\%$. Line 1 is given by GOERLICH *et al.* [7] and line 2 has been determined in our laboratory. The standards of French multiplier producers agree satisfactorily with both the above-mentioned lines, but the relationship published by the Russian author MELAMID [8] differs appreciably. We can conclude, therefore, that for a multiplier-user the only sensible presentation of cathode sensitivity is expressed as quantum efficiency.

VI. Some tube performances

Since the multiplier tube is manufactured on laboratory scale only, all the data cited below are based on an average of results after testing several dozen tubes:

overall length	150 ± 5 mm
bulb diam.	50 ± 0.5 mm
cathode diam.	40 mm
base:	standard diheptal
photocathode quantum efficiency ($\lambda = 440$ m μ)	15%
photocathode sensitivity (2800° K)	50 μ A/1 m
gain	10^6 at 1450 V
dark current (at 10^6 gain)	0.05 μ A
resolution for Cs ¹³⁷ radiation	< 9.5%

From the data cited above, we may conclude that the photomultiplier tube FM 50 in general approaches the characteristics of corresponding commercially available types of tubes, and can therefore be used for standard work in scintillation counters.

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ÉTUDE DES CARACTÉRISTIQUES LOCALES DES PHOTOMULTIPLICATEURS

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Abstract — Résumé — Аннотация — Resumen

A study of the local characteristics of photomultipliers. The authors present various devices for analysing the local characteristics of photomultipliers (changes in transit time and variations in sensitivity from the point of view of the anode or of the cathode itself).

In the Algiers Institute of Nuclear Studies a device has been built with which it is possible, by means of a spiral sweep, to scan the entire surface of a photocathode with a succession of short luminous pulses supplied by a flying-spot. A cathode-ray tube is used to translate the data (differences in transit time or anode sensitivity) into a homothetic chart of the scanning or, in the case of radial scanning, into the form of Cartesian co-ordinates. Absolute measurements of the anode sensitivity can be made correct to 5%, and of differences in transit time correct to 2×10^{-10} s.

At the Centre d'études nucléaires de Saclay, two continuous-operation instruments are in use. With one of them a photocathode can be scanned by a light-spot in a succession of diametral sweeps; the sweep is slow enough for the data (photocathode current or current from some other electrode) to be recorded on a potentiometric millivoltmeter. The second apparatus was designed to measure the continuous-current characteristics of photomultipliers; by measuring the anode current with the photocathode diaphragmed at various diameters it indicates the mean relative sensitivity of different annular zones of the photocathode.

The test results presented are mainly for the following tubes: 53 AVP, 54 AVP, 56 AVP and 58 AVP.

Étude des caractéristiques locales des photomultiplicateurs. Les auteurs présentent plusieurs dispositifs permettant l'analyse des caractéristiques locales des photomultiplicateurs (variations de temps de transit, de sensibilité vue de l'anode ou de la photocathode elle-même).

L'Institut d'études nucléaires d'Alger a réalisé un dispositif qui permet, par un balayage spiral, d'explorer par une succession d'impulsions lumineuses brèves fournies par un flying-spot toute la surface d'une photocathode. Les informations (différences de temps de transit ou sensibilités anodiques) sont traduites sur un tube cathodique sous forme de carte homothétique de l'exploration ou, pour l'exploration radiale, en coordonnées cartésiennes. La mesure absolue de la sensibilité anodique se fait à 5%, et celle des différences de temps de transit à $2 \cdot 10^{-10}$ s près.

Au Centre d'études nucléaires de Saclay, deux appareils, qui fonctionnent en continu, sont utilisés. L'un permet, par une succession de balayages diamétraux, d'explorer une photocathode avec un spot lumineux; le balayage est suffisamment lent pour que les informations (courant de photocathode ou d'une électrode quelconque) puissent être enregistrées sur un millivoltmètre potentiométrique. L'autre, qui a été conçu pour mesurer les caractéristiques en continu des photomultiplicateurs, permet entre autres, par mesure du courant anodique avec la photocathode diaphragmée à différents diamètres, de connaître la sensibilité relative moyenne de diverses zones annulaires de celle-ci.

Les résultats d'essais présentés se rapportent plus particulièrement aux tubes suivants: 53 AVP, 54 AVP, 56 AVP et 58 AVP.

Изучение локальных особенностей фотоумножителей. Авторы представляют несколько устройств, позволяющих проанализировать локальные особенности фотоумножителей (изменения времени пролета, рассматриваемая чувствительность анода или чувствительность самого фотокатода).

Институт ядерных исследований в городе Алжире создал аппарат, позволяющий методом спиральной развертки бегущим лучом при помощи непрерывного ряда коротких световых импульсов, исследовать всю поверхность фотокатода. Показания (разность времени пролета или анодные чувствительности) преобразуются в электронно-лучевой трубке в гомотетическую карту развертки или, при радиальной развертке, в виде декартовых координат. Абсолютное измерение чувствительности анода составляет 5%, а измерение разности времени пролета около 2×10^{-10} сек.

В Центре ядерных исследований в Сакле были использованы оба аппарата, которые функционируют непрерывно. Один из них позволяет при помощи последовательности диаметральной развертки исследовать фотокатод со световым пятном; развертка происходит достаточно медленно с тем, чтобы данные (ток фотокатода или любого электрода), могли быть регистрируемы на потенциометрическом милливольтметре. Другой аппарат, который был задуман для измерения непрерывных характеристик фотоумножителей, позволил с помощью анодного тока при диафрагмировании фотокатода до различных диаметров узнать относительную среднюю чувствительность различных кольцевых зон этого фотокатода.

Результаты представленных опытов распространяются в особенности на следующие трубки: 53 AVP, 54 AVP, 56 AVP и 58 AVP.

Estudio de las características locales de los fotomultiplicadores. Los autores describen varios dispositivos que permiten analizar las características locales de los fotomultiplicadores (variaciones del tiempo de tránsito, de la sensibilidad vista desde el ánodo o desde el propio fotocátodo).

El Instituto de Estudios Nucleares de Argel ha construido un dispositivo que permite, gracias a un barrido en espiral, explorar toda la superficie de un fotocátodo por una sucesión de impulsos luminosos breves emitidos por un spot móvil. Las informaciones (diferencias de tiempo de tránsito o sensibilidades anódicas) se representan en un tubo catódico bajo forma de mapa homotético de exploración o, para la exploración radial, en coordenadas cartesianas. La medición absoluta de la sensibilidad anódica se efectúa con una precisión del 5% y la de las diferencias de tiempo de tránsito, con una precisión de $2 \cdot 10^{-10}$ s.

En el Centro de Estudios Nucleares de Saclay se utilizan dos aparatos que funcionan en régimen continuo. Uno permite explorar un fotocátodo con un spot luminoso por una sucesión de barridos diametrales; el barrido es lo suficientemente lento para permitir el registro de las informaciones (intensidad de la corriente del fotocátodo o de un electrodo cualquiera) con un milivoltímetro potenciométrico. El otro, concebido para medir en régimen continuo las características de los fotomultiplicadores, permite, entre otras cosas, determinar, por medición de la corriente anódica para diferentes diámetros del diafragma del fotocátodo, la sensibilidad relativa media de las diversas zonas anulares de éste.

Los resultados de los ensayos descritos en la memoria se refieren en particular a los tubos siguientes: 53 AVP, 54 AVP, 56 AVP y 58 AVP.

Introduction

Le développement des détecteurs à scintillations s'est effectué à un rythme très rapide, et les constructeurs ont d'abord orienté principalement leurs efforts vers la satisfaction des besoins essentiels des utilisateurs. Ce stade primaire étant dépassé, on assiste maintenant à l'adaptation des scintillateurs et des photomultiplicateurs afin de satisfaire la demande pour les équipements spéciaux tels que: ensembles de comptage à faible mouvement propre, à faible bruit de fond, circuits de mesure de temps ultra-rapides, spectromètres à résolution en énergie élevée, etc.

Nous ne parlerons ici que des appareillages et méthodes de mesures permettant d'analyser l'isochronisme et l'uniformité de sensibilité de photocathode des photomultiplicateurs.

La connaissance de ces propriétés est utile à la fois à l'utilisateur pour savoir comment utiliser correctement les tubes et au constructeur pour apporter d'éventuelles améliorations aux défauts constatés. Citons trois exemples:

a) La «rapidité» d'un tube tel que le 56 ou 58 AVP est une propriété obtenue par construction. Cependant, des défauts de centrage des électrodes peuvent introduire un certain défaut d'isochronisme. Il est donc souhaitable qu'une méthode de contrôle rapide permette d'éliminer les tubes défectueux, afin d'éviter des incidents de manipulation auprès des accélérateurs de particules.

b) Les tubes couplés à des scintillateurs minces sont éclairés localement par les scintillations. Si l'homogénéité de sensibilité de la photocathode n'est pas bonne, à la dispersion en amplitude normale s'ajoutera une dispersion supplémentaire due à ce défaut, d'où des pertes de comptage et des erreurs de mesure.

c) En spectrométrie gamma, pour avoir une excellente résolution en énergie, il importe de régler le tube afin d'améliorer la statistique et également d'obtenir une collection des photoélectrons optimale.

Nous allons d'abord décrire les appareillages et méthodes d'analyse utilisés. Nous donnerons ensuite quelques résultats.

Appareillage et méthodes d'analyse

Trois appareils sont utilisés:

- a) Lampemètre pour photomultiplicateurs rapides.
- b) Appareil de mesure d'homogénéité de réponse des photocathodes.
- c) Banc de mesure des PM en continu — méthode des diaphragmes.

LAMPEMÈTRE POUR PHOTOMULTIPLICATEURS RAPIDES

Cet appareil, réalisé sous contrat C.E.A. à l'Institut d'études nucléaires d'Alger [1], permet d'analyser en impulsions les principales caractéristiques d'un photomultiplicateur. Son principe de fonctionnement est schématisé sur la figure 1.

Le faisceau d'un tube «flying spot» est défléchi en spirale et son wehnelt débloquent périodiquement par des impulsions électriques brèves, à front raide. Il en résulte une succession d'impulsions lumineuses dont une optique donne l'image sur la photocathode du photomultiplicateur analysé.

Les impulsions recueillies à l'anode sont dirigées vers deux voies:

- a) Une voie temps qui permet de transformer la différence de temps entre la voie mesure et la voie de référence en un signal d'amplitude qui lui est proportionnelle;
- b) Une voie sensibilité qui délivre des signaux mis en forme d'amplitude proportionnelle aux signaux anodiques.

Les signaux issus de ces deux voies peuvent être appliqués au wehnelt des tubes cathodiques récepteurs balayés en synchronisme avec l'analyse de la photocathode; on observe alors des cartes de sensibilité ou de retard. Les différences de sensibilité ou de retard se traduisent par des différences de brillance. Ils peuvent être aussi appliqués aux plaques verticales, le déclenchement du «flying spot» ne se faisant plus que sur un rayon que l'on peut choisir. L'exploration est radiale et l'affichage se fait en XY, permettant ainsi des mesures précises.

L'intérêt de cet appareil est de permettre d'affecter à un certain nombre de points de la photocathode une sensibilité relative précise [2], et de présenter une grande sensibilité. Par contre, à cause de sa trop grande lenteur, il n'est pas commode pour déterminer les réglages optimum d'un tube. Afin de faciliter les réglages préalables à la mesure, on a la possibilité d'éclairer en totalité la photocathode du tube par un dispositif annexe. L'exploitation des résultats pour obtenir une carte de sensibilité est assez longue. Aussi nous a-t-il semblé utile d'employer une méthode plus grossière mais plus rapide, qui se justifie parfaitement pour le test de tubes devant être couplés avec des scintillateurs de hauteur sensiblement aussi grande que le diamètre.

MÉTHODE DES DIAPHRAGMES

Elle consiste, en éclairant la photocathode avec un flux continu et uniforme, à relever les courants de photocathode ou d'anode correspondant à des diamètres éclairés différents. Par différence, on peut connaître la sensibilité relative moyenne de chaque zone annulaire ainsi définie.

L'appareil utilisé est celui qui sert habituellement dans le laboratoire pour toutes les mesures courantes en continu sur les photomultiplicateurs.

Optimalisation du fonctionnement d'un tube

Il n'est pas question pour nous de concevoir un tube répondant à certaines caractéristiques, mais, étant donné un tube, de déterminer ses réglages optima et ses performances limites.

Nous disposons des paramètres suivants.

Du point de vue *isochronisme* [3] [4], nous avons, pour les tubes «rapides» :
différence de potentiel appliquée à l'optique d'entrée:

$$V_{PK} - D_1 = V_{OE}$$

potentiels des électrodes:

$$\begin{cases} \text{focalisatrices} & V_{F_1} \text{ et } V_{F_2} \\ \text{accélératrice} & V_{ACC} \\ \text{déflectrice} & V_{DEF} \end{cases}$$

En *sensibilité locale* nous avons, pour les tubes à optique d'entrée:

$$\begin{array}{ll} \text{diode} & V_{OE} \\ \text{triode} & V_{OE} - V_{ACC} \\ \text{tétrode} & \begin{cases} V_{OE} - V_{F_1} \\ V_{DEF} \end{cases} \\ \text{pentode} & \begin{cases} V_{OE} - V_{F_1} - V_{F_2} \\ V_{DEF} \end{cases} \end{array}$$

La sensibilité locale de photocathode vue de l'anode sera la résultante d'effets se produisant à trois niveaux successifs: a) sensibilité locale de la photocathode elle-même; b) facteur de collection des photoélectrons sur la première dynode pour le point de la photocathode considéré; c) émission secondaire de la première dynode, dépendant à la fois de la zone de la dynode utilisée et de l'inclinaison des trajectoires des photoélectrons. Au-delà de la première dynode, le flux électronique est mélangé et on n'observe plus d'effets locaux intéressant pour une zone de photocathode. Les essais que nous avons faits avec la troisième dynode comme collectrice nous ont donné des résultats identiques à ceux obtenus à l'anode.

Résultats expérimentaux

1° Le lampemètre pour photomultiplicateurs est l'appareil idéal pour observer la «vie» d'un tube en fonction des réglages des potentiels des diverses électrodes.

En carte de sensibilité et de retard, on voit nettement l'effet d'iris de la focalisatrice F_1 . D'autre part, le multiplicateur des tubes rapides étant focalisant, il importe de régler la déflectrice à un potentiel tel que les photoélectrons arrivent sur la première dynode sur la zone optimale. On voit au lampemètre, lorsqu'on change le potentiel de la déflectrice, la zone sensible de la photocathode se déplacer parallèlement à l'axe des dynodes.

Lorsque les réglages des potentiels de F_1 et de la déflectrice sont dégrossis par observation des cartes de sensibilité et de retard, on passe à l'affichage en XY correspondant à l'exploration d'un rayon de la photocathode. Par exploration de tous les rayons, on peut arriver aux réglages optima du tube en sensibilité et retard. Ce sont ces résultats que nous fournissons pour un 56 AVP (fig. 2a) et un 58 AVP (fig. 2b) pour deux diamètres respectivement parallèles et perpendiculaires à l'axe des dynodes. On constate qu'une zone est moins bonne en sensibilité et retard: c'est celle pour laquelle les photoélectrons arrivent sur D_1 le plus perpendiculairement.

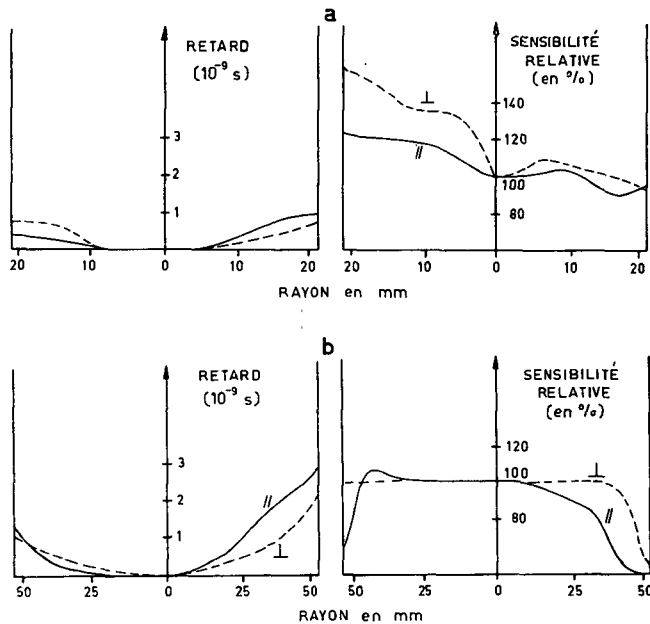


Fig. 2

Mesures faites avec le lampemètre pour photomultiplicateurs.

// Mesures parallèlement à l'axe des dynodes

— Mesures perpendiculairement à l'axe des dynodes

a) 56 AVP

THT = 1800 V

$$V_{PK/F_1} = 56 \text{ V}$$

$$V_{D_{ef}/D_1} = 32 \text{ V}$$

$$V_{OE} = 3 V_0 = 318 \text{ V}$$

b) 58 AVP

THT = 1925 V

$$V_{PK/F_1} = 150 \text{ V}$$

$$V_{D_{ef}/D_1} = 20 \text{ V}$$

$$V_{OE} = 5 V_0 = 505 \text{ V}$$

F_2 relié à D_{11}

2° Avec l'appareil de mesure d'homogénéité de réponse de photocathode, nous avons pu, ce qui était impossible avec le lampemètre, pousser l'analyse de la sensibilité locale plus loin. Nous avons pu connaître à la fois l'uniformité de réponse de la photocathode elle-même et celle observée de l'anode (ou de la troisième dynode, ce qui revient au même).

La figure 3 donne les courbes d'isosensibilité vue de PK et de l'anode pour un 58 AVP. Ces courbes sont typiques [5] et se retrouvent pour les tubes de provenance étrangère que nous avons pu essayer.

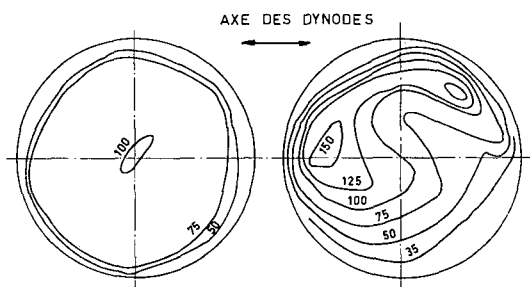


Fig. 3

Homogénéité de réponse d'un 58 AVP. *A gauche*: vue de la photocathode. *A droite*: vue de l'anode.

On en tire les indications suivantes:

a) La photocathode des tubes DARIO a une sensibilité d'une excellente uniformité. Sur des tubes 6363 et 6364 Dumont, nous avons constaté une sensibilité environ 50% plus grande sur le bord qu'au centre, sans doute afin de compenser la perte de collection des photoélectrons sur les bords de la photocathode et d'avoir vue de l'anode une uniformité de sensibilité meilleure.

b) On constate, comme plus haut, une sensibilité plus faible vue de l'anode pour la zone d'où les photoélectrons arrivent le plus perpendiculairement sur D_1 . Le remède à ce défaut serait de rendre les trajectoires des photoélectrons parallèles avant d'arriver sur D_1 .

3° Avec l'appareil de mesure d'homogénéité de photocathode, nous avons, en utilisant la méthode des diaphragmes, relevé les courbes de sensibilité moyenne vue de photocathode et de l'anode pour des tubes 53, 55 et 54 AVP en fonction des paramètres disponibles pour chacun de ces tubes.

Les figures 4, 5 et 6 donnent, en fonction du diamètre moyen de la surface annulaire éclairée, la sensibilité anodique de cette zone en % de celle au centre de la photocathode.

La figure 4 est relative à un 53 AVP pour lequel l'accélératrice est reliée à la première dynode. On constate que la collection des photoélectrons marginaux se fait de moins en moins bien plus on augmente V_{OE} .

La figure 5 correspond à un tube 55 AVP qui possède une optique d'entrée identique à celle du 53 AVP, mais avec le potentiel de l'accélératrice réglable. La courbe 2 est celle obtenue avec V_{ACC} à l'optimum du signal anodique, et la courbe 3 celle obtenue avec l'accélératrice reliée à la première dynode. On constate que l'homogénéité de la photocathode est meilleure avec l'accélératrice reliée à D_1 , mais que par contre la collection sur D_1 des photoélectrons est alors loin d'être optimum.

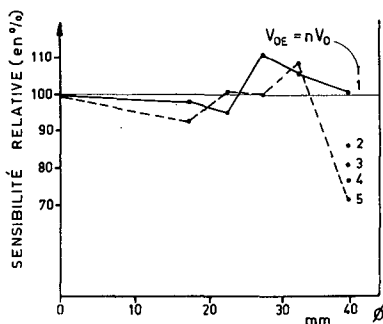


Fig. 4

Homogénéité de réponse d'un 53 AVP en fonction de $V_{0E} = n V_0$ ($V_0 = 100$ V).

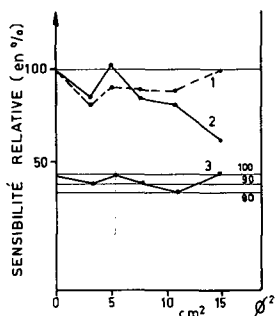


Fig. 5

Homogénéité de réponse de la photocathode d'un 55 AVP.

- 1 mesurée par le courant de photocathode
- 2 vue de l'anode (accélératrice à l'optimum)
- 3 vue de l'anode (accélératrice au potentiel de D_1)

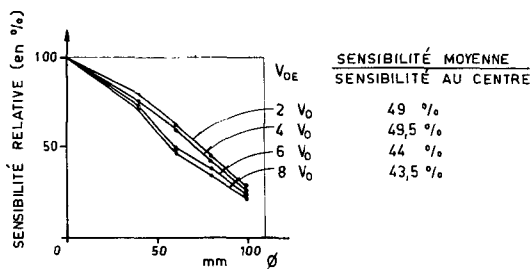


Fig. 6

Homogénéité de réponse d'un 54 AVP en fonction de V_{0E} (accélératrice réglée à l'optimum).

La figure 6 est relative à un 54 AVP [6]. Les courbes correspondent à des potentiels de l'optique d'entrée respectivement de 200, 400, 600 et 800 V, l'accélératrice étant réglée au potentiel optimum. On constate que, dans tous les cas, la collection de l'optique

d'entrée reste sensiblement constante. Il semble que la défocalisation introduite par la variation du potentiel de l'optique d'entrée soit compensée par le réglage de celui de l'accélératrice.

Influence des paramètres précédents sur la résolution en énergie obtenue avec des cristaux INa (TI)

En spectrométrie γ , si l'on teste une série de tubes de même type avec le même cristal INa (TI), on devrait trouver une résolution en énergie proportionnelle à $1/\sqrt{q}$, q étant le rendement quantique de la photocathode.

En fait, les résultats obtenus sont très dispersés. Différents facteurs peuvent varier d'un essai à un autre: transmission optique cristal-photomultiplicateur, collection de l'optique d'entrée (centrage mécanique du tube potentiel effectivement appliqué sur l'optique d'entrée), émission secondaire de D_1 , effets magnétiques parasites internes.

Si l'on suppose gaussienne la distribution des amplitudes dans le pic photoélectrique on a:

$$R \% = 2,36 \sigma$$

R étant la résolution en énergie en % et σ l'écart quadratique moyen, avec:

$$\sigma^2 = \frac{1}{N} + \frac{1}{Nqk} + \frac{1}{Nqkg}$$

N étant le nombre moyen de photons arrivant par impulsion sur la photocathode, q le rendement quantique de photocathode, k le facteur de collection de l'optique d'entrée et g le gain de la première dynode.

La figure 7 donne l'influence de ces paramètres sur la résolution en énergie en supposant que, pour la raie 662 KeV du caesium-137, 8000 photons arrivaient sur la photocathode par scintillation. L'examen de ce graphique montre que l'on a intérêt à avoir une photocathode de rendement excellent, et une collection des photoélectrons élevée. Le premier point est bien satisfait actuellement, mais le second laisse encore souvent à désirer. L'utilisation de photomultiplicateurs en spectrométrie nécessite une optique d'entrée

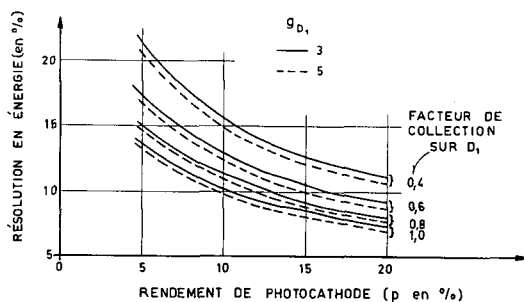


Fig. 7

Résolution en énergie pour $E = 662 \text{ keV}$ en fonction de divers facteurs.

g_{D_1} : — 3 --- 5

triode qui permet, en augmentant la différence de potentiel appliquée à l'optique d'entrée, d'améliorer la résolution par augmentation de l'émission secondaire de D_1 , tout en optimisant la focalisation en agissant sur le potentiel de l'accélératrice (fig. 8).

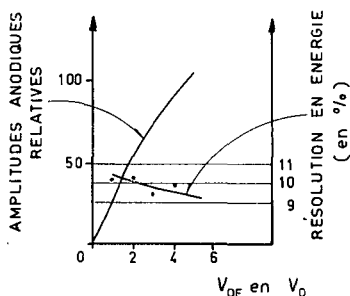


Fig. 8

Résolution en énergie pour un 54 AVP en fonction de V_{OE} .

Conclusion

L'analyse des caractéristiques locales des photomultiplicateurs est riche en renseignements. Elle permet de mettre en évidence, mieux que par des essais globaux, les conditions optima de leur utilisation correcte. Elle est indispensable pour le constructeur désirant orienter en connaissance de cause l'amélioration de ses productions.

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III.

IONIZATION, GASEOUS AND LIQUID DETECTORS

(SESSION 3)

EXPÉRIMENTATION D'UNE CHAMBRE A ÉTINCELLES

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Abstract — Résumé — Аннотация — Resumen

Experiments with a spark chamber. The authors constructed an experimental spark chamber with a useable volume of $7 \times 7 \times 5$ cm having six parallel 2-mm thick stainless steel plates. The distance between each plate is 8 mm. The chamber is filled with neon under a pressure of one atmosphere.

On applying a pulse of about 10 keV on the plates immediately after the passage of a charged particle through the chamber, sparks form along the trajectory of the particle and may easily be photographed.

The chamber was first used with cosmic ray μ mesons and then put into the π -meson beam of the SATURN synchrocyclotron. The efficiency of the chamber as a function of voltage and retardation of the applied electric pulse and the dead time are given.

The first results obtained with a chamber of 10-litre volume are also presented.

Expérimentation d'une chambre à étincelles. Les auteurs ont construit une chambre à étincelles expérimentale de $7 \times 7 \times 5$ cm de volume utile comportant six plateaux parallèles de 2 mm d'épaisseur en acier inoxydable. L'intervalle entre deux plateaux est de 8 mm. La chambre est remplie de néon sous une pression de 1 atmosphère.

Si l'on applique, immédiatement après le passage d'une particule chargée dans la chambre, une impulsion de 10 kV environ sur ses plateaux, des étincelles apparaissent le long de la trajectoire de la particule et peuvent aisément être photographiées.

La chambre a été expérimentée tout d'abord avec les mésons μ provenant du rayonnement cosmique, puis mise dans un faisceau de mésons π du synchrocyclotron SATURNE. L'efficacité de la chambre en fonction de la tension et du retard de l'impulsion électrique appliquée et le temps mort de la chambre sont donnés.

Les auteurs présentent en outre les premiers résultats obtenus avec une chambre d'un volume de 10 l.

Испытания искровой камеры. Авторы сконструировали экспериментальную искровую камеру с полезным объемом в $7 \times 7 \times 5$ см, имеющую 6 параллельных дисков толщиной 2 мм из нержавеющей стали. Промежутки между дисками равняются 8 мм. Камера заполнена неоном под давлением, равным одной атмосфере.

Если непосредственно вслед за прохождением заряженной частицы в камере направить импульс мощностью около 10 KV на эти диски, то вдоль траектории частицы появятся искры, которые можно легко сфотографировать.

Вначале эта камера опробовалась с мю-мезонами космических лучей, а затем была введена в пучок мезонов синхроциклотрона САТУРН. В работе приводятся эффективность камеры в зависимости от напряжения и запаздывания применяющегося электрического импульса, а также мертвое время камеры.

Кроме того, авторы представляют первые результаты полученные с помощью камеры объемом в 10 литров.

Ensayos efectuados con una cámara de chispas. Los autores han construido una cámara de chispas experimental de $7 \times 7 \times 5$ cm de volumen útil que lleva seis placas paralelas de acero inoxidable de 2 mm de espesor. El espacio entre dos placas es de 8 mm. La cámara está rellena con neón a la presión de 1 atmósfera.

Si se aplica un impulso de unos 10 kV a las placas inmediatamente después de que una partícula cargada haya atravesado la cámara, aparecen chispas a lo largo de su trayectoria, que puede ser fotografiada fácilmente.

Los autores ensayaron primero la cámara con mesones μ de origen cósmico y a continuación la introdujeron en el haz de mesones π del sincrociclotrón SATURNO. Indican la eficacia de la cámara en función de la tensión, del retardo del impulso eléctrico aplicado, así como el tiempo muerto de la cámara.

Los autores presentan también los primeros resultados obtenidos con una cámara de 10 l de volumen.

Avantages de la chambre à étincelles

Depuis l'été 1960 un nouveau détecteur de particules ionisantes de haute énergie, la chambre à étincelles, est apparu autour des grands accélérateurs, notamment à BERKELEY [1] [2]. Plusieurs auteurs avaient déjà signalé la possibilité de visualiser la trajectoire d'une particule ionisante dans une chambre à étincelles [3] [4].

Le principe de fonctionnement de ce détecteur (impulsion brève de haute tension appliquée entre des plateaux parallèles immédiatement après le passage de la particule dans la chambre) nous rappelle celui de la chambre de Wilson, mais la chambre à étincelles présente sur cette dernière un avantage considérable: sa «rapidité» (temps de sensibilité et temps mort pouvant être inférieurs respectivement à la microseconde et à la milliseconde).

Par rapport à la chambre à bulles nous gagnons un facteur 1000 en «rapidité», avec en plus l'avantage de pouvoir déclencher la chambre sur l'évènement intéressant.

Essais d'une chambre de 0,25 l

DESCRIPTION

La chambre que nous avons construite (fig. 1) comporte six plateaux de 2 mm d'épaisseur et 50 cm² de surface utile en acier inoxydable, polis mécaniquement et

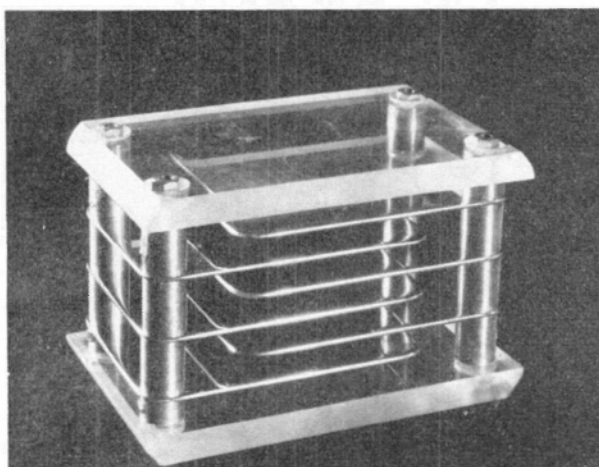


Fig. 1
Chambre à étincelles.

espacés de 8 mm. Ils sont alternativement réunis trois par trois par des entretoises en laiton qui assurent le contact électrique et le soutien mécanique. La chambre est placée dans une enceinte en «pyrex» remplie de néon à la pression atmosphérique.

ELECTRONIQUE DE DÉCLENCHEMENT

L'impulsion de haute tension est fournie par une capacité de 1000 pF portée à 10 kV environ, qui se décharge dans une résistance de 100 Ω mise en parallèle sur les plateaux de la chambre (fig. 2). La décharge est commandée par un thyatron à hydrogène 5C22. L'ensemble thyatron-capacité est monté dans une enveloppe coaxiale mise à la masse. La grille du thyatron est commandée par un trigger déclenché lui-même par deux photomultiplicateurs 56 AVP en coïncidence, mis de part et d'autre de la chambre. Le trigger est constitué par une EFP 60 dont l'anode est portée à 1000 V et dont la dynode délivre dans une impédance de 5000 Ω une impulsion positive de 300 V montant en 20 ns [5].

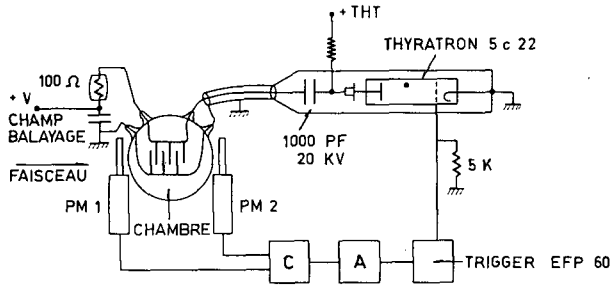


Fig. 2

Electronique de la chambre à étincelles.

RÉSULTATS

Les photos que nous montrons (fig. 3 et 4) ont été obtenues dans un faisceau parasite de mésons π^- du synchrotron SATURNE. Lorsque la trajectoire des particules fait un angle inférieur à 30° par rapport à la direction perpendiculaire aux plateaux, les étincelles ont tendance à suivre cette trajectoire. La largeur des étincelles étant de 1 mm environ, nous pouvons espérer dans une grande chambre une précision angulaire pour les faibles angles de l'ordre de 1° .

Pour les angles de trajectoire supérieurs à 40° , les étincelles éclatent perpendiculairement aux plateaux, et de ce fait la précision angulaire devient plus mauvaise.

Projet d'une chambre pour le rayonnement cosmique primaire

Nous décrivons maintenant une chambre qui est en construction dans notre laboratoire. Elle est destinée à une expérience en ballon à haute altitude (supérieure à 30 km) en vue de préciser la composition du rayonnement cosmique primaire et notamment le flux d'électrons et de photons gamma primaires atteignant les hautes couches de l'atmosphère. Cette expérience est entreprise en collaboration avec G. P. S. Occhialini et le Laboratoire de l'université de Milan.

La chambre se composera d'une dizaine de plateaux en plomb de 2,5 mm d'épaisseur et 100 cm² de surface utile, espacés de 6 mm.



Fig. 3

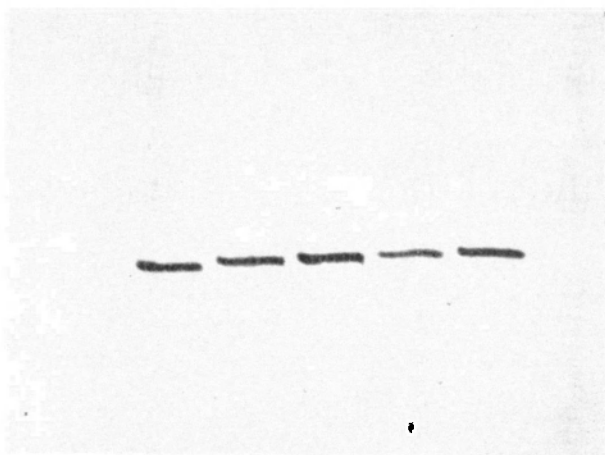


Fig. 4

La chambre ne sera déclenchée que lorsqu'une cascade sera créée à l'intérieur d'un des plateaux par un proton, un électron ou un photon gamma, l'électronique associée devant supprimer les particules lourdes et les particules alpha.

La distinction entre les cascades dues aux électrons et aux photons gamma et celles dues aux protons se fera d'une manière statistique, compte tenu de la différence entre les libres parcours moyens de production de cascade par les électrons et les gamma d'une part, et les protons d'autre part.

L'avantage d'une chambre à étincelles par rapport à la chambre de Wilson dans ce type d'expérience tient à la possibilité, d'abord de réduire considérablement le poids

et l'encombrement de l'appareillage (nous pensons ne pas dépasser dans cette expérience un poids total d'une vingtaine de kilogrammes, et ensuite, le temps mort de la chambre étant relativement très court (de l'ordre de 1 ms), d'augmenter le nombre de photos prises et par suite d'améliorer la statistique.

Etude pour une chambre de grandes dimensions

Enfin, nous avons fait, à partir d'un modèle réduit à l'échelle 1/5, une étude des caractéristiques électriques d'une chambre de grandes dimensions (quarante plateaux de 1000 cm^2 de surface utile, espacés de 8 mm) en assimilant la chambre à une ligne à constantes de temps distribuées. L'impédance caractéristique trouvée est de l'ordre de 10Ω , et le temps de propagation de l'impulsion le long de la chambre de $3 \cdot 10^{-7} \text{ s}$. Cette dernière valeur nous montre qu'il y a une certaine limitation dans le nombre de plateaux d'une chambre de grandes dimensions si l'on désire garder une efficacité voisine de 100 % dans les derniers intervalles.

Conclusion

Actuellement, le programme de notre laboratoire est d'abord la construction de la chambre destinée à l'étude du rayonnement cosmique primaire en haute altitude, ainsi que le test de cette chambre avec des rayons gamma et des électrons issus d'un faisceau de mesons π^- du synchrotron SATURNE; ensuite, une étude du remplissage (nature et pression du gaz, espacement des plateaux) afin d'augmenter la finesse des étincelles et de diminuer le temps mort de la chambre; enfin, nous envisageons la construction d'une chambre de grandes dimensions.

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A SPARK-CHAMBER SPECTROMETER

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Abstract — Résumé — Аннотация — Resumen

A spark-chamber spectrometer. A programme of developing techniques for the construction and use of spark chambers in high-energy physics experiments has been undertaken. Several methods of construction have been tested and found satisfactory.

One method is to cement aluminium plates to frames made from glass or Plexiglas strips. Another is to place the aluminium plates in grooves machined in Plexiglas, forming a "shelf" design. A chamber made of rows of wires was successfully operated with a He-alcohol mixture. These chambers can either be filled with gas and sealed, or gas can be passed through them continuously.

Chambers have been constructed with plates of various thicknesses ranging from 0.032 in downwards. The operation of the chambers with various spacings between the plates was also investigated.

The performance of these chambers, when filled with several different gases (Ne, He, A) and with gas-alcohol mixtures, has been investigated. Several methods of applying high-voltage pulses to the chambers have been attempted. The results of these investigations are presented.

Spark chambers placed in a magnetic field can be used in principle to determine the momentum of charged particles and if lead converter-plates are incorporated with them, the resulting system should serve as a gamma-ray spectrometer of high resolution and high efficiency. A magnet with an 18-in useful diameter and a 13000-G field is being fitted with spark chambers, whose performance will be tested with cosmic rays and with an accelerator beam. Results from such tests are presented.

Spectrographe avec chambre à étincelles. L'exécution d'un programme de construction de chambres à étincelles et d'utilisation de ces appareils pour l'étude de la physique des hautes énergies vient d'être entreprise. Plusieurs procédés de construction ont été essayés; ils ont donné des résultats satisfaisants.

L'un d'entre eux consiste à sceller des plaques d'aluminium dans des cadres en lames de verre ou de plexiglas; une autre à glisser les plaques d'aluminium dans les rainures d'une plaque de plexiglas, de manière que le montage ressemble à une étagère. Un autre type de chambre, composé de rangées de fils, a donné d'excellents résultats avec un mélange d'hélium et d'alcool. Ces chambres peuvent être remplies de gaz puis scellées ou être traversées par un courant gazeux continu.

Des chambres ont été construites avec des plaques de diverses épaisseurs, le maximum employé étant 0,032 pouce. L'influence de l'écartement des plaques sur le fonctionnement des chambres a également été étudié pendant les essais.

L'étude a également porté sur le comportement des chambres après remplissage avec des gaz différents (Ne, He, A) ou des mélanges de gaz et d'alcool. Plusieurs méthodes permettant d'appliquer des impulsions de haute tension à ces chambres ont été expérimentées; l'exposé traitera des résultats obtenus.

Des chambres à étincelles placées dans un champ magnétique peuvent, en principe, être utilisées pour déterminer la quantité de mouvement des particules chargées; lorsqu'on y incorpore des plaques en plomb, le dispositif ainsi obtenu constituera un spectrographe gamma ayant un grand pouvoir de résolution et un rendement élevé. Les auteurs ont construit un dispositif se composant d'un aimant-diamètre utile, 18 pouces; champ, 13000 gauss — et des chambres à étincelles; son comportement est étudié sous l'action des rayons cosmiques et du faisceau d'un accélérateur. Le mémoire présente les résultats de ces expériences.

Спектрометр с искровой камерой. Была предпринята программа разработки методов конструкции и использования искровых камер при физических экспериментах большой энергии. Были испытаны и найдены удовлетворительными несколько методов конструкции.

Один из методов заключается в прикреплении алюминиевых плит к рамкам, сделанным из полос стекла или плексигласа. Другой метод состоит в помещении алюминиевых пластин в прорезанные в плексигласе желобки, образующие конструкцию в виде „этажерки“. С успехом была использована камера, состоящая из рядов проводов и наполненная смесью гелия со спиртом. Эти камеры либо могут быть наполнены газом и герметически закрыты, либо газ может пропускаться через них непрерывно.

Эти камеры были выполнены с плитами различной толщины от 0,032 дюйма и меньше. Была исследована также работа этих камер с различными расстояниями между плитами.

Была исследована работа этих камер при наполнении их различными газами (Ne, He, A) и смесями газов со спиртом. Было испробовано несколько методов передачи импульсов высокого напряжения в эти камеры. Сообщаются результаты этих исследований.

В принципе, помещенные в магнитном поле искровые камеры, могут быть использованы для определения количества движения заряженных частиц, а в случае снабжения этих камер свинцовыми пластинами преобразователя, получающаяся таким образом система может служить в качестве спектрометра гамма-лучей, обладающего большой разрешающей способностью и большой эффективностью. Такими искровыми камерами снабжается электромагнит с полезным диаметром в 18 дюймов и с полем в 13000 гауссов; его действие будет испробовано при работе с космическими лучами и с пучком лучей из ускорителя. Будут сообщены результаты таких испытаний.

Espectrómetro de cámara de chispa. Los autores han iniciado un programa de trabajo para mejorar la construcción de cámaras de chispa y estudiar la manera de emplearlas en experimentos de física de altas energías. Varios de los procedimientos de construcción ensayados dieron resultados satisfactorios.

Uno de estos procedimientos consiste en cementar placas de aluminio en bastidores hechos con listones de vidrio o de plexiglás. Según otro, las placas de aluminio encajan en ranuras hechas en el plexiglás, dando un diseño en «estante». Una cámara construida con series de alambres paralelos funcionó perfectamente con una mezcla de He-alcohol. Estas cámaras pueden ir rellenas de gas y cerradas herméticamente, o bien el gas puede circular a través de ellas en forma continua.

Han construido cámaras con placas de diversos espesores hasta un máximo de 0,032 pulgadas (0,008 cm). Asimismo, han estudiado el funcionamiento de esas cámaras con distintos espaciados entre las placas.

Se ha estudiado el funcionamiento de estas cámaras con diferentes gases (Ne, He, A) y mezclas de gas y alcohol. Se han ensayado varios métodos para aplicar a las cámaras impulsos de alta tensión. La memoria describe los resultados de estas investigaciones.

En principio, una cámara de chispas colocada en un campo magnético puede servir para determinar la cantidad de movimiento de partículas cargadas y si se les añaden placas convertidoras de plomo, el sistema resultante debería servir como espectrómetro de rayos gamma, de elevado poder de resolución y alta eficacia.

Se han acoplado cámaras de chispas a un imán de 18 pulgadas (45,7 cm) de diámetro útil y 13000 gauss, y se las ha ensayado con rayos cósmicos y con el haz de un acelerador. En su disertación, los autores presentan los resultados obtenidos.

I. Introduction

The idea of using parallel-plate electrodes with a high potential between them as a detector of charged particles dates back many years [1]. It was fairly recently, however, that the possibility of using arrays of parallel plates as a visual detector for high-energy

particles was realized. The basic idea is that the particle in passing through such an array leaves behind it a trail of ions and if a high-voltage pulse is applied to alternate plates soon after the passage of the particle (the other plates being grounded), electrical breakdowns will take place between adjacent plates. These sparks will tend to follow the path of the particle, so that a record of this path can be made either by photographing the sparks or by using some electrical device to record the positions of the sparks on the plates. The chamber is generally provided with a clearing field, which improves its time resolution by sweeping out the ions.

Many workers in high-energy physics have investigated the properties of these devices, which are generally referred to as spark chambers. A summary of the results of many of these studies is contained in the proceedings of the Symposium on Spark Chambers, which was held at Argonne National Laboratory on 7 February, 1961 [2].

We have recently begun a programme of developing techniques for the construction of spark chambers and of studying their properties. Our work has been aimed particularly toward using the chambers in a magnetic field as a momentum-analysing device, i.e., a spectrometer. The present state of this programme is described in this paper; further work is in progress.

II. Methods of construction

We have found several satisfactory methods of constructing plate-type spark chambers [2]. One method involves cementing together strips of Plexiglas to form a rectangular frame as the first step. A typical dimension of a strip is $1/2 \times 1/4 \times 17$ in long. The cement used is PS-18 (Cadillac Plastic and Chemical Co., Detroit, Michigan). The chamber is then made by cementing aluminium plates $1/32$ in thick between these frames. The edges of the plates are recessed $1/8$ in from the edge of the frames, and a bead of cement is placed in the "valley" which is formed. A step milled on the outside edge of the frame serves to increase the width of this valley. The bonding agent used is Biggs 363 (Carl G. Biggs Co., Santa Monica, California).

Another method of construction, which does not require cementing, involves a "shelf-type" design. Grooves slightly wider than the thickness of the aluminium plates to be used are milled $1/4$ in apart in four pieces of Plexiglas, 1 in thick. Three of these pieces are fastened together to form three sides of a box, the aluminium plates are slid in and the fourth side is placed on, completing the box. Nylon screws are used to hold the chamber together. The top and bottom of the chamber are made, for example, of $1/2$ -in aluminium plates which are sealed by "O" rings. The electrical connections are made with stainless-steel wire pressing against the edges of the plates in the grooves; the wires are taken out of the chamber through Stupakoff seals in the walls. The void space in the grooves is filled with silicone grease to prevent sparking at the edges of the plates. A photograph of a chamber of this type is shown in Fig. 1.

A shelf-type chamber which will use thin aluminium plates (about 0.003 in thick) is now under construction. The plates are formed by etching thick aluminium plates until they reach the desired thickness. A narrow band near the edges of the plates is masked with tape during the etching, so that it is not affected. This band then serves as a supporting frame for the thin etched portion of the plates.

An unconventional type of spark chamber can be made by using rods or wires rather than plates. This was suggested to us by MANN [3]. In this design, alternate wires along the x and y directions receive the high-voltage pulse. This means that the nearest neighbours of a wire are at an opposite potential, so that the spark may travel parallel

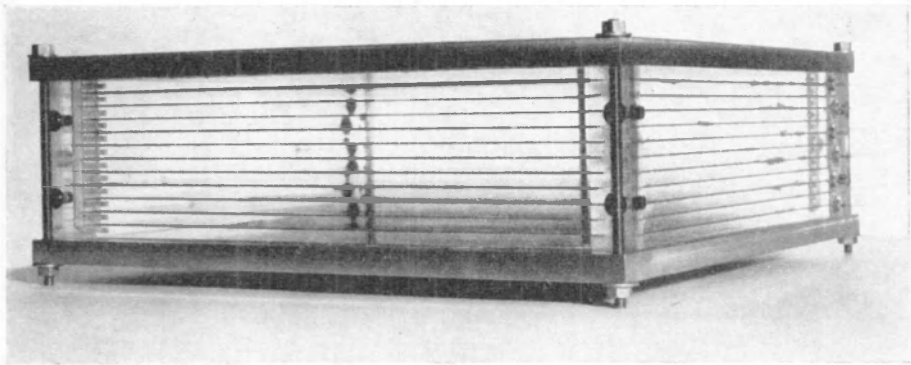


Fig. 1

Photograph of a "shelf-type" spark chamber

to either the x or y axis. Such a chamber should have an advantage over a plate chamber in recording the curved trajectory of a particle in a magnetic field, particularly for that case in which the particle would be travelling in a direction nearly parallel to the plates. One such chamber has been constructed using rods $1/16$ in in diam. embedded in the Plexiglas walls of the chamber. A photograph of this chamber is shown in Fig. 2. Fig. 3 shows a photograph of two views of the track of a cosmic ray seen in the chamber. Other designs of chambers of this type are now being built and tested.

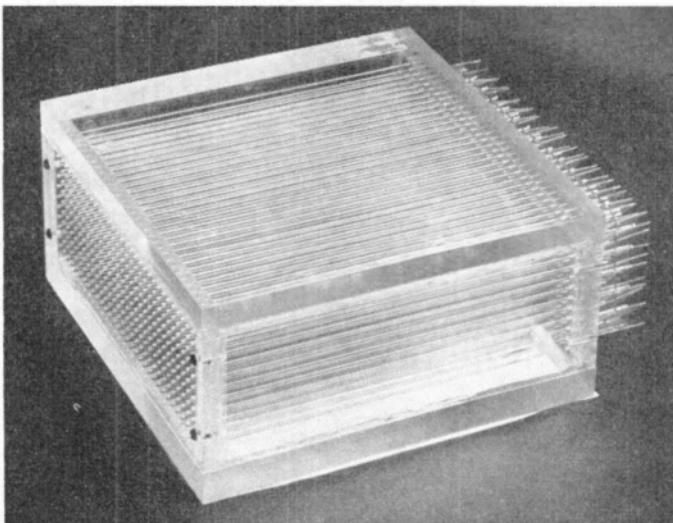


Fig. 2

Photograph of a rod-type spark chamber

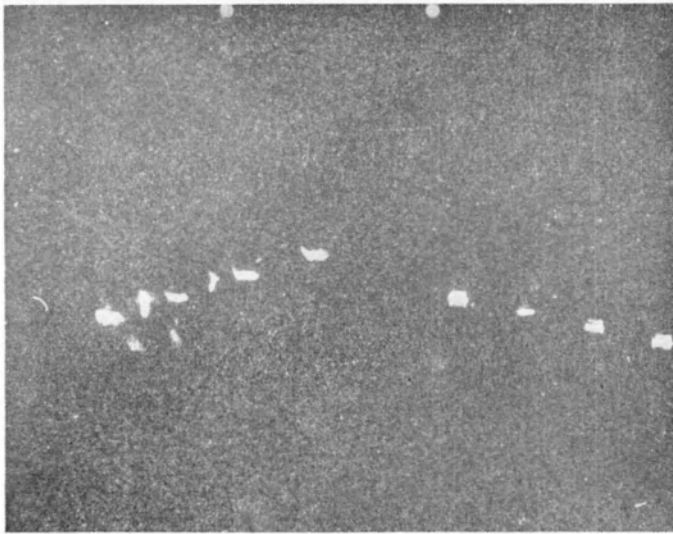


Fig. 3

Photograph of the track of a cosmic ray seen in the chamber shown in Fig. 2

III. Operation of the chamber

Fig. 4 shows a block diagram of the electronic system used in an investigation of the performance of these chambers. Cosmic rays, detected by two plastic scintillation counters placed above and below the chamber, were used in these tests.

A fast pulse from the coincidence circuit is sent to a trigger circuit which provides pulses to a camera-advance circuit, a scaler and a high-voltage pulser. Each alternate plate in the spark chamber is connected to a 1500-pF condenser and to ground through a $500\ \Omega$ resistor. When a cosmic ray is detected by the scintillation counters, a negative high-voltage pulse is applied to these plates. The rise-time of the pulse is about 25 ns ($1\text{ ns} = 10^{-9}\text{ s}$). There is a 300-ns delay between the pulse and the detected particle. The remaining plates are connected in parallel to a DC voltage which could be varied from -600 to $+600\text{ V}$ to provide a clearing field.

The schematic diagram of the high-voltage pulser is shown in Fig. 5. The pulser consists of an EFP60 tube which triggers a 5C22 hydrogen thyatron (Penta Laboratories Inc., Santa Barbara, California). In order to decrease the inherent delay in the firing of the 5C22, a positive bias of 35 V is applied to the grid of the thyatron. With such a bias, the overall delay between the input pulse to the EFP60 and the high-voltage pulse on the plate of the 5C22 is 120 ns. The pulser is constructed inside an aluminium tube 2 in long and 5 in in diam. Such a design provides an electrostatic shielding and makes it possible for the pulser to be placed near the spark chamber, so that the length of the high-voltage pulse leads can be reduced.

The chambers have been filled with helium, argon, and helium-argon mixtures by flowing the gas continuously through the chamber. Ethyl alcohol vapour has also been added by bubbling a portion of the gas entering the chamber through liquid alcohol.

To date, only qualitative observations have been made, but we plan to begin making quantitative measurements of the efficiency of the chamber with various gas mixtures soon. In general, a small quantity of alcohol tends to increase the efficiency of the chamber and to decrease the number of spurious discharges. This effect is particularly noticeable in the wire chamber, which will not operate satisfactorily without alcohol. A large amount of alcohol, however, causes a pronounced drop in the efficiency of the chamber.

In testing the operation of these chambers, photographic as well as visual methods of observation were used. One set of photographs was taken in colour with High Speed Ektachrome Film (Eastman Kodak Co., Rochester, New York). The gas mixture used was roughly one part helium, two parts argon, and a small amount of alcohol. One striking feature seen in the photographs was a tendency for the sparks to be either blue or pink in colour; frequently a single spark was found to be blue in one region and pink in another. We also noticed that very faint sparks seem to stand out more clearly in colour photographs than in black-and-white ones.

IV. Operation of the chambers in a magnetic field

Spark chambers operated in a magnetic field should in principle serve as a device for measuring the momentum of charged particles. In addition, if lead converter-plates are inserted parallel to the plates at certain fixed intervals along the chamber, the resulting system should serve as a detector of high-energy gamma rays. Thus a spark chamber can be made to resemble either a bubble chamber or a pair-spectrometer. It should have advantages over a bubble chamber in that it has a much shorter resolving

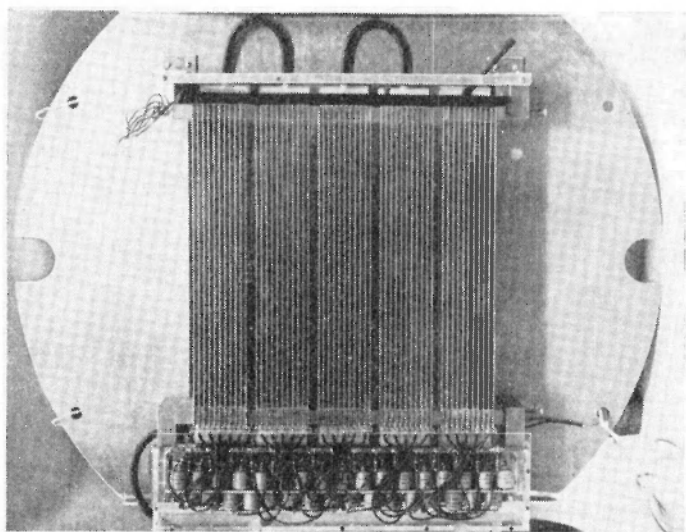


Fig. 6

Photograph of the spark-chamber assembly removed from the magnet. The chambers are of the cemented type. On the bottom is a bank of $1500\ \mu\text{F}$ condensers, each of which is connected to one of a set of alternate plates of the chamber

time and can be triggered only for the event one wishes to observe. It should also have better energy resolution than a pair-spectrometer and it can probably be made to have higher efficiency.

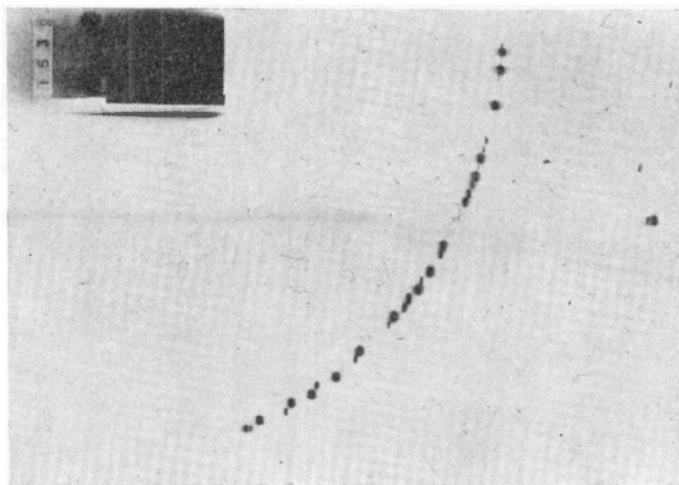
We have set up an array of spark chambers in a magnetic field and have begun a series of tests of the system, using cosmic rays. The magnet was formerly used with a diffusion cloud chamber at the University of Chicago [4]. It has a circular pole about 20 in in diam. and a maximum field of about 13000 G. The gap between the coils is about 4 in wide.

Five cemented-type spark chambers are used, each having eleven plates spaced $1/4$ in apart with a sensitive area of $15\frac{1}{2} \times 3\frac{1}{4}$ in. The chambers are spaced $1/2$ in apart. Fig. 6 shows a photograph of the assembly taken before it was placed in the magnet.

Scintillation counters $4 \times 17 \times 1/2$ in placed above and below the spark-chamber array, provide a cosmic-ray trigger and photographs are taken of the events through a large conical hole in the upper pole of the magnet. To date, only non-stereo photographs have been taken of the events.

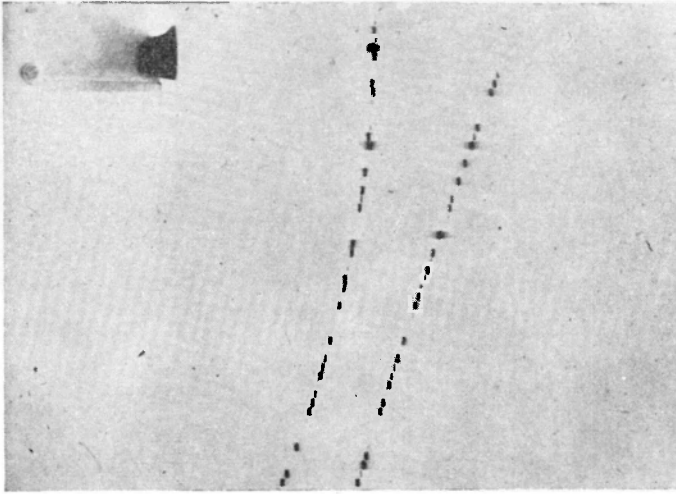
For a field of 13000 G, a sagitta equal to one-gap spacing corresponds to a particle momentum of about 1.2 GeV/c; such a sagitta can easily be measured. The track of a particle with a momentum of 120 MeV/c is shown in Fig. 7a. Fig. 7b shows the track of two particles of opposite charge, one with momentum smaller than the other; they apparently originate from a single vertex at top of the chamber. In many photographs, tracks of a delta ray can be seen. One such event is shown in Fig. 7c.

We have made studies of the effect of a clearing field on the efficiency of these chambers, both with and without a magnetic field. These studies were made for various time delays between the photomultiplier-tube pulse and the application of the high-

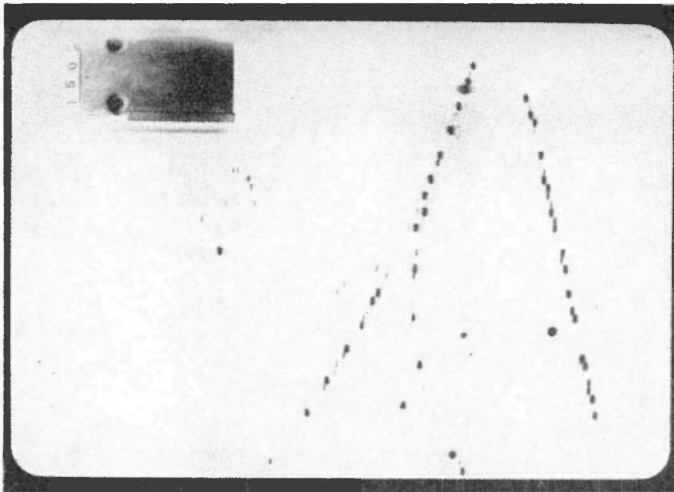


(a)

The track of a particle with momentum 120 MeV/c



(b)
Tracks of particles of opposite charge



(c)
Track of a particle accompanied by a delta ray

Fig. 7

Cosmic ray events photographed in the spark-chamber assembly of Fig. 6 in a magnetic field of 13 000 G.

voltage pulse. The minimum delay due to the electronics was $0.265\ \mu\text{s}$. Both positive and negative DC voltages ranging up to 600 V were applied to alternate plates to supply the clearing field. The high-voltage pulse was $-12000\ \text{V}$ and it was applied to the remaining plates. Thus a negative DC voltage corresponds to a clearing field opposite in sign to the pulsed field. For these studies, helium gas with a controlled amount of alcohol was used as the atmosphere of the chambers.

For each set of conditions, about 100 photographs were taken. These were scanned for both "track efficiency" and "gap efficiency". "Track efficiency" is defined as the ratio of the number of pictures found with recognizable tracks (which is taken to mean a minimum of 6 sparks in a line passing through at least two chambers) to the total number of pictures taken that had any sparks at all in them. The "gap efficiency" was measured for the centre chamber only; it is the ratio of the number of sparks found in the pictures with recognizable tracks to the total number of sparks that would have been found if all gaps in the centre chamber had fired each time.

We believe the track-efficiency results to be particularly significant, since they are in a sense a measurement of the ability of the clearing field to wipe out a particle track as a whole, rather than only parts of it. The criterion of observation used is that of the ability of a human scanner to reconstruct a track, which is the same one used in scanning photographs of events taken in an experiment.

The results of the studies of track efficiency are shown in Figs. 8 and 9; the results of the gap-efficiency measurements are qualitatively the same. The track efficiency for the zero-clearing field and the minimum delay were found to be about 83%. It should be less than 100%, since the area of the scintillation detectors triggering the chamber was greater than the useful area of the chambers, so that some triggers would correspond to cosmic rays that did not pass through the sensitive part of the chamber.

The general behaviour of both sets of curves is the same, the main difference being that the clearing times are somewhat shorter if there is no magnetic field present. In

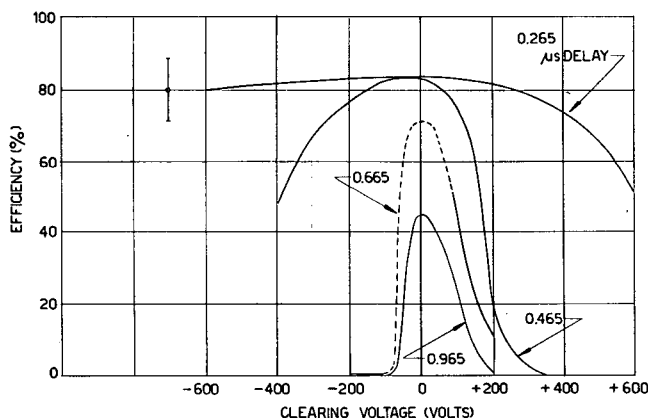


Fig. 8

Plots of the track efficiency of the spark chambers of Fig. 6 as a function of clearing voltage for various pulse delay times in a zero magnetic field

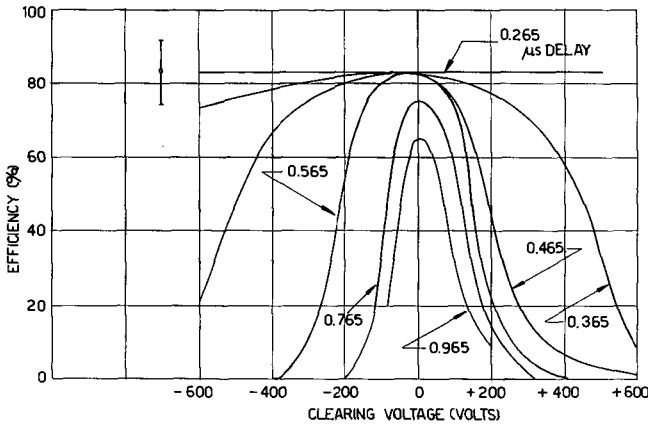


Fig. 9

Plots of the track efficiency of the spark chambers of Fig. 6 as a function of clearing voltage for various pulse delay times in a magnetic field of 13000 G

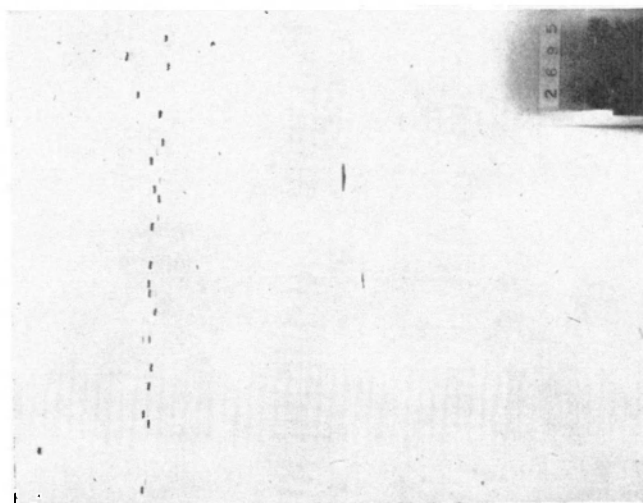
both sets of curves a tendency is seen for the efficiency to drop fairly uniformly with increasing delay time for a clearing field in the same direction as the pulsed field. For a clearing field opposite to the pulsed field, however, the efficiency tends to drop slowly at first, but then more sharply, with increasing delay time.

For two runs (0.265 μ s delay, 0 V and -600 V), the photographs were scanned to look for a tendency for any gap in the centre chamber to fire more or less frequently than any of the other gaps. In each case it was found that within statistical error the same number of sparks was found in each gap, so that no such effect was found. This leads us to believe that all gaps are electrically and mechanically identical.

The clearing fields had a very marked effect on the appearance of the tracks. In general, the sparks in alternate gaps were displaced in opposite directions and the width of the sparks was increased. Both of these effects are due to the cycloidal motion of electrons in crossed electric and magnetic fields. The direction of both the displacement and the widening of the spark is $-\mathbf{E} \times \mathbf{B}$, where $\mathbf{E}$ is the clearing field. For a clearing voltage of -300 V, the displacement between successive sparks ranged up to $1/8$ in, and for -600 V up to $3/16$ in. For positive voltages, the displacements were slightly greater.

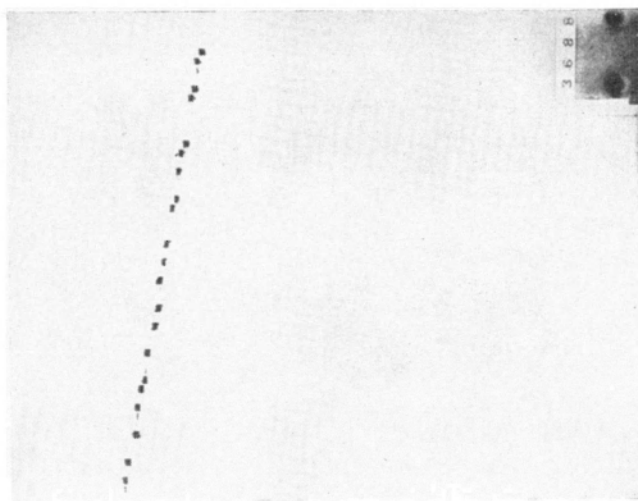
There was a striking difference in the appearance of the sparks with the two signs of clearing voltages. A positive voltage gave sparks of not greatly increased width, but they were frequently accompanied by a "curtain" of discharge on both sides of them. This effect can be seen in Fig. 10a. A negative voltage, however, did not give such a curtain but tended to produce wide sparks of uniform intensity, as is shown in Fig. 10b. For a negative voltage, the width of the sparks ranged up to $1/8$ in for -300 V and up to $3/16$ in for -600 V. For a positive voltage the width of the curtain ranged up to $1/8$ in for 300 V and up to $3/4$ in for 600 V.

This alternation of sparks was also found occasionally under conditions of no clearing field but a long time-delay. An example of this is shown in Fig. 10c.



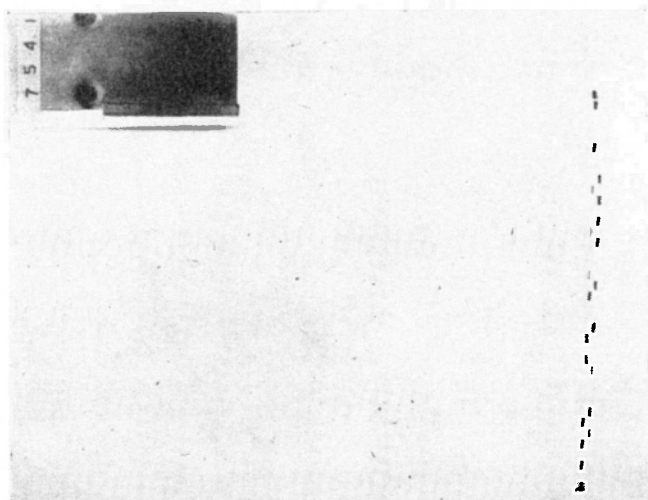
(a)

+ 600 V clearing voltage; 0.265 μ s pulse delay



(b)

— 600 V clearing voltage, 0.265 μ s pu delay



(c)

0 clearing voltage, 0.565 μ s pulse delay

Fig. 10

Cosmic-ray tracks photographed in the spark-chamber assembly of Fig. 6 in a magnetic field of 13000 G

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DISCUSSION

C. Franzinetti (Italy): Could Professor Roberts tell us what was the maximum detectable momentum for the magnetic field he was using in the last chamber he showed?

A. Roberts (United States of America): The measurable momentum is given by the sagitta. The sparks in the track appear to have a width between 0.5 and 1 mm and a sagitta of 1 mm or more will determine the sign of the particles. With a sagitta of 2 mm we think we can give the momentum to within 50%. Consequently with a magnetic field of 13000 G and a track length of 40 cm we would be certain of the sign of a particle which had a momentum of about 1.25 or 1.50 GeV/c. Our experience is that for most of these tracks a sagitta between 1 and 2 mm can be quite readily observed.

B. V. Sreekantan (India): I would like to know what is the largest possible chamber that one can easily build with an assembly of this type.

A. Roberts: I know that chambers are being built 1.5×2 m in cross-section, and 1—2 m in length, for the detection of neutrinos. These are being built at Brookhaven

by a group from Columbia University. I knew of no particular limitation as to the size except the mechanical difficulties of construction.

H. L. Anderson (United States of America): Could you describe the experiment that you are planning to do with this chamber?

A. Roberts: The experiment that is being planned is on the leptonic decay modes of K^+ and will be done with a chamber and a magnetic field somewhat larger than what I have shown. We have been able to obtain a magnet with a gap of dimensions $110 \times 70 \times 25$ cm. We expect to get a field of about 14 kG in our chamber. With this chamber we propose to make a measurement of the decay spectra of the K^+ meson, particularly decay modes $Ke3$ and $K\mu3$. This requires that we detect the charged particle, which has a continuous spectrum, and the neutral pion, which also has a continuous spectrum. In half of the chamber we will intersperse lead plates spaced about 10 or 15 cm apart so as to produce pairs in the lead plates and detect the neutral pions, while in another part of the chamber there will be nothing but spark chamber gaps, in which we measure the momentum of the charged particle. In order to identify the charged particle—electron, muon or pion—in other modes of decay, we will also insert a chamber in which we measure the range of the charged particle. This chamber will contain brass plates, and if the particle is a muon or pion we will be able to identify it by measuring both the momentum and the range, while if it is an electron it will produce a soft shower or scatter very highly and will be identified in that way, so we anticipate no difficulty in identifying the particle and in measuring the momenta. The experiment is now being set up and we hope it will be performed late this year on the proton synchrotron at CERN in Geneva.

A CYLINDRICAL SPARK COUNTER

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Abstract — Résumé — Аннотация — Resumen

A cylindrical spark counter. A parallel-plate spark counter consisting of an eight-gap array of coaxial cylinders surrounding a two-liter liquid hydrogen target is nearing completion. An optical system with some unusual features has been devised to permit a direct measurement of particle trajectories in cylindrical coordinates. The essential design features and test results are given.

Compteur cylindrique à étincelles. Les auteurs sont sur le point de terminer la construction d'un compteur à étincelles à plaques parallèles, qui se compose d'un ensemble de cylindres coaxiaux à huit intervalles entourant une cible composée de deux litres d'hydrogène liquide. Ils ont mis au point un appareil optique, comportant certains dispositifs tout à fait spéciaux, qui permet de mesurer directement les trajectoires des particules en coordonnées cylindriques. Le mémoire indique les principales caractéristiques de l'appareillage et donne les résultats des essais.

Цилиндрический искровой счетчик. Завершается создание искрового счетчика с параллельными пластинами, состоящего из восьмизазорной системы коаксиальных цилиндров, окружающих мишень из жидкого водорода объемом в 2 литра. Была изобретена оптическая система с некоторыми необычными деталями для непосредственного измерения траекторий частиц в цилиндрических координатах. Будут представлены существенные особенности проекта и результаты испытаний.

Contador cilíndrico de chispa. Se está terminando de construir un contador de chispa de placas paralelas; consiste en ocho cilindros coaxiales que rodean a un blanco de dos litros de hidrógeno líquido. Se ha ideado un sistema óptico con ciertas características poco comunes que permitirá medir directamente trayectorias de partículas en sistemas de coordenadas cilíndricas. Los autores expondrán los detalles fundamentales del diseño y los resultados de los ensayos del instrumento.

In order to study the interactions of certain high-energy particles with protons, we are building a detector which consists of a triggered spark chamber of cylindrical shape surrounding a liquid hydrogen target. The design is intended to allow the photography of particle trajectories with uniform coverage of a large fraction of the total solid angle about the target. The liquid hydrogen target is a thin-walled, vacuum-insulated, stainless-steel cylinder of 2-liter capacity; surrounding this and coaxial with it are 12 nested aluminium cylinders which are arranged to form 8 spark-gaps, each with 5 mm spacing. As seen from the target, the detector subtends about 2π steradians. The spark-gap assembly is supported in a tank containing pure argon at 1 atm pressure.

The optical system is a large-aperture reflecting telescope which is on axis and views the cylindrical spark gaps from one end. A small-angle stereo view is provided by a mirror at the opposite end. The mirror is a circular array of 15 sectors in a fan-like arrangement; i.e., each sector is rotated slightly about a radial line. A photograph of the chamber records each spark and its reflected image in the fan mirror. The tangential displacement of the reflected image from the original spark is a direct measure of the axial distance of the spark from the mirror; i.e., the Z co-ordinate of the spark.

SPARK CHAMBER FOR RARE MODES OF MESON DECAY

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Abstract — Résumé — Аннотация — Resumen

Spark chamber for rare modes of meson decay. Spark chamber-scintillation counter combination will be described which makes effective use of the property of the spark chamber to preserve good angular resolution within a large solid angle to identify rare modes of meson decay. The branching ratios of the order of 10^{-8} for the modes $\mu^+ \rightarrow e^+ + \gamma$, $\pi \rightarrow \pi^0 + e + \gamma$, and $\pi \rightarrow e + \nu + \gamma$, are accessible with this arrangement. Prototype chambers have been built whose operating characteristics will be described.

Chambre à étincelles pour les modes rares de désintégration des mésons. L'auteur décrit la combinaison chambre à étincelles — compteur à scintillation, qui utilise pleinement la propriété de la chambre à étincelles de conserver une bonne résolution angulaire dans un grand angle solide, pour identifier les modes rares de désintégration des mésons. Cette combinaison permet d'étudier des rapports de branchement de l'ordre de 10^{-8} pour les modes $\mu^+ \rightarrow e^+ + \gamma$, $\pi \rightarrow \pi^0 + e + \gamma$ et $\pi \rightarrow e + \nu + \gamma$. L'auteur expose les caractéristiques de fonctionnement des prototypes de chambres qui ont été construits.

Искровая камера для редких видов мезонного распада. В докладе дается описание комбинации искровая камера-сцинтилляционный счетчик, позволяющей эффективно использовать свойства искровой камеры с тем, чтобы сохранить хорошее угловое разрешение в пределах большого телесного угла для распознавания редких видов мезонного распада. Такое приспособление позволяет получать соотношения ветвей распада порядка 10^{-8} для видов $\mu^+ \rightarrow e^+ + \gamma$, $\pi \rightarrow \pi^0 + e + \gamma$ и $\pi \rightarrow e + \nu + \gamma$. Были созданы камеры-прототипы, рабочие характеристики которых приводятся в докладе.

Cámara de chispas para modos de desintegración mesónicos poco frecuentes. El autor describe una combinación de una cámara de chispas y de contador de centelleo que aprovecha eficazmente la propiedad que posee la cámara de chispas de conservar satisfactoriamente la resolución angular dentro de ángulos sólidos de gran abertura, para identificar modos de desintegración mesónica poco frecuentes. Este dispositivo permite determinar relaciones de ramificación del orden de 10^{-8} para las desintegraciones $\mu^+ \rightarrow e^+ + \gamma$, $\pi \rightarrow \pi^0 + e + \gamma$ y $\pi \rightarrow e + \nu + \gamma$. Se han construido prototipos de cámaras y el autor describe sus características de funcionamiento.

I. Introduction

Recent attempts [1]—[4] to observe the process $\mu \rightarrow e + \gamma$ have been unsuccessful even though the sensitivity achieved was of the order of 10^{-6} in the branching ratio with respect to the normal $\mu \rightarrow e + \nu + \bar{\nu}$ mode. The distinguishing characteristic of the rare mode is that there are two particles rather than one which can be detected in time coincidence. The previous work depended on two scintillation detectors, one for the gamma ray and one for the electron, set in a 180° orientation. In the latest attempt [1] a measure of the energy was obtained by using a NaI crystal for the γ -ray and a multilayer graphite-range telescope for the electron. The normal mode is not detected with this arrangement, but there still remains the radiative modification, $\mu \rightarrow e + \nu + \bar{\nu} + \gamma$ which can simulate the $\mu \rightarrow e + \gamma$ mode quite closely if scintillation counters alone are used. This is because there is an appreciable chance that the electron

and γ -ray can be emitted each with energy close to 50 MeV and at angles not too far from 180° with respect to one another. Much of the advantage that might be gained by using larger scintillators to obtain a greater solid angle and higher counting rate would be lost by the increase in the number of these events which can occur at angles other than 180° .

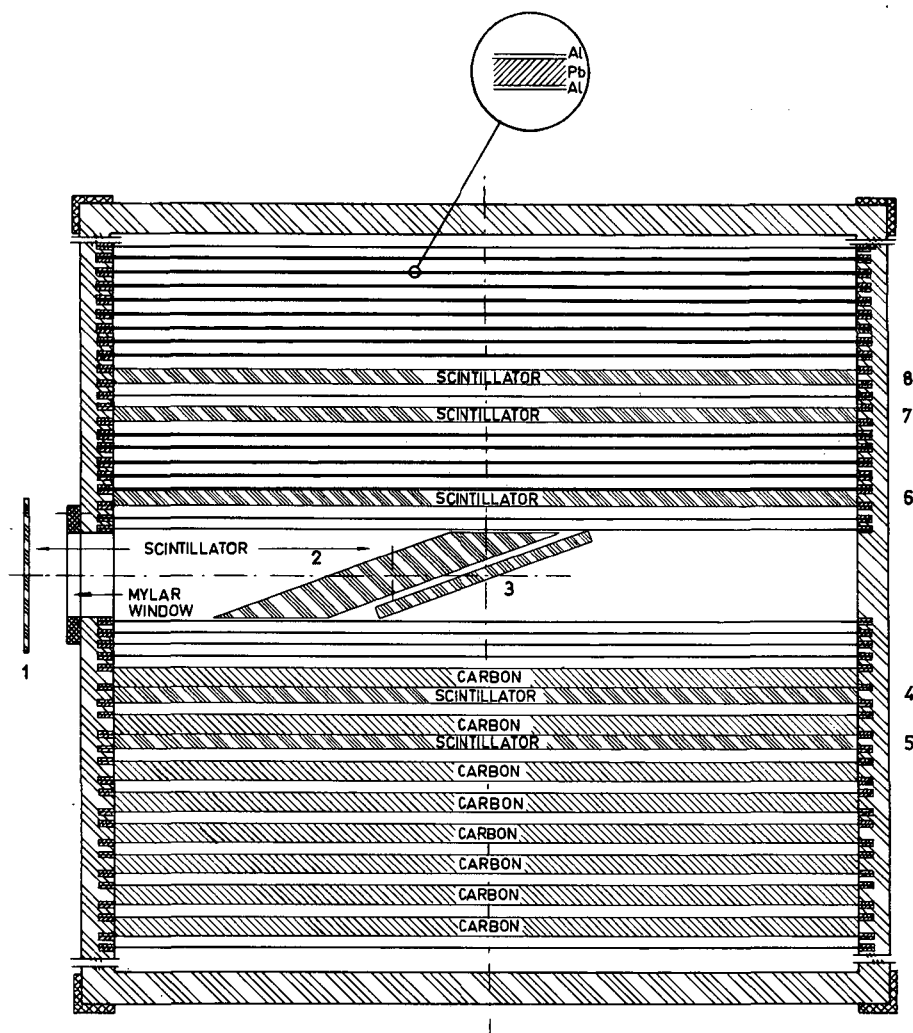


Fig. 1

Spark chamber for rare modes of meson decay:

Pions enter through thin counter on the left (1), are slowed down in thick scintillator (2) and come to rest in the target scintillator (3) in the centre of the chamber. Counters (1) and (5) are set between carbon plates on the electron side of the chamber. On the other side, first scintillator (6) is used in anti-coincidence with the scintillators (7) and (8) which follow the lead plates to record γ -rays

It is in this connection that the spark chamber can offer a distinct advantage. Without sacrificing anything in time resolution a large solid angle can be employed while maintaining a high degree of angular resolution. This permits a reliable verification of the angular relationship which must obtain in the $\mu \rightarrow e + \gamma$ process. The visual record of each event that is obtained can add greatly to the certainty that what is observed is not spurious. Insofar as true events of the type $\mu \rightarrow e + \nu + \bar{\nu} + \gamma$ are obtained, the angular relationship between the electron and the γ -ray can be measured and a useful study of this process made at the same time.

II. Operation

Fig. 1 shows the particular configuration of spark chamber and scintillation counters adopted for the present experiment. The spark chamber is arranged in a $60\text{ cm} \times 60\text{ cm} \times 60\text{ cm}$ cubical lucite box with five $60\text{ cm} \times 60\text{ cm}$ plastic scintillation counters interspersed among the spark gaps to identify the events of interest. Positive pions enter one face of the chamber and are brought to rest in the target, which is itself a scintillation counter. The coincidence (1, 2, 3) marks an entering π^+ meson and opens a delayed gate. Triggering of the spark chamber requires a coincidence (2, 3, 4, 5) on the electron side of the spark chamber and a coincidence (6, 7, 8) on the γ -ray side of the chamber. The anti-coincidence $\bar{6}$ assures that the particle is initially neutral but converts to an electron-positron pair, presumably in one of the lead plates, after having traversed counter 6. The pulses from (2, 3, 4, 5) and from (6, 7, 8) must be in fast coincidence with one another and within the time that the (1, 2, 3) gate is open. The anti-coincidence requirement $\bar{2}$ in (2, 3, 4, 5) reduces the likelihood of certain kinds of accidental triggers and possible spurious events. An oscillographic record of the pulses in 3 verifies, by the presence of three pulses with the proper time sequence, that a $\pi \rightarrow e$ decay actually did take place in counter 3. The π pulse is identified by its time correlation with a second but simultaneous oscillographic record of the pulses on 1, while the electron is identified by its time correlation with the pulses in 5 and 8 as shown in a third separate, but simultaneous oscillographic trace.

The spark chamber is arranged to record the trajectory of the electron and to trace its penetration through a number of graphite plates on one side. The γ -ray is intended to convert in one of the lead plates preceding counters 7 and 8 on the other side. The subsequent development of the shower should be revealed by the sparks between the succeeding lead plates. The thickness of material which the electron must penetrate to reach counter 4 is kept small to keep the multiple-scattering at a low value for a fairly precise determination of the direction of the electron trajectory. An extension of this line should meet the point of origin of the conversion electron-positron pair if the emission of the γ -ray is at 180° from the electron. Multiple scattering and the finite thickness of the target and lead plates limit the precision to which this angle can be established to about 3° .

The solid angle which can be utilized in the detection of the $\mu \rightarrow e + \gamma$ process is 0.3 of the sphere. The efficiency for detecting the electron (52.85 MeV) is 0.8, while for the γ -ray it is 0.5. Thus the fraction of $\mu \rightarrow e + \gamma$ decays which are detectable is 0.12. With 10^4 stoppings π^+ per second in the target, this gives about 1 event a day if the branching ratio is as small as 10^{-8} . In the case of the process $\mu \rightarrow e + \nu + \bar{\nu} + \gamma$ we calculate [5] that the number of events with the e - γ angle within 3° of 180° which triggers the spark chamber is about $1/3$ as many. Using the added information obtained

from the penetration of the electron in the graphite and the γ -ray shower in the lead to help discriminate against the latter, a determination of the branching ratio for $\mu \rightarrow e + \gamma$ down to 10^{-8} seems quite feasible.

III. Construction

The construction of the spark chamber uses plates which slide into place in slots milled in the sides, top and bottom of the lucite box. The spacing is 1 cm and the gas is neon at 1 atm with a small admixture of argon (0.01%) to increase the efficiency of ionization. The lead plates are stiffened by enclosing them as a sandwich between two 0.04-cm aluminium sheets cemented to the lead with Eastman cement. The graphite is also sandwiched between aluminium sheets by means of double adhesive tape. The edges of all plates are double adhesive-taped to lucite strips to reduce corona effects.

A separate electrical connection is made to each plate to decouple each from the other during the triggering. Thus, each gap has its own condenser bank but a single thyatron discharges all of these at once into their respective spark gaps.

The photography is done in 90° stereo. A 75-cm diam. lucite field lens with 300-cm focal length and a system of mirrors brings the image of the sparks from the bottom and one side of the chamber to a single lens which records both views on a single frame of 35-mm film.

This experiment is being carried out with the collaboration of Drs. S. Penman and S. Parker, Mr. C. Rey and Mr. C. O. Kim.

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DISCUSSION

F. de Martini (Italy): I would like to ask Professor Anderson and the authors of the two preceding papers whether any studies or experiments have been made to find the best gas mixtures and the best pressures and applied tensions with a view to increasing the light and reducing the width of the light trace. Further, have any theoretical studies been made on the mechanism of light generation in spark chambers? This is of considerable interest for my colleagues and myself at the University of Milan: we are going to measure ranges for low-energy particles using a light chamber.

H. L. Anderson (United States of America): In our own laboratory we have made no systematic studies of the type to which you refer. I understand that a more systematic study has been made by Fisher and collaborators at Brookhaven National Laboratory, and I believe a paper was presented in the *Review of Scientific Instruments* (if I remember correctly), and there was also a report at a spark chamber symposium held earlier this year at the Argonne National Laboratory organized by Professor Roberts. That paper includes some of the theoretical work to which you refer. In our own case we have not studied gas mixture systematically; we have used, primarily, fillings of

neon with some argon added and have developed a system of filling the chamber employing carbon dioxide. One problem that arose in connection with the last chamber you saw was that it was not possible easily to evacuate the chamber, so a technique of flushing was developed such that the difference of pressure within the chamber as compared with the outside was at no time more than several millimeters of mercury. This was done by first flushing the chamber with carbon dioxide gas; after several volumes had been passed through the chamber, neon was introduced to displace the carbon dioxide; then the gas was circulated through a system with a liquid-air trap to remove the carbon dioxide. We found that having a small amount of carbon dioxide was not prejudicial to the functioning of the chamber, and—without making any careful measurements—we gained the impression that a small amount of carbon dioxide was beneficial and seemed to suppress the spread of sparks which may occur, depending to some extent on the timing with which the voltage is put on the electrodes. I should also mention that the large chamber which I described last did not use a thyratron for triggering, but a spark gap, which served to put the voltage on the plate in a much shorter time than we had been able to obtain with the thyratron and could handle much more efficiently the large charging currents which one encounters as one increases the size of the chamber to the size that we had to deal with here.

H. E. Wegner (United States of America): You implied that the non-uniform sparking in your early test chamber was due to non-uniform plate spacing. Has the dependence of spark intensity on plate separation been demonstrated, and is it understood?

H. L. Anderson: I cannot say that I understand all the aspects of the sparking in the spark chamber. There are clearly a number of factors involved here, such as the spacing of the electrodes, the way in which the avalanche develops as determined by the detailed nature of the gas mixture, the rise-time of the pulse and its decay. All these factors are clearly important in the development of the spark, and in the efficiency with which it is produced. There are various ways in which sparks may develop in a spark chamber—as a result of corona, field effects, photo-electric emission or perhaps some sort of conduction which might take place along the insulator surfaces; alternatively—and this is what we want to happen—they may develop where ions have been produced by the particle we are interested in. To assure that they develop in this way, we try to make use of the differences in timing which these various ways of sparking might prefer: usually those sparks which are developed by corona effect or by photo effect take a longer time to develop, and one seems to get the best results by making the voltage rise quickly and then cut it off rather abruptly.

A. Roberts (United States of America): I should like to comment on the answer that Professor Anderson just gave. At the University of Michigan Meyer and Terwilliger have investigated experimentally the effect of different gap-widths and they found that with a 15% difference in two sets of gaps put in parallel, the smaller gap would always fire and not the larger one; if the difference reaches as much as 15% the efficiency of the larger gap will thus be adversely effected. As to the efficiencies of different gases, there are many different opinions. It seems that one gets the highest efficiency with neon. At atmospheric pressure, with neon and 6 or 10-mm gaps, the efficiency reaches as much as 97 or 98%; with argon one seems to get values around 95% and our own experience is that with helium the values are lower, ranging from 70 to 90%. The admixture of either neon or argon to helium will raise the efficiency of the helium considerably.

H. L. Anderson: Everything Professor Roberts says is in agreement with our own experience, but I would like to mention that these figures largely depend, I believe, first on the nature of the gas employed and secondly on the rise time and shape of the pulse which is applied. I think somewhat larger tolerances will become possible if one can improve the rise time and give a better shape to the pulse which is applied to the plates.

STUDIES ON RADIATION-IMAGE DETECTORS

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Abstract — Résumé — Аннотация — Resumen

Studies on radiation-image detectors. Work underway on radiation detectors capable of preserving spatial distribution information is described. We are concerned primarily with problems of determining intensity distributions in a plane or possibly over a cylindrical surface. This class of problems includes neutron diffraction, neutron radiography and X-ray and γ -ray radiography or scattering studies with these radiations. Emphasis is being given to imaging radiation detectors based on spark breakdown and on luminescence or stimulated phosphorescence.

We have developed very large spark counters which weigh over 100 lb and have sensitive areas of about 2000 cm² defined by staggered planar arrays of up to 400 anode and cathode wires. Flow-counter operation using an air or argon-methane gas atmosphere provides an alpha-sensitive system and slow neutron detection is accomplished with enriched B¹⁰ converter plates. With other fill gases, proton and electron sensitivity has been demonstrated. Read-out of the intensity distribution is by photographic recording of the spark distribution. Neutron Laue patterns have been recorded in ten minutes using the Armour Research Reactor at low power; peak core flux was 10¹¹ nv and the collimator was a straight 1 × 1 cm tube.

Application of these counters to other neutron studies are described with comments on the ultimate resolution to be obtained with smaller electrode spacings, dynamic scanning and possibly space filtering of the optical image.

A second general approach to radiation-image detection concerns the use of luminescent or phosphorescent converter screens. Matrices of luminescent fibres are being tested which comprise very thin glass tubes filled with liquid scintillator. These are useful in X-ray and γ -ray detection and either the wall materials or the core liquid may be "loaded" to obtain neutron sensitivity. New methods of fabricating various types of luminescent fibre screens are presented together with optical performance data also germane to scintillation-chamber technology. Possible imaging detectors using thick blocks of material which are capable of significant energy storage and stimulated phosphorescence upon irradiation are discussed briefly along with read-out methods using optical scanning beams to eliminate resolution loss due to finite phosphor thickness.

Etudes sur les détecteurs à images de rayonnements. Le mémoire décrit les travaux qui ont été entrepris sur des détecteurs de rayonnements capables de fournir des informations tout à fait exactes sur la distribution spatiale. Il s'agit avant tout de déterminer des distributions d'intensités dans un plan, ou éventuellement sur un cylindre. Cette catégorie de problèmes comprend la diffraction des neutrons, la radiographie des neutrons, ainsi que la radiographie aux rayons X ou γ ou les études de diffusion avec ces rayons. L'auteur s'occupe surtout des détecteurs à images de rayonnements, fondés sur la distribution des étincelles et sur la luminescence ou la phosphorescence stimulée.

Le laboratoire de Armour Research a mis au point de très grands compteurs à étincelles, pesant plus de 100 livres et comportant des zones sensibles de l'ordre de 2000 cm², définies par des assemblages de plans comprenant chacun jusqu'à 400 fils d'anode et de cathode, les anodes et les cathodes étant respectivement disposées en quinconce. Un compteur à courant gazeux contenant de l'air ou un mélange d'argon et de méthane constitue un système sensible aux rayonnements alpha; la détection des neutrons lents se fait avec des plaques en ¹⁰B enrichi. Avec d'autres gaz de remplissage l'appareil est sensible aux protons et aux électrons. La lecture de la distribution d'intensité se fait par enregistrement photographique de la distribution des étincelles. Des diagrammes de taches de Laue ont pu être enregistrés en dix minutes à l'aide

ду реактора d'Armor Research функционирующего на слабой мощности; ле поток дн крест в центре был дн 10^{11} н/см² с и ле коллиматор был состои из трубки прямого дн 1 см на 1 см.

Ле автор описывает ле применение дн дн счетчиков к дн другим исследованиям нейтронным и представляет наблюдения на ле самое большое умение дн разрешения ле ле которое можно получить с дн дн самыми малыми расстояниями дн электродов, на ле действуя на ле динамическое удаление и, возможно, на ле фильтрацию дн ле оптического изображения.

Ле другое общее метод дн дн обнаружения дн радиации на ле изображение состои в ле использовании дн экранов дн конверсионных люминесцентных или фосфоресцентных. Дн матрицы на дн волокнах люминесцентных, состои дн трубок дн стекла дн очень тонких состои дн сквентилляционной жидкостью. Эти матрицы описываются дн полезными на ле обнаружении рентгеновских лучей и гамма-излучений; дн получения дн чувствительности к нейтронам могут „зарядаться“ либо материалы стенок, либо состои дн жидкостью внутри трубок. Будут описаны новые методы дн выработки люминесцентных волоконистых экранов дн различного типа с указанием дн их оптических свойств.

Изучение детекторов изображения радиации. Описана проводимая в настоящее время работа по изучению детекторов изображения радиации, способных сохранять информацию о пространственном распределении. Мы занимаемся, главным образом, изучением проблем, связанных с определением распределения интенсивности радиации на плоскости, а возможно, и на цилиндрической поверхности. В эту категорию проблем входят дифракция нейтронов и радиография, а также радиография рентгеновских лучей и гамма-излучений, или же исследование рассеяния с помощью таких видов излучений. Особый упор делается на изучение детекторов изображения радиации, основанных на разрушении искр, и на люминесценции или наведенной фосфоресценции.

Мы разработали счетчики искр очень больших размеров, весом более 100 фунтов, имеющие светочувствительные поверхности порядка 2000 кв. см., которые снабжены системой уступчатых плоскостей почти с 400 анодных и катодных проводов. Применение счетчиков, наполненных воздухом или газовой смесью аргона с метаном для измерения потока, создает устройство, чувствительное к альфа-частицам, а обнаружение медленных нейтронов достигается пластинами преобразователя, обогащенного В¹⁰. С другими заполняющими газами обнаруживалась чувствительность к протонам и электронам. Регистрация распределения интенсивности достигается фотографической съемкой распределения искр. При работе с исследовательским реактором Армор на режиме малой мощности за десять минут была заснята картина распределения нейтронов по Лауэ; пиковый поток активной зоны составлял 10^{11} н/с, а коллиматор состоял из прямой трубки диаметром 1 × 1 см.

Описано применение этих счетчиков для других нейтронных исследований с указанием наилучшей достижимой разрешающей способности, которая может быть получена при меньших расстояниях между электродами, использовании динамической развертки, а, возможно, и при пространственном фильтровании оптического изображения.

Вторым общим подходом к обнаружению изображения, вызываемого радиацией, является использование в преобразователе люминесцирующих и фосфоресцирующих экранов. В настоящее время испытываются матрицы люминесцирующих волокон, состои дн из весьма тонких стеклянных трубок, состои дн сквентилляционной жидкостью. Эти матрицы описываются дн полезными на ле обнаружении рентгеновских лучей и гамма-излучений; дн получения дн чувствительности к нейтронам могут „зарядаться“ либо материалы стенок, либо состои дн жидкостью внутри трубок. Будут описаны новые методы дн выработки люминесцентных волоконистых экранов дн различного типа с указанием дн их оптических свойств.

что также тесно связано с технологией сцинтилляционных камер. Будут кратко обсуждены возможности постройки воспроизводящих изображения детекторов с использованием толстых блоков материала, способных хранить значительный запас энергии и вызывать фосфоресценцию при их облучении; будут также описаны методы отсчета показаний при помощи оптической развертки лучей для устранения потерь в разрешающей способности из-за конечной толщины люминофора.

Estudios sobre detectores de radiaciones productores de imágenes. El autor describe los trabajos sobre detectores de radiaciones capaces de proporcionar información sobre la distribución espacial de éstas. Las investigaciones se refieren principalmente al problema de determinar la distribución de intensidades en un plano, o, si es posible, en una superficie cilíndrica. Ello implica estudios sobre difracción y radiografía neutrónicas, sobre radiografía con rayos X y con rayos gamma o sobre la dispersión de estas radiaciones. Se concede especial atención a los detectores capaces de producir imágenes, basados en el principio de la descarga disruptiva de la luminiscencia o de la fosforescencia estimulada.

Se han construido contadores de chispa muy grandes, que pesan más de 100 libras y tienen zonas sensibles de unos 2000 cm², definidas por redes planas alternadas de hasta 400 hilos anódicos y catódicos. Como contadores de flujo gaseoso, utilizando aire o argón-metano, permiten obtener un sistema sensible a las partículas alfa; la detección de neutrones lentos se efectúa por medio de placas convertidoras de ¹⁰B enriquecido. Utilizando otros gases de llenado, se ha observado que el contador es sensible a los protones y a los electrones. La lectura de la distribución de intensidades se efectúa por reproducción fotográfica de la distribución de las chispas. Se han obtenido diagramas de difracción neutrónica de Laue en diez minutos, utilizando el reactor de investigaciones de Armour en régimen de baja potencia; el flujo máximo en el núcleo fue de 10¹¹ nv y se utilizó como colimador un tubo recto de 1 cm × 1 cm.

El autor describe las aplicaciones de estos contadores a otros estudios sobre neutrones y expone consideraciones sobre el poder de resolución que se podrá obtener con menor separación entre los electrodos, exploración dinámica y, posiblemente, filtrado espacial de la imagen óptica.

Otro método para abordar la detección de radiaciones con reproducción de imágenes consiste en el empleo de pantallas convertidoras de material luminiscente o fosforescente. Se están ensayando matrices de fibras luminiscentes compuestas de tubos de vidrio muy finos, rellenos de un líquido centelleador. Estas matrices son útiles para detectar rayos X y rayos gamma, y es posible «cargar» el material de los tubos o el líquido de relleno para hacerlas sensibles a los neutrones. El autor describe nuevos métodos para fabricar varios tipos de pantallas de fibra luminiscente y expone datos relativos a sus características ópticas, que son también aplicables a la tecnología de la cámara de centelleo. Examina brevemente algunos tipos de detectores productores de imágenes, que podrían construirse empleando gruesos bloques de sustancias capaces de acumular energía en cantidad considerable y de producir fosforescencia estimulada cuando se someten a irradiación, así como algunos métodos de lectura en los que se emplean haces ópticos de exploración para evitar la disminución de poder de resolución debida al espesor finito del fósforo.

I. Introduction

Various radiation detectors capable of preserving spatial distribution information are under investigation in this laboratory. In contrast to imaging detectors for high-energy physics which are generally designed to handle three-dimensional problems, we are concerned primarily with situations where it is desirable to determine intensity distributions in a plane, or over a cylindrical surface. The class of problems in which we have greatest interest includes neutron diffraction by polycrystalline and single-crystal samples, neutron radiography and X-ray or gamma-ray radiography. However, many of the techniques we shall discuss in this progress report are also applicable to

certain three-dimensional problems which have stimulated recent interest in spark chambers and scintillation chambers.

In many two-dimensional problems, it is usual to scan the radiation field with a point detector which requires that any time dependence of the radiation intensity does not introduce unknown errors. This is the approach used in neutron diffraction studies with BF_3 counters—a method which has been extensively developed in many laboratories and which is especially useful in certain types of single-crystal studies and in the Debye-Scherrer powder-pattern technique. Assuming a known time-dependence for the radiation field, the major disadvantage of a point-by-point method is that it wastes most of the radiation. If, for example, a typical Debye-Scherrer powder pattern is considered it might contain three to five diffraction rings out to a Bragg angle of 30° . If the instrumental resolution is such that about ten points are taken over the angular interval covered by one such ring, then of the scattered neutrons containing structural information, only about one part in several thousand is being utilized at any given moment. Clearly if one could develop a system where all points of the radiation field were measured simultaneously, very large increases in information gathering power per unit time could be achieved. Similar arguments could of course be made for other experimental situations.

A second class of difficulties encountered with the point-detector approach to the mapping of a radiation field is typified by efforts by SAWYER *et al.* [1] to use such devices as the Cauchois curved crystal-transmission monochromator. In this method considerable mechanical difficulties are encountered in attempting to make the point detector follow the curve of best focus for the instrument. If one could successfully develop a cylindrical imaging detector such difficulties could be eliminated. Generally speaking, single-crystal diffraction studies on upper-layer lines using the rotating-crystal method are inconvenient with point detectors and this has slowed application of these methods in neutron diffraction. In the analogous case of X-ray diffraction, the imaging properties of a cylindrical photographic film have allowed single-crystal methods to attain a high degree of development exemplified, for example, by the Weissenberg camera. When one adds to these considerations the unexplored potential of neutron radiography using thermal, resonance, or fast neutrons, it is clear that there is ample motivation for the development of effective two-dimensional imaging detectors for neutrons.

Imaging detectors for gamma ray and X-ray radiation fields are, of course, already in existence. Photographic film methods as well as electronic image-intensifier techniques are well known. Our work with X-ray and gamma-ray imaging devices has therefore been concentrated on the development of energy-conversion schemes analogous to the "intensifier screen techniques" of radiography. In particular, we are undertaking investigations of "high-energy to optical" radiation conversion systems which provide for high efficiency of conversion and utilization of the incident energy. To this end, methods allowing the use of very thick conversion screens without attendant loss of spatial resolution are receiving primary attention.

II. Spark counters as imaging detectors

We have previously demonstrated the feasibility of using a novel type of multi-wire spark counter as an imaging detector for thermal neutrons [2]. The highly localized development of luminous spark channels in the region of a suitable initiating event

forms the basis for the method. The electrode configuration of Fig. 1, operating in air or in an atmosphere of 10% methane and 90% argon, can be triggered only by highly ionizing events such as alpha-particle tracks. Neutron sensitivity must therefore be obtained by (n, α) reactions in a converter. Either gas-phase conversion, as in a BF_3 counter, or solid converter plates of boron are useful, but we have worked exclusively with the latter as indicated in Fig. 1. Since the spark occurs very close to the point where the alpha track from the (n, α) reaction penetrates the region between the electrode planes and the discharge does not strike the converter itself, both long life and good image definition are possible. The counter operates at about 2000 V in argon-methane and at about 4000 V in air at atmospheric pressure. The required operating potential is supplied to electrodes in groups of four pairs each, isolated by individual load resistors. To insure controllable and reproducible characteristics, the device is operated as a flow counter from a gas supply of known quality. The counter is insensitive to electrons when used with air or argon-methane.

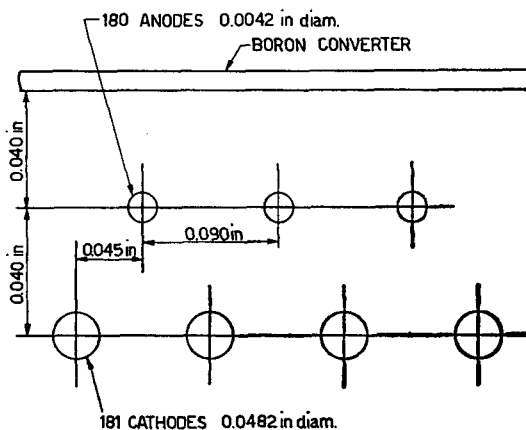


Fig. 1

Electrode configuration for imaging neutron detector

The electrode configuration of Fig. 1 is considerably less directional than the more usual wire and plate or on-centre wire configuration and exhibits close to 100% alpha counting efficiency. It can be operated in very high gamma-ray fields (up to 10^5 r/h) without causing any increase in the background counting rate which is of the order of counts per hour. This property can be of great importance in reactor and certain accelerator experiments and is not generally available with imaging detectors operating on other principles.

Each spark discharge, representing the detection of a single alpha particle, which in turn is produced by one detected neutron, can be photographically recorded and contributes one element to building a picture of the incident-radiation distribution over the area covered by the electrodes. Since the individual sparks can be made almost arbitrarily bright, the energy-intensification factor for the incident radiation is extremely large. The spark distribution can be recorded by a camera arranged to take a time

exposure of the entire counter area. At low f-number settings of the camera lens, each spark is sufficiently intense to saturate the film and a "half-tone" picture of the incident-radiation distribution results. At high f-numbers, a number of sparks are required to saturate a given area of the film and an image with an extended gray scale is obtained.

The results of our earlier experiments with multiple wire spark counters [2] encouraged us to design a large version of the device which would permit an increased number of individual electrodes to contribute to building up a given fraction of the incident-radiation distribution. For ease of construction and because of long-term creep problems associated with wire electrodes under high mechanical tension, electrode diameters and spacings are not freely variable. Therefore, if one wishes to have a large number of counting elements, one must expand the size of the radiation image projected on to the counter and this requires a larger sensitive area. In addition, a large sensitive area is desirable for certain types of neutron radiographic problems. A counter has therefore been constructed with some 400 anode and cathode wires covering a sensitive area of about 2000 cm². In Fig. 2 the anode plane for the counter is shown and Fig. 3 shows the assembled counter. The steel frame is massive so that relatively high tensile loads of the wires themselves can be sustained and long-term stability of the chamber insured.

This counter has been applied to neutron radiography problems and also to the problem of obtaining neutron Laue patterns. For the latter purpose, the counter was slightly modified to allow the main neutron beam to pass through a hole in the centre

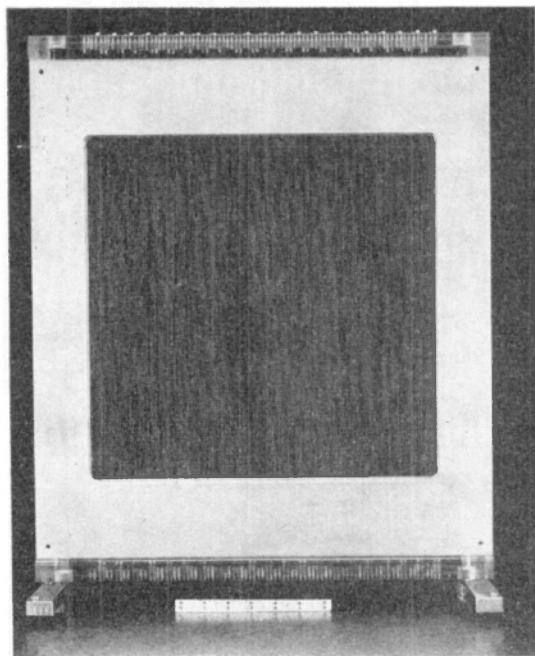


Fig. 2

Anode assembly for imaging neutron detector (scale in inches)

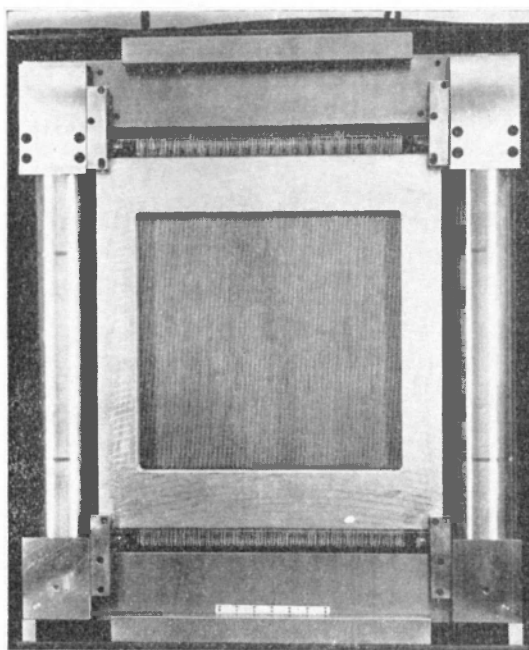


Fig. 3

Fully assembled detector system outside atmosphere control chamber (scale in inches)

of the cathode plane. Since we are still at what we consider to be the developmental stage of the counter itself we have not installed elaborate shielding for diffraction work, but rather are using the simple arrangement shown in Fig. 4. It is our intention to reduce instrumental backgrounds both by reduction of air-scattered neutrons by means of an evacuated flight path and by employing more complete shielding. Nevertheless, with the simple arrangement of Fig. 4, we have achieved what we consider to be promising results as typified by the Laue pattern shown in Fig. 5. This Laue pattern was obtained in an exposure time of slightly less than ten minutes with a reactor power of 50 kW using a four-section converter plate of enriched boron-10.

The converter plates were flat and provided a detection efficiency of about 5%. Using converter plates on both sides of the electrodes could almost double the detection efficiency and reduce the exposure time to about five minutes. We are now investigating analytically the conversion efficiency to be expected from saw-tooth-type converter plates where the teeth are either continuous or separated from each other by flats. For continuous saw-tooth designs, it appears that reductions in effective solid angle for the emission of alphas almost completely compensate for the increased number of alphas which can escape the converter surface. When the teeth are separated by flat regions some net gain may be achieved.

To date only planar spark counters have been constructed, but it is obvious that the geometry of Fig. 1 adapts itself very readily to construction of cylindrical spark

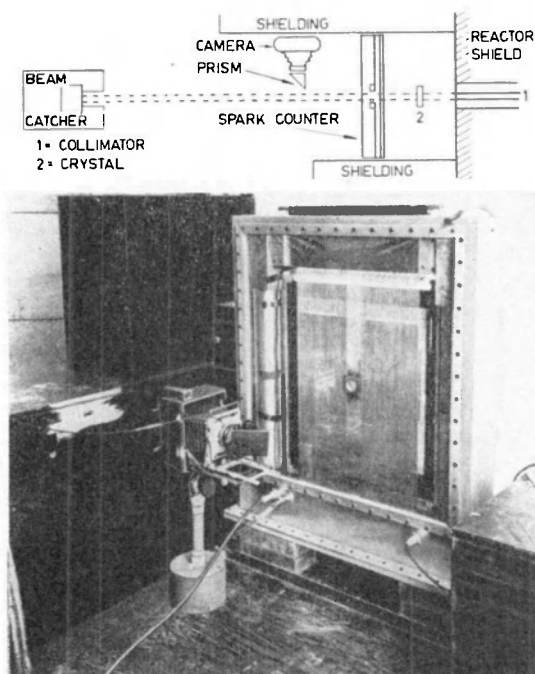


Fig. 4

Detector system set up for neutron diffraction. The atmosphere control chamber is shown with its mylar window and the cathode assembly of the counter has been modified to reduce scattering of the main neutron beam. The sketch shows the geometry employed for recording Laue patterns

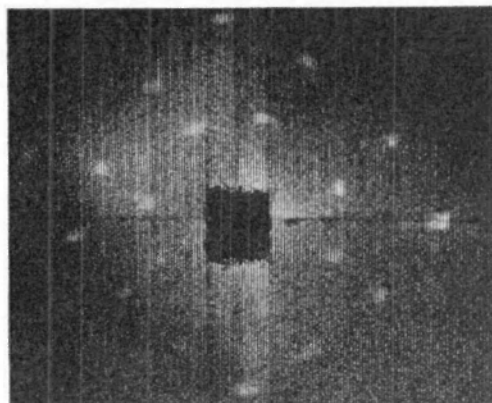


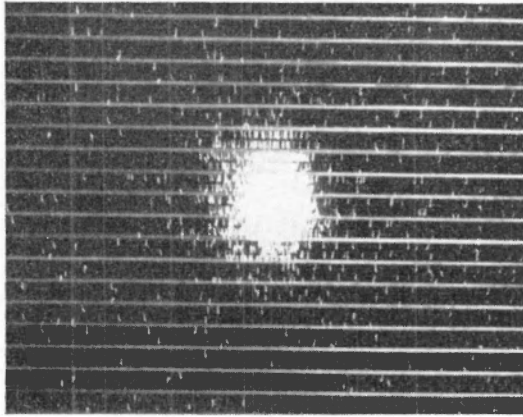
Fig. 5

Neutron Laue pattern of NaCl obtained in 10 min at a reactor power of 50 kW

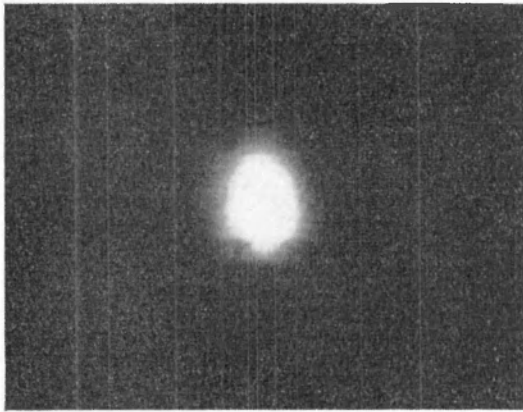
counters with the axis of the cylinder parallel to the axes of the electrodes. Such cylindrical multi-wire spark counters would be very well suited for studying single-crystal neutron-diffraction patterns using any of the classical X-ray methods. Measurements on upper-layer lines using the rotating-crystal method become straightforward and an extension to a Weissenberg camera technique or similar method is also direct and obvious. A cylindrical powder camera is now being designed which will have coverage capabilities analogous to the Straumanis film arrangement of X-ray diffraction.

With a cylindrical geometry, a minor problem is encountered with regard to read-out because a simple camera system is obviously no longer applicable. We therefore have experimented with recording methods which do not rely upon lenses to transfer the light from the sparks to the recording film. The spark distributions can be recorded directly on photographic film using optical collimators comprising opaque glass plates containing very small holes. These are close-spaced and their diameter is small compared to the plate thickness. The multi-hole plates which are formed by photo-etching are placed immediately over the film and the entire assembly is positioned close to the cathode plane of the spark counter. Light from the sparks is collimated through the holes and localized on the film. Since the sparks are very intense, large amounts of light can be wasted without consequence. Such direct recording of the spark distribution on the film appears to be ideally suited to use with cylindrical spark counters because both the collimator plates and the film can be appropriately curved.

Since film-recording techniques are generally contemplated for use with spark-counter imaging detectors, the problem of film densitometry is encountered when one wishes to obtain radiation-intensity information. The most accurate, albeit most laborious, method of intensity read-out is to actually count the number of sparks in a given region of the film. This method is useful only until the number of sparks per unit area gets large enough so that the individual events cannot be adequately distinguished. At higher integrated intensities, provided care is taken to insure that the film is not saturated, instrumental densitometry should be applicable. In this regard we are considering methods which operate on the original image or which use an image pre-treated to suppress the detail associated with individual sparks. To illustrate this point, in Fig. 6a is shown a simulated Laue spot photograph obtained in a few-second exposure by allowing a circular thermal-neutron beam 6 mm in diam. to impinge upon the counter. It is to be noted that the spark counter gives an elliptical pattern and that collimator leakage or a penumbra effect around the main beam is discernible. The elliptical pattern is caused by the dependence of counting efficiency on alpha-track angle. While, as stated earlier, this angular dependence is not as pronounced as in other geometries, it is still measurable. The counter maintains high efficiency to more grazing angles of incidence when the alpha track lies in a plane perpendicular to the electrode axis. This is simply because the radial electric fields of the counting geometry can collect charge from a track in the perpendicular plane and concentrate it in a very small volume, whereas for a track parallel to the electrodes, the radial fields cannot so concentrate the charge. In Fig. 6b is shown the same simulated Laue spot, recorded as in Fig. 6a, but the individual spark structure has now been suppressed by a random motion during the printing process. Such a pattern would seem to be useful with ordinary densitometric equipment. Intensity measurements on Debye-Scherrer patterns would ideally employ densitometry techniques exploring an entire diffraction ring simultaneously. In this way statistical fluctuations would be minimized for a given exposure time. Suitable ring densitometer methods together with other ways of suppressing undesired components of the image structure are currently under investigation.



(a) as recorded



(b) with individual spark structure suppressed

Fig. 6

Image obtained with circular neutron beam 6 mm in diam.

While in Fig. 6 we have shown the effect of motion of the recorded image itself, it is important to note that it is also possible and frequently desirable to shift systematically the spark counter during recording relative to a stationary radiation pattern. By moving the spark counter, the effective resolution can be increased since it is not so directly determined by the electrode spacing. Thus the blank lines of Fig. 5 which represent the obscuration of the image by the relatively thick cathode wires of the counter can be filled in by oscillating the counter during the exposure over a distance equal to one-half the spacing of the cathode wires.

At present we are investigating the general utility of the radiation imaging methods outlined above to a variety of problems. In addition to these applications studies, we are proceeding with investigations of the practical lower limits to electrode diameters and spacings for an attempt to increase the spatial resolution. In particular, operation under pressurized conditions is being considered with smaller electrodes. It is noteworthy that these devices can be made sensitive to protons and to a limited extent also to electrons by operating in atmospheres such as carbon dioxide. Shortly we hope to examine the application of these methods to fast neutron problems. If the electron counting efficiency can be increased, it may be possible to develop useful multi-wire, multiple-layer, spark chambers for high-energy physics.

III. Luminescent image detectors

In the classical X-ray regime, intensifier screens using zinc-sulphide phosphors to enhance the sensitivity of photographic film have been in use for many years. For radiations of greater penetrating power, the effectiveness of this simple technique is greatly reduced. Thus, for gamma-ray radiography in the MeV range and upward and for certain neutron radiography problems, it would be highly desirable to possess screens which could convert a large fraction of the incident radiation to usable light without suffering the severe resolution and light losses that would accompany the direct approach of thickening an ordinary polycrystalline intensifier screen. If thick intensifier screens could be developed they would, of course, be applicable to film-recording methods or could provide the input to any of the many electronic-image-intensifier devices now becoming available.

We have previously emphasized [3] that light-piping techniques, as developed in "fibre optics" and now applied to luminescent-chamber development, are also applicable to this problem. Several factors entering into the performance of single luminescent fibres and fibre arrays were discussed in detail in this earlier work. It is obvious that one can assemble a converter screen comprised of a close-packed array of optically insulated luminescent fibres of length sufficient to stop most of the incident radiation. The resolution of the resulting optical image would be determined only by the diameter of the luminescent fibres employed and by the fundamental properties of the incident radiation. Obviously the plastic fibres developed for luminescent chamber work are applicable to this situation. In addition, we have been interested in examining the limitations of luminescent fibres comprised of thin-wall glass tubing filled with liquid scintillator. Both plastic and liquid-filled fibres would seem to have specific advantages and disadvantages and we have concentrated primarily on the latter because of the considerable attention being given to the former in other laboratories. The necessity for using some sort of fibre structure when thick converters are desired is illustrated in Fig. 7. In this Figure we show the light distribution from an infinitely thin pencil of radiation impinging normally upon an optically homogeneous slab of thickness t . If there is no change in refractive index between the slab and the recording device, so that no total internal reflection occurs at the exit face, then it is apparent that a significant fraction of the emergent light leaves the slab at very large distances from the centre of the ideal image. If one includes the effect of total internal reflection caused by a refractive index step at the exit face of the slab, the intensity distribution is significantly narrowed, but unfortunately a large fraction of the otherwise useful light is lost. Ignoring Fresnel losses, it is easily shown that the fraction of potentially useful light actually escaping is given by $F = 1 - (N^2 - 1)^{1/2}/N$ where N is the relative refractive index

of the slab. The dotted curve of Fig. 7 shows the relatively small change in the distribution if Fresnel losses at the exit face of the slab are also considered. Since fibre transmission in reasonably long lengths is very good [3] and since the fibres serve to confine the light almost completely, their applicability in this situation is obvious.

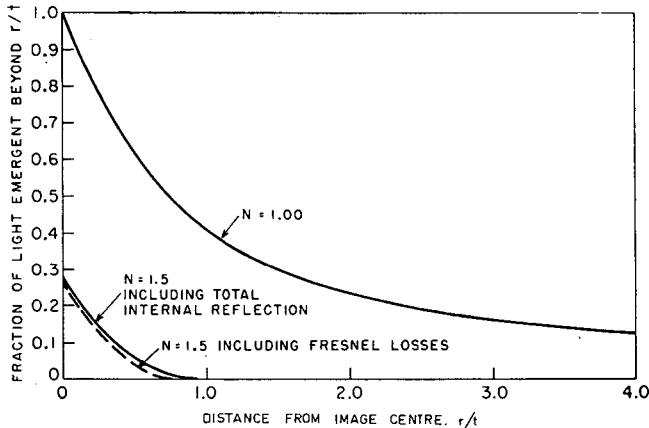


Fig. 7

Light emergent from a luminescent slab converter of relative refractive index N

Luminescent Slab Converter
 Fraction of useful light emergent beyond distance r/t from point beam
 (assuming negligible absorption)
 N = Relative refractive index
 $\uparrow$ = Slab thickness

Experiments have been performed using an 180 MeV betatron as a source of X-rays for radiographic purposes. The imaging detector employed consisted of a 1-in thick 7-in diam. single crystal of thallium-activated sodium iodide [4]. With such a detector, the difficulties epitomized by Fig. 7 could be only partially overcome through the use of a lens system and at the expense of a considerable loss of light. The results do, however, provide guidance on the fundamental effects on attainable resolution of the electrophotonic cascade initiated by high-energy photons in a thick converter. From these results it appears that the limit of resolution, set by the properties of the high-energy radiation, is about 750μ . For this reason and because of the general requirements imposed by typical scintillation chamber applications in high-energy physics, we have been experimenting with fibres of about 500μ in diam.

An assembled small bundle of tubular fibres with $50\text{-}\mu$ walls constructed so that the interstices contain air, but are completely sealed at the ends by fused glass, is shown in Fig. 8. This all-glass assembly may be totally immersed in liquid scintillator and read-out of the optical image may be achieved through a thin end-window in the gross container for the liquid. Since the fibre exteriors are in air, total internal reflection will occur entirely at protected glass-to-air interfaces with a high index difference and high efficiency. Parenthetically, it might be noted that such all-glass systems are chemically and optically stable and radiation damage or the possibility of long-term degradation [5]

of plastic phosphors which might represent a nuisance in the case of large assemblies of plastic scintillator fibres can be easily and inexpensively handled.

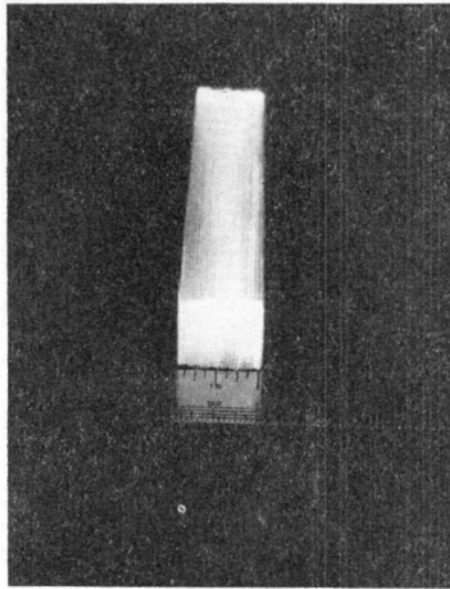


Fig. 8

Assembled all-glass array of tubular fibres with sealed air interstices

Fabrication methods for much larger assemblies of tubular fibres are now being perfected taking into consideration the need for good optical insulation between individual fibres. Spacers are used to keep fibres apart during stacking and end-sealing of the interstitial spaces. The excellent mechanical properties of glass, along with the advantages indicated above, seem to make these techniques of potential interest for the construction of scintillation chambers. To this end, assembly methods for spaced sheets of tubular fibres, oriented at right angles to each other, are also being considered. The scintillator medium in these system can be varied at will and, furthermore, the glass walls of the fibres can be designed to contain elements with desirable nuclear properties. For example, boron, lithium or uranium glasses might be used for neutron detection and certain types of resonant detectors may be feasible.

Another principle, which would permit the use of very thick converter screens without attendant loss of resolution due to optical effects, is shown in Fig. 9. This technique might be useful with detector materials which cannot be fabricated in the form of optical quality fibres or for situations where only the converter screen and not the final image-presentation device may be in place during the irradiation. The detector slab shown in Fig. 9 is composed of a material which is either radio-photo-luminescent, or which exhibits simulated phosphorescence or fluorescence after being subjected to high-energy radiation. An example of the latter is silver-activated sodium chloride which is known

to store a substantial fraction of the incident radiation energy in sites which can be stimulated by optical irradiation [6]. An example of the former is the silver metaphosphate glass developed by the United States Naval Research Laboratory [7] for radiation dosimetry purposes. With either class of material, a stimulating optical beam is used to read the information stored in the slab by a previous high-energy irradiation. The resolution of the system is determined by the properties of the high-energy radiation *per se* and by the diameter of the scanning beam. All of the light emergent from the slab for a given position of the scanning beam contains useful information, hence reflection or lens losses need not be sustained and read-out can be accomplished with available large-area photomultipliers rather than requiring large-area image-intensifier tubes. By suitable design, refraction of the scanning beam can be eliminated and multiple reflection of the beam minimized. The read-out method can automatically compensate for distortions produced by a finite radiation source-to-object distance by arranging for the same divergence in the optical beam as was present in the high-energy beam. Note that the only component required at the point of measurement is the slab of material itself. After exposure, the slab can be transported to the read-out apparatus at some other location.

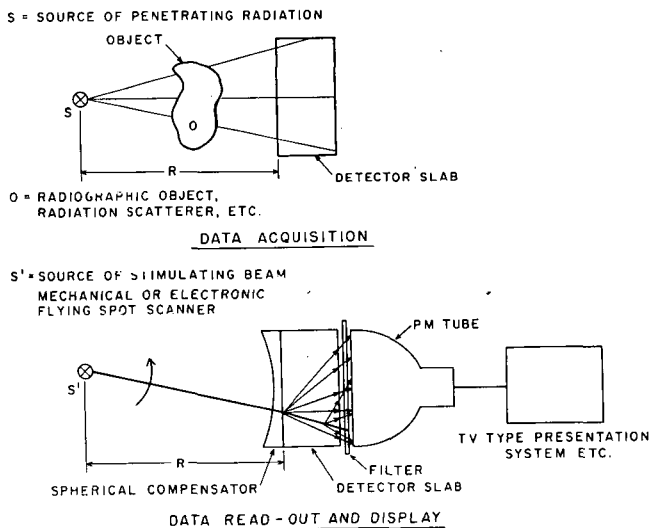


Fig. 9

Imaging detector system using scanning beam for read-out of thick detector slabs

The minimum dose required to produce a usable image for both classes of materials appears to be a sensitive function of purity and preparation methods. Various materials are now being examined with regard to their suitability for use in this system. The possibility of using thermo-luminescent or photo-stimulated fibre arrays to the same end of achieving thick high energy-to-optical conversion screens with good resolution is also being borne in mind.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of Joel Lemke and Robert Norton in the performance of experiments with spark counters and to express his appreciation to Hans Leu for his expert construction of these counters. Fibre scintillator assemblies are being fabricated by Anthony Brushenko.

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DISCUSSION

A. Roberts (United States of America): I did not understand exactly how you were using these hollow fibres. Is it to replace the solid scintillator?

L. Reiffel (United States of America): We are planning to use them as image-converter screens for radiography. One inserts a thick slab of fibres in front of the film, and the transmitted image is then converted to optical energy and recorded on the film, in the same way that the ZnS intensifier screen is used.

A. Roberts: Are the fibres filled with normal scintillating liquid—I mean with a scintillator rather than anything particularly sensitive to gamma rays?

L. Reiffel: They are not filled with anything particularly sensitive to gamma rays although if heavy elements were included in the scintillator this would presumably help. Heavy elements can, of course, also be put in the tubing walls. We have so far just been using such things as standard POPOP, terphenyl and xylene.

A. Roberts: Did you notice any particular advantage of these fibres over solid plastic scintillators?

L. Reiffel: Not yet. We can make them smaller with good surfaces and they are very easy to handle. At this stage I think that is all I can say. We are also experimenting with the plastic ones, but find them rather more delicate and it is a little more difficult to get close packing.

A. Roberts: You remarked that you can make these fibres in bundles a foot square. I wonder if you really mean this literally; this could be quite important to people working with scintillation chambers.

L. Reiffel: We can do it with this technique using the 500- μ fibres. We would not want to try to make them a foot square using much smaller diameters. There is no problem in stacking these fibres up, and we have an automatic machine for pulling them and cutting them off, so that we can make them at a great rate. Nor does one have to handle them carefully, which makes it easier to make a bundle a foot square.

A. Roberts: How long are the fibres?

L. Reiffel: The length can be selected at will—it depends on the optics and the transmission characteristics. That particular bundle I showed was three inches, but it could easily be made six inches or even a foot long, although there I think the alignment problems would result in some breakages. In many of these experiments we have used vibration to align the fibres. I am not sure how the vibration would work on a very long fibre.

FONCTIONNEMENT, A LA TEMPÉRATURE AMBIANTE, DE CHAMBRES D'IONISATION REMPLIES D'UN DIÉLECTRIQUE LIQUIDE

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Abstract — Résumé — Аннотация — Resumen

Performance, at ambient temperature, of ionization chambers filled with a liquid dielectric. The authors describe the performance characteristics of ionization chambers filled with carefully purified normal hexane. A detailed study of the background of a detector of this type enabled them to define the conditions in which it is possible to stabilize this background and to reduce it to about 10^{-14} A/cm², for a uniform electric field of 8000 V/cm.

Under irradiation with alpha or gamma rays, and at laboratory temperature, the current which passes through the chamber is a linear function of the applied electric field, up to a critical field value which is a function of the degree of purity of the liquid. Above that critical value, a process of ion-multiplication takes place, somewhat similar to that which takes place in gases. The change in the ionization current then becomes exponential.

In that area of multiplication the authors detected impulses created by the passage of individual alpha particles. The low mobility of the ions in the hexane and their extensive recombination considerably limits the amplitude of the impulses, which can easily be confused with the amplifier's background if a certain number of precautions are not taken. Impulses were recorded with amplitudes varying between 2.5×10^{-5} and 25×10^{-5} V, and with growth-times between 2 and 20 μ s in electric fields of 21600 to 65600 V/cm.

A number of preliminary results for other liquid fillings are given.

Fonctionnement, à la température ambiante, de chambres d'ionisation remplies d'un diélectrique liquide. Les auteurs présentent les caractéristiques de fonctionnement de chambres d'ionisation remplies d'hexane normal, purifié avec soin. L'étude détaillée du bruit de fond d'un tel détecteur leur a permis de définir les conditions dans lesquelles on peut stabiliser ce bruit de fond et le diminuer jusqu'à 10^{-14} A/cm² environ, pour un champ électrique uniforme de 8000 V/cm.

Sous l'irradiation de rayons α ou γ , et à la température du laboratoire, le courant qui traverse la chambre est une fonction linéaire du champ électrique appliqué, jusqu'à une valeur critique du champ, fonction du degré de pureté du liquide. Au-dessus de cette valeur critique se produit un processus de multiplication ionique, assez analogue à celui qui a lieu dans les gaz. La variation du courant d'ionisation devient alors exponentielle.

Dans cette région de multiplication, les auteurs ont mis en évidence les impulsions créées par le passage de particules α individuelles: la faible mobilité des ions dans l'hexane, leur recombinaison, très importante, limitent considérablement l'amplitude des impulsions, qui risquent de se confondre avec le bruit de fond de l'amplificateur si l'on ne prend un certain nombre de précautions. Ils ont enregistré des impulsions dont les amplitudes varient de $2,5 \cdot 10^{-5}$ à $25 \cdot 10^{-5}$ V, avec des temps de montée compris entre 2 et 20 μ s, dans des champs électriques de 21600 à 65600 V/cm.

Le mémoire contient quelques résultats préliminaires concernant d'autres remplissages liquides.

Ионизационные камеры, наполненные жидким диэлектриком и действующие при комнатной температуре. Описаны рабочие характеристики ионизационных камер, наполненных обычным тщательно очищенным гексаном. Подробное изучение фоновых токов такого детектора позволяет определить, при каких условиях этот фоновый ток можно сделать устойчивым и уменьшить приблизительно до 10^{-14} ампер/см² в однородном электрическом поле в 8000 вольт/см.

При альфа- и гамма-излучении при температуре лаборатории ток, пересекая камеру, оставляет линейную функцию примененного электрического поля при критической величине поля, будучи сам функцией чистоты жидкости. При надкритической величине происходит процесс ионного размножения, имеющий сходство с газовым процессом.

Затем изменение ионизационного тока становится показательным. В этой зоне размножения авторы обнаруживали импульсы, производимые прохождением отдельных альфа-частиц. Как слабая подвижность ионов в гексане, так и их большая способность рекомбинации значительно ограничивают амплитуду импульса, который, если не принять ряд мер, можно спутать с фоном усилителя. Мы записали импульсы с амплитудами, колеблющимися в пределах от $2,5 \times 10^{-5}$ до 25×10^{-5} вольт и с временем нарастания между 2 и 20 микросекундами в электрическом поле между 21 600 вольт/см и 65 600 вольт/см.

Далее, мы даем предварительные результаты относительно других жидкостных наполнителей.

Cámaras de ionización llenas con un dieléctrico líquido que trabajan a la temperatura ambiente. Los autores dan las características de funcionamiento de cámaras de ionización llenas con hexano normal cuidadosamente purificado. El estudio de la corriente de fondo de un detector de esta clase les permitió establecer las condiciones necesarias para estabilizar dicha corriente y reducirla hasta unos 10^{-14} A/cm² en un campo eléctrico uniforme de 8000 V/cm.

Bajo el efecto de radiaciones alfa o gamma, a la temperatura ambiente, la corriente que atraviesa la cámara sigue siendo una función lineal del campo eléctrico que se aplique hasta un cierto valor crítico de la intensidad de campo que, a su vez, depende de la pureza del fluido. Por encima de este valor, se produce un proceso de multiplicación iónica que presenta cierta analogía con el que se observa en el gas.

Después, la variación de la corriente de ionización se hace exponencial. Los autores han analizado en esta zona de multiplicación los impulsos que se producen cuando partículas alfa aisladas atraviesan el campo. De no operar con cuidado, tanto la reducida movilidad de los iones en el hexano como su gran poder de recombinación limitarán considerablemente la amplitud del impulso, que puede llegar a confundirse con el fondo del amplificador. Los autores han registrado impulsos de amplitudes comprendidas entre $2,5 \cdot 10^{-5}$ y $25 \cdot 10^{-5}$ V, y tiempos de elevación entre 2 a 20 μ s al trabajar en campos eléctricos de 21 600 a 65 600 V/cm.

Además, dan los resultados preliminares obtenidos con otros líquidos.

Introduction

L'augmentation de la conductibilité électrique de liquides isolants placés dans des faisceaux de rayons X a été notée pour la première fois en 1896 par J. J. Thomson. P. CURIE [1] confirma l'existence d'un phénomène analogue sous l'irradiation des particules émises par des sources radioactives. Les premières déterminations quantitatives furent effectuées par JAFFÉ [2], qui mesura la variation du courant obtenu I en fonction de l'intensité E du champ électrique appliqué. D'après lui:

$$I = f(E) + CE \quad (1)$$

la fonction $f(E)$ devenant constante au-dessus d'une valeur déterminée de E ; la constante C est différente de zéro: I n'atteint pas la valeur de saturation, comme c'est le cas pour les gaz.

Partant de ces mesures, Jaffé a établi une théorie dont l'hypothèse fondamentale est la suivante [3]. L'ionisation d'un certain volume de liquide diélectrique par des particules ionisantes n'est pas homogène; les ions produits s'accumulent dans un cylindre entourant la trajectoire de la particule pour former une «colonne» ionisée de faible rayon. Cette distribution varie en fonction du temps sous l'effet de l'agitation thermique,

de la recombinaison, de l'action du champ électrique appliqué. Tenant compte de ces divers paramètres, Jaffé a calculé quelle est la fraction des ions produits qui doit atteindre les électrodes. La mesure des courants d'ionisation dans les liquides diélectriques à la température ambiante, et la vérification de la théorie de Jaffé, ont fait l'objet d'un certain nombre de publications [4]. Les travaux les plus récents sont ceux de RICHARDS [5] et de GIBAUD [6]. Dans tous les cas, les champs électriques ne dépassaient pas 15000 V/cm.

A partir de 1948, on a essayé de mettre en évidence les impulsions créées par des particules individuelles. A la température ambiante, les tentatives ont été négatives; ces impulsions n'ont pu être décelées que dans l'argon liquide [7] [8].

Nous avons repris ce problème pour examiner la validité de la théorie de Jaffé dans le cas de champs appliqués intenses (jusqu'à 100000 V/cm), pour tenter de mettre en évidence, à la température ambiante, les impulsions dues à des particules α , enfin pour définir les conditions d'emploi pratique de tels détecteurs.

Il faut noter que le pouvoir d'arrêt d'un liquide pour les particules nucléaires est beaucoup plus grand que celui d'un gaz; une telle chambre d'ionisation doit trouver des applications dans la mesure de l'intensité absolue de sources radioactives, dans la détection de particules rapides, et enfin dans la dosimétrie des neutrons rapides par détection de protons de recul.

Dispositif expérimental

CHAMBRES D'IONISATION

Il s'agit de chambres à électrodes planes parallèles dont la distance d est réglable entre 0 et 5 mm; le parallélisme des deux électrodes est réglé à $10\ \mu$ près. L'électrode collectrice a un diamètre de 50 mm; elle est plongée dans un champ électrique E pratiquement uniforme. Les diamètres des passages isolants de téflon sont calculés de telle sorte que le courant de fuite qui les traverse soit négligeable devant celui qui traverse le liquide.

En purifiant avec le plus grand soin l'hexane utilisé pour le remplissage, et en étuvant la chambre avant remplissage, nous sommes parvenus à abaisser le courant résiduel dans le liquide à des valeurs de l'ordre de 10^{-14} A/cm² pour un champ E de 20000 V/cm, la chambre étant placée dans un château de plomb de 5 cm d'épaisseur.

APPAREILS DE MESURE ET DE COMPTAGE

Pour mesurer le courant qui traverse le liquide, nous utilisons un électromètre à condensateur vibrant, équipé de résistances d'entrée égales à 10^8 , 10^{10} et $10^{12}\ \Omega$; les résultats sont envoyés sur un enregistreur graphique placé en série.

Pour mettre en évidence et compter les impulsions, nous employons un amplificateur linéaire de gain maximal égal à 200000, suivi d'un système classique de mise en forme et de numération; en parallèle avec ce système est disposé un oscillographe cathodique équipé d'un appareil photographique.

L'alimentation en tension de la chambre est constituée par une batterie de piles sèches permettant d'atteindre 5000 V. Ainsi, la stabilité est excellente.

Les perturbations électriques extérieures sont éliminées par une cage de Faraday qui entoure l'ensemble des appareils.

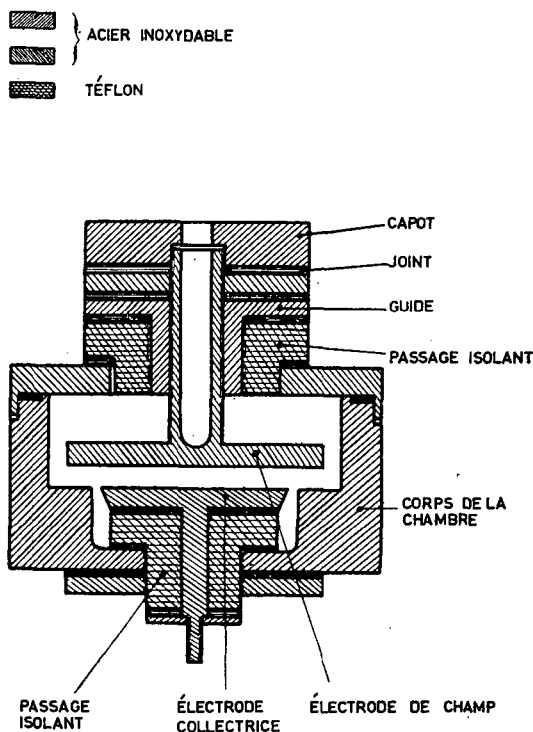


Figure 1

Vue en coupe du modèle de chambres d'ionisation utilisé.

Courant résiduel dans le liquide (bruit de fond)

VARIATION EN FONCTION DU TEMPS

Immédiatement après l'application de la tension entre les électrodes de la chambre, le courant résiduel subit des variations rapides à partir de sa valeur moyenne i : les fluctuations peuvent atteindre 10 fois la valeur moyenne; elles s'atténuent progressivement, en même temps que leur fréquence diminue. Après plusieurs heures de fonctionnement, les variations sont inférieures à 5% de la valeur moyenne. On trouvera sur la figure 2 un enregistrement de ces fluctuations au bout de 50 heures de fonctionnement à -10°C : le phénomène est très régulier.

La valeur moyenne i du courant résiduel décroît en fonction du temps, pour atteindre, au bout de 10 à 15 heures, une valeur pratiquement constante, de l'ordre de 10^{-14} A/cm^2 à la température du laboratoire et pour E voisin de 10000 V/cm . Lorsque l'on supprime l'alimentation HT de la chambre et qu'on la rétablit au bout de quelques minutes, i reprend une valeur initiale plus grande, pour diminuer à nouveau en fonction du temps. Ce phénomène s'explique — en partie tout au moins — par la présence dans le liquide d'impuretés à caractère ionique, qui s'éliminent progressivement par purification électrolytique.

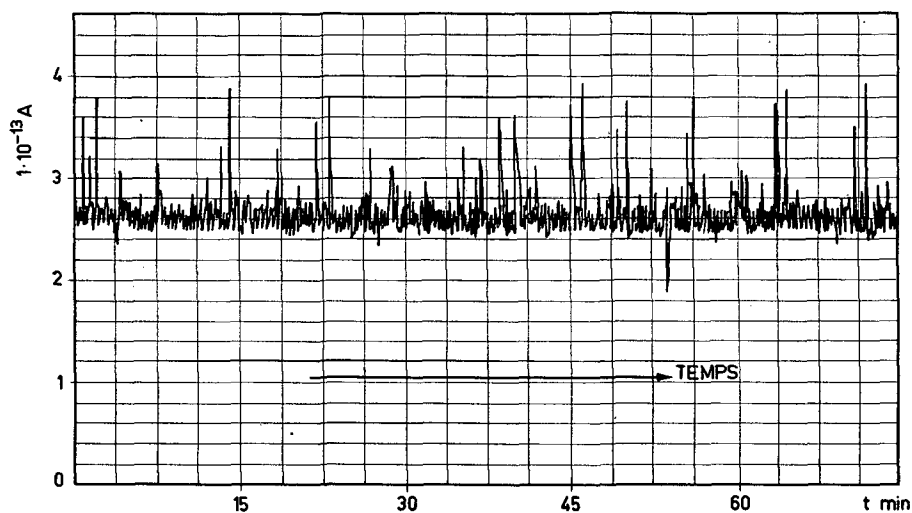


Figure 2

Enregistrement du courant résiduel 50 heures après mise sous tension de la chambre.

VARIATION EN FONCTION DU CHAMP E APPLIQUÉ

On trouvera sur la figure 3 la variation de i en fonction de E pour $d = 1$ mm: la courbe (a) a été mesurée 6 heures après mise sous tension, la courbe (b) au bout de 12 heures, la courbe (c) au bout de 60 heures. Au-dessus d'une certaine valeur du champ, i se met

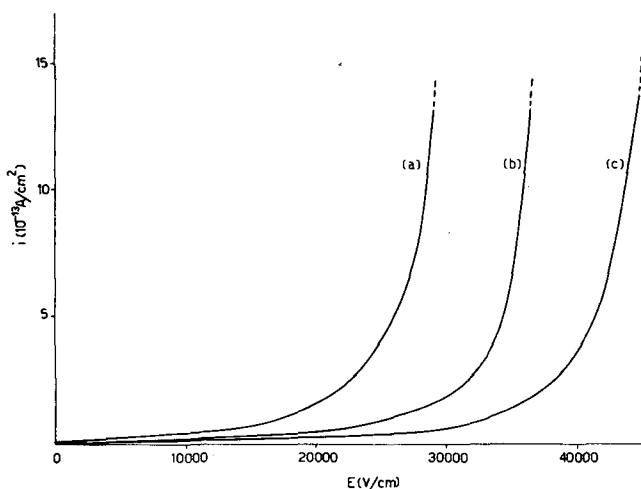


Figure 3

Variation de la valeur moyenne du courant résiduel en fonction du champ appliqué ($d = 1$ mm, 26°C).

à augmenter rapidement: pour l'échantillon utilisé, la résistivité, de $10^{18} \Omega/\text{cm}$ pour E inférieur à 20000 V/cm , atteint $1,3 \cdot 10^{15} \Omega/\text{cm}$ pour $E = 50000 \text{ V/cm}$. Ce phénomène d'amplification ionique à l'intérieur du liquide présente un seuil d'autant plus élevé que la purification électrolytique est plus poussée.

VARIATION EN FONCTION DE LA TEMPÉRATURE

La figure 4 donne les résultats obtenus pour $E = 8200 \text{ V/cm}$, le liquide ayant été maintenu au préalable sous tension pendant 72 heures, pour que le courant résiduel soit très stable. Le cycle thermique a été décrit en 70 heures afin que le refroidissement, très lent, soit bien homogène. A -10°C , i , qui est environ 5 fois plus faible qu'à $+10^\circ\text{C}$, possède une stabilité remarquable et les fluctuations sont très peu nombreuses. A $+35^\circ\text{C}$, la valeur de i est trop faible pour être mesurée à l'aide de l'électromètre dont nous disposons. La variation thermique de i paraît associée à une émission thermo-ionique depuis la cathode.

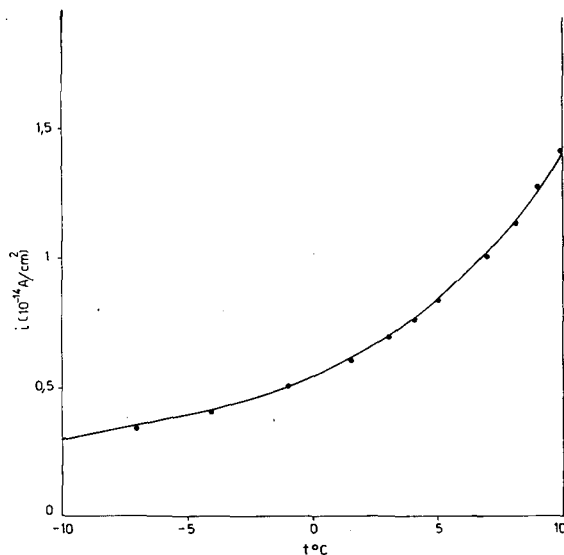


Figure 4

Variation de la valeur moyenne du courant résiduel en fonction de la température ($E = 8200 \text{ V/cm}$).

Fonctionnement de la chambre en courant

Une source de cobalt-60 (12 mc) est placée en position invariable à l'intérieur de la cavité ménagée dans l'électrode supérieure (fig. 1). Avant les mesures, la chambre est maintenue sous tension assez longtemps pour que i atteigne sa valeur limite.

La figure 5 présente le phénomène produit par l'introduction de la source: le courant passe de sa valeur résiduelle ($i = 2,5 \cdot 10^{-13} \text{ A/cm}^2$ dans l'exemple choisi) à une valeur I beaucoup plus élevée ($2,8 \cdot 10^{-12} \text{ A/cm}^2$), très stable ($E = 20000 \text{ V/cm}$); i est négligeable devant la valeur du courant dû à l'ionisation dans le liquide. Nous avons vérifié que I est proportionnel à l'intensité du rayonnement γ qui traverse le volume utile de la

chambre, en modifiant la position de la source dans la cavité (fig. 1): le fonctionnement du détecteur est donc correct.

Les résultats obtenus avec des sources de rayons α (^{210}Po) sont analogues à ceux donnés plus bas.

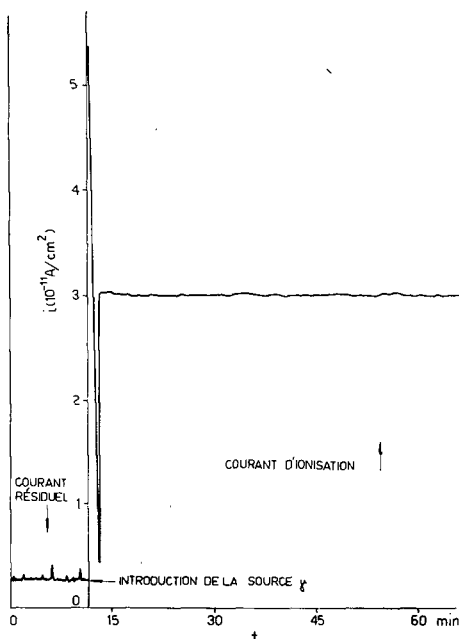


Figure 5

Enregistrement du courant traversant la chambre après introduction d'une source de ^{60}Co ($E = 20000 \text{ V/cm}$).

COMPARAISON AVEC LA THÉORIE DE JAFFÉ

Lorsque E est inférieur à une certaine valeur critique, comprise entre 10000 et 30000 V/cm selon le degré de pureté du liquide (fig. 3), le courant total I est une fonction linéaire de E (fig. 6): la formule (1) est bien vérifiée. De plus, l'ordonnée à l'origine de la droite obtenue est proportionnelle à la distance d séparant les électrodes, ce qui confirme le bon fonctionnement du détecteur. Enfin, la forme de la courbe $I = f(E)$ prouve que l'on n'atteint pas la valeur de saturation du courant d'ionisation dans le liquide.

RÉGION DE MULTIPLICATION IONIQUE

Lorsque E dépasse la valeur critique, I cesse d'être une fonction linéaire de E , tout en restant proportionnel à l'intensité du rayonnement qui traverse la chambre: la courbe $I = f(E)$ est une exponentielle.

Ce phénomène, que les auteurs précédents n'ont pas signalé parce qu'ils employaient des valeurs de E trop faibles, prouve qu'il existe un processus de multiplication ionique

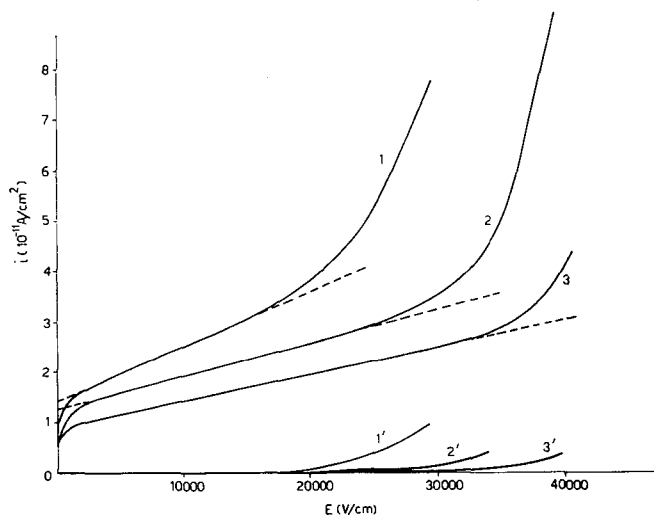


Figure 6

Variation de I et i en fonction de E pour divers degrés de pureté de l'hexane.

à l'intérieur du liquide [9]; ce processus se déclenche avant que I n'ait atteint la saturation, contrairement à ce que pensait Jaffé.

Les courbes de la figure 6 ont été prises dans les conditions suivantes: la chambre est maintenue 24 heures sous tension ($E = 15000$ V/cm); on trace alors les caractéristiques donnant I (courbe 1) et i (courbe 1'). Après avoir maintenu à nouveau la chambre 24 heures sous tension, on obtient les courbes 2 et 2'; enfin, après un séjour supplémentaire de 48 heures sous tension, les courbes sont 3 et 3'.

Cette expérience montre que, pour E donné, le courant d'ionisation dans l'hexane est d'autant plus faible que le liquide est plus pur et que le seuil d'amplification augmente avec le degré de pureté. Ceci confirme l'importance des impuretés dans le mécanisme de fonctionnement d'un tel détecteur.

Fonctionnement de la chambre en impulsions

L'existence d'impulsions dans l'hexane à la température ambiante n'ayant jamais été mise en évidence antérieurement, nous avons choisi une source de particules α , très ionisantes, pour nous placer dans les conditions optimales permettant d'isoler les impulsions individuelles: une source de polonium-210 (alphas de 5,3 MeV) a été déposée au centre de la face interne d'une cathode spéciale en argent; l'intensité de la source est très faible (60 particules α par seconde, environ) pour que le temps qui sépare deux impulsions successives soit supérieur à la constante de temps du circuit d'entrée.

EXISTENCE DES IMPULSIONS

Nous avons réglé la distance d entre les électrodes à une valeur voisine du parcours des particules α dans l'hexane, parce que les mobilités ioniques y sont très faibles. Moyennant cette précaution, nous avons obtenu des impulsions pour les valeurs de E correspondant à la région d'amplification; les impulsions ont des amplitudes très

supérieures au bruit de fond et suffisantes pour être comptées par les circuits de comptage décrits plus haut, et pour être photographiées sur l'écran de l'oscillographe cathodique.

CARACTÉRISTIQUES DES IMPULSIONS

On trouvera sur la figure 7 deux impulsions successives, prises en balayage déclenché, la vitesse de la base de temps étant de 160 cm/ms.

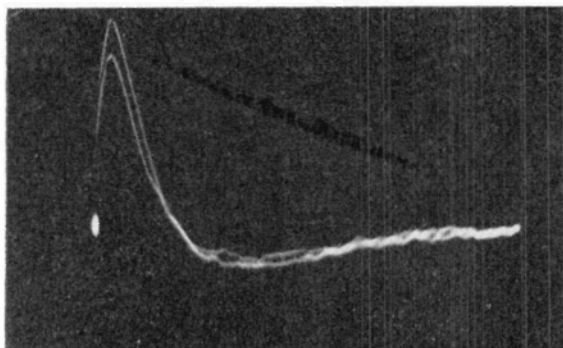


Figure 7

Deux impulsions successives dans l'hexane liquide (vitesse de balayage: 160 cm/ms; $E = 44000$ V/cm).

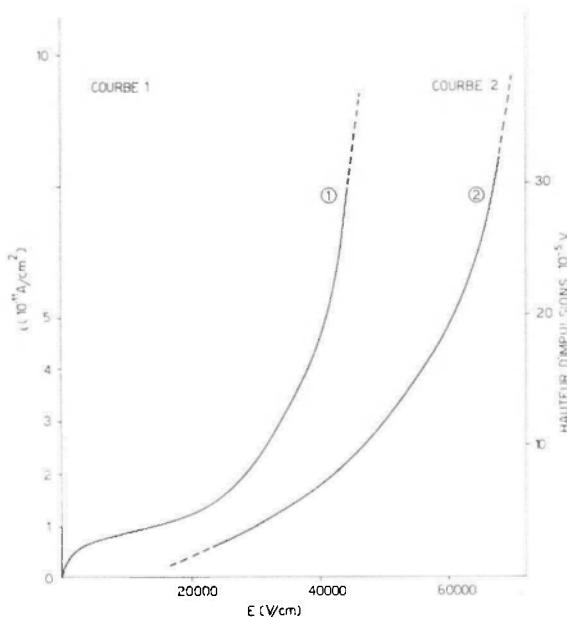


Figure 8

Variation, en fonction de E , 1) de I sous irradiation γ , 2) de la hauteur maximale des impulsions.

Les impulsions ne sont pas de hauteur uniforme. On trouvera sur la figure 8 la variation de leur amplitude maximale en fonction du champ (courbe 2). La courbe 1, qui donne le courant d'ionisation I sous irradiation gamma, montre que les impulsions ne deviennent détectables que dans la région d'amplification: c'est pour cette raison qu'aucun auteur n'était parvenu, jusqu'alors, à les mettre en évidence.

On trouvera enfin sur la figure 9 la variation de l'amplitude maximale des impulsions en fonction de leur temps de montée pour $E = 44000$ V/cm.

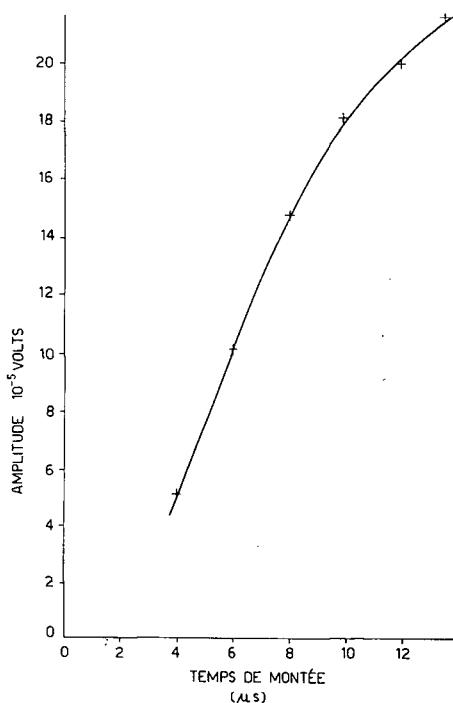


Figure 9

Hauteur maximale des impulsions en fonction du temps de montée ($E = 44000$ V/cm).

Résultats préliminaires obtenus avec des remplissages de benzène

Comme l'hexane, le benzène possède une conductivité électrique théorique égale à zéro, et sa purification est moins difficile que celle de l'hexane. Les résultats obtenus avec le benzène sont analogues à ceux donnés plus haut.

a) Le courant résiduel moyen i diminue en fonction du temps pour atteindre une valeur constante d'autant plus grande que le champ électrique appliqué est plus élevé (fig. 10). D'autre part, la purification du liquide s'effectue beaucoup plus rapidement que dans le cas de l'hexane.

b) On retrouve un effet d'amplification ionique pour des valeurs du champ suffisamment élevées (fig. 11); ce phénomène est d'autant plus rapide que la température est

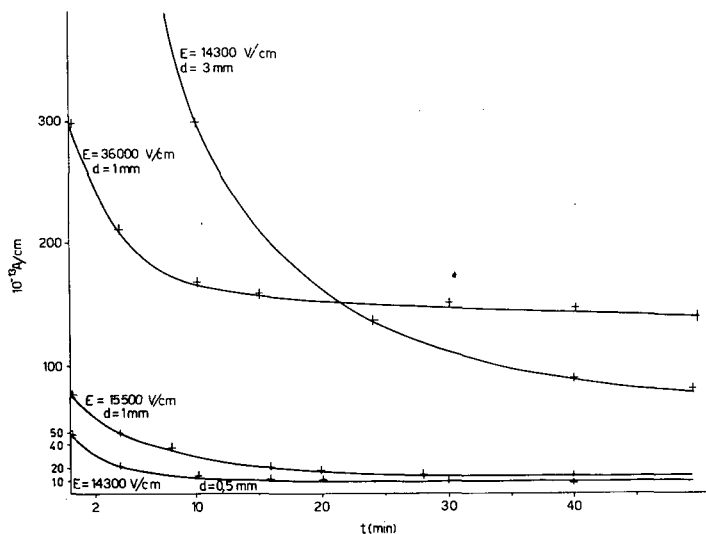


Figure 10

Variation de la valeur moyenne du courant résiduel en fonction du temps (20°C).

plus élevée. Dans la région d'amplification, l'intensité du courant qui traverse le liquide est une fonction exponentielle de E . Comme dans le cas de l'hexane, le seuil du phénomène est d'autant plus élevé que le liquide est plus pur.

c) La réponse de la chambre d'ionisation à des sources radioactives est analogue à celle d'un remplissage d'hexane liquide.

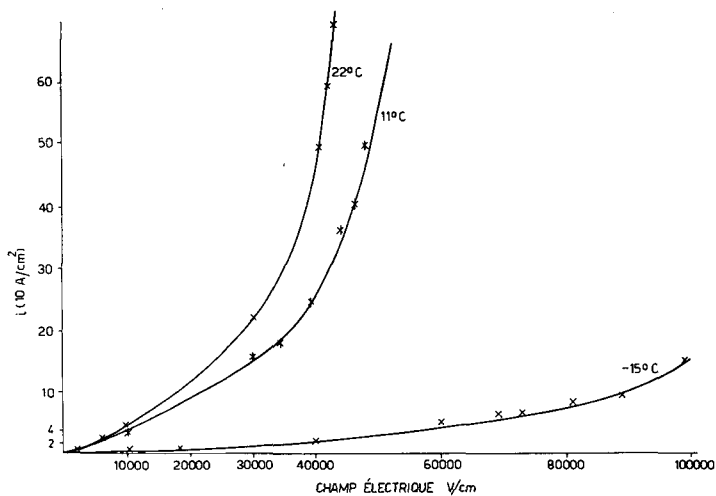


Figure 11

Variation de la valeur moyenne du courant résiduel en fonction du champ appliqué ($d = 1 \text{ mm}$), après un séjour de 24 heures sous tension.

Conclusion

Nos expériences montrent que, moyennant une purification très soignée du liquide, les chambres d'ionisation remplies d'hexane ou de benzène fournissent des résultats stables et reproductibles.

Nous avons mis en évidence un phénomène de multiplication ionique; cet effet est à rapprocher de celui qui se produit dans les gaz et dans les jonctions (p-n) de semi-conducteurs.

REMERCIEMENTS

Ces recherches ont été effectuées dans des laboratoires mis aimablement à notre disposition par M. le Pr. Blaizot, directeur de l'Institut de physiologie de l'université de Toulouse.

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DISCUSSION

G. L. Miller (United States of America): Can you say what resolution you obtained with α particles?

F. Cambou (France): I have not participated in this work, but I believe the resolution was approximately 10%.

M. Paic (Yugoslavia): For what neutron energy is the chamber intended?

F. Cambou: The chamber is intended for measurements on neutrons produced by d, d or d, t reactions and in particular for monitoring 3 MeV neutrons in low-energy d, d reactions.

EXPERIMENTAL TECHNIQUES IN LOW-LEVEL ALPHA SPECTROMETRY

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Abstract — Résumé — Аннотация — Resumen

Experimental techniques in low-level alpha spectrometry. Several ionization chambers designed for the study of extremely weak alpha activities are described. Sources from one to 6000 cm² are used, and by special coincidence techniques a background value of less than 0.01 counts/channel (30 keV) per hour is achieved. The preamplifiers consist of one PCC 88 and one 6AK5 and photographic recording is used in most measurements. By careful stabilization an alpha-line with a half-width of less than 100 keV is routinely achieved in exposures lasting hundreds of hours. By using a clipping time-constant of about 1 μ s the alpha activity of sources containing 100 to 200 μ c of beta activity can be studied. Under these circumstances an alpha branching of 10^{-8} to 10^{-9} is detectable.

Techniques expérimentales pour la spectrométrie alpha de faible intensité. L'auteur décrit plusieurs chambres d'ionisation destinées à l'étude d'activités alpha très faibles. Il utilise des sources de 1 à 6000 cm² et, en appliquant des méthodes spéciales de coïncidence, il obtient un bruit de fond inférieur à 0,01 coup par canal (30 keV) et par heure. Les deux préamplificateurs sont l'un du type PCC 88 et l'autre du type 6AK5; la plupart des mesures sont enregistrées photographiquement. Avec une bonne stabilisation, on peut normalement obtenir une demi-largeur de bande alpha inférieure à 100 keV, pour des expositions se prolongeant plusieurs centaines d'heures. En utilisant une constante de temps d'écrêtage de l'ordre de 1 μ s, on peut étudier l'activité alpha des sources contenant 100 à 200 microcuries d'activité bêta. Dans ces conditions, on peut déceler un branchement alpha de l'ordre de 10^{-8} à 10^{-9} .

Экспериментальные методы спектрометрии слабых альфа-излучений. Описывается целый ряд ионизационных камер, предназначенных для исследования чрезвычайно слабой альфа-активности. Были использованы источники от одного до 6000 кв. см., благодаря применению особых методов совпадения удалось достичь обнаружения значений фона менее чем в 0,01 отсчетов на канал (30 кэв) в час. Предварительные усилители состоят из одного усилителя типа PCC 88 и другого усилителя типа 6AK5; при производстве большинства измерений применялась фоторегистрация. Благодаря тщательной стабилизации при выдержках, длящихся сотни часов, удается достигать полуширины альфа-линии менее чем 100 кэв. Путем использования константы времени прерывания порядка одной микросекунды удается изучать альфа-активность источников, содержащих от 100 до 200 микрокури бета-активности. Эти условия позволяют обнаруживать альфа-разветвление в интервале от 10^{-8} до 10^{-9} .

Técnicas experimentales en espectrometría de radiaciones alfa muy débiles. Se describen varios tipos de cámaras de ionización adecuadas para el estudio de actividades alfa sumamente débiles. Con fuentes de 1 a 6000 cm² y utilizando técnicas especiales de coincidencia se logra reducir el fondo a menos de 0,01 impulsos por canal (30 keV) y por hora. Los preamplificadores constan de una lámpara PCC 88 y una 6AK5 y la mayor parte de las medidas son registradas fotográficamente. Mediante una estabilización cuidadosa pueden conseguirse normalmente picos de anchura media inferior a 100 keV, en exposiciones de una duración de centenares de horas. Utilizando tiempo de corte constante de un μ s aproximadamente se puede estudiar la actividad alfa de fuentes que contengan de 100 a 200 μ c de actividad beta. De esta manera pueden estudiarse ramificaciones alfa de unos 10^{-8} a 10^{-9} .

I. Introduction

The instruments described below have been designed for the study of very weak natural and artificial alpha emitters. A total of eight ionization chambers for sources from 5 cm² to 6000 cm² in area have been constructed together with four analysers each consisting of amplifiers, an oscillograph with a moving-film camera, and power supplies.

The natural activities of rare earths and other medium-heavy elements are being systematically studied. In an investigation on Sm, KARRAS [1] discovered the alpha activities of Sm¹⁴⁸ and Sm¹⁴⁹. A search for alpha activity in neutron-deficient isotopes of Pb, Tl, Hg and Te has been made in co-operation with the Gustaf Werner Institute in Sweden [2]. Recently we discovered the alpha branching in Pb²¹⁰ which led to the identification of a new natural radio-nuclide, Hg²⁰⁶ [3].

II. The ion chambers

Most of the work is being done with parallel-plate gridded ion chambers of the type described recently by KARRAS [1]. The "small chambers" accommodate circular sources 6 cm in diam. while the "large chambers" take sources with a diameter of up to 20 cm.

The chambers are made of steel and copper-plated inside while the electrodes are made of copper and brass and are heavily silver-plated. Glass is used as insulator and lead wire as packing; no organic materials are used.

The chambers are filled with a mixture of 90% A + 10% CH₄ to a pressure of 1 to 4 atm depending on the alpha-energy region studied. By observing strict cleanliness and avoiding the use of organic fluids in cleaning, the chambers can be routinely operated for hundreds of hours continuously without any measures to purify the gas filling.

III. The electronics

A schematic diagram of an ion chamber and the associated electronic circuits is shown in Fig. 1. The source (1) is placed between two earthed grids (2) which act as shields defining the sensitive volume of the chamber. The source is held at a negative potential of a few hundred volts while the collectors (3) and guard rings (4) are maintained at a somewhat larger negative potential; the ratio of these potentials is adjusted for

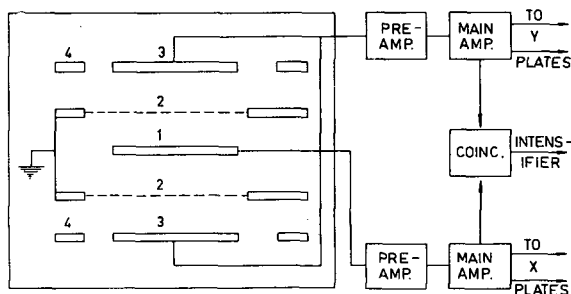


Fig. 1

Schematic diagram of an ion chamber with associated electronic systems. 1 — source, 2 — grids, 3 — collectors, 4 — guard rings

optimum resolution. In many investigations only one side of the source is used; the unused collector is then disconnected to decrease the input capacitance of the pre-amplifier.

The alpha particles emitted by the source spend their range in the sensitive volume and produce an electron cloud which moves through the grid to the collecting electrode inducing a pulse to both the source and the collector. These pulses are separately amplified in the preamplifiers and main amplifiers and applied to the *X* and *Y* plates of a cathode-ray tube. Upon simultaneous arrival of both pulses the coincidence circuit produces an intensifier and enables the pulse to be photographed.

The circuit diagram of the preamplifier is shown in Fig. 2. It is followed by an adjustable RC network which determines the shape of the pulses. A rise-time of 2–4 μ s and a clipping time of 5–10 μ s are normally used.

The final amplifier consists of an EF 80 and an ECF 82 in a feedback loop followed by a pair of EF 80's in push-pull with plate-to-grid feedback. The maximum gain is 1000; it is adjustable by steps of 2 db in the first feedback loop.

The *X* and *Y* pulses are finally fed to a cathode-ray tube of the type 5ADP11 operated at a total accelerating voltage of 4 kV.

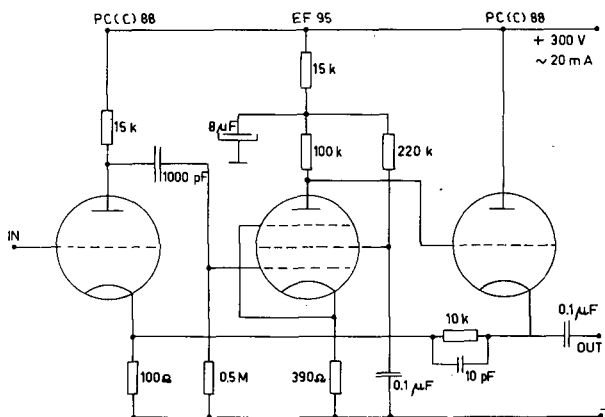


Fig. 2
Circuit diagram of the preamplifier

Each analyser is run on AC stabilized with a Servomex stabilizer, the total consumption being 250 W. In addition, the 300-V HT for all units and the DC for preamplifier filaments are separately stabilized with Servomex units.

The components are chosen for stability and low noise, and open-rack construction is used to minimize heating.

With selected preamplifier tubes the noise level of the system corresponds to about 5 μ V rms at the input which is equivalent to an alpha-line width of 10 keV in the small chamber and 16 keV in the large chamber.

IV. The method of spectrum analysis

Each alpha particle which spends a part of its range within the sensitive volume of the chamber will produce an oblique line in the cathode-ray tube. The *Y* amplitude

of the line will be proportional to the energy of the alpha particle while its X amplitude depends in addition on the location of the "centre of gravity" of the electron cloud between source and grid. Too large X amplitude indicates that part of the Y amplitude has been lost; the alpha particle concerned was probably emitted from the source holder whereupon part of its electron cloud failed to reach the collector. Too small X amplitudes distinguish pulses due to alpha particles emitted from the grid toward the source; their electron clouds form too close to the grid to induce normal X pulses to the source electrode.

Each pulse is separately photographed on a 35-mm film moving at a speed of 3 to 300 cm/h. The film is then analysed by measuring the Y amplitude of each pulse with an optical projector. An example of spectra thus obtained is shown in Fig. 3. The source consisted of 3 mg of natural Dy_2O_3 containing about 100 ppm of Sm and 50 ppm of Th vacuum-evaporated on one side of a 6-cm source plate. The measurement was carried out in a small chamber and lasted for 265 h. A small decrease of pulse amplitudes was observed during the measurement; to counteract it the optical magnification used upon analysing the film was increased by 0.5% at 180 h.

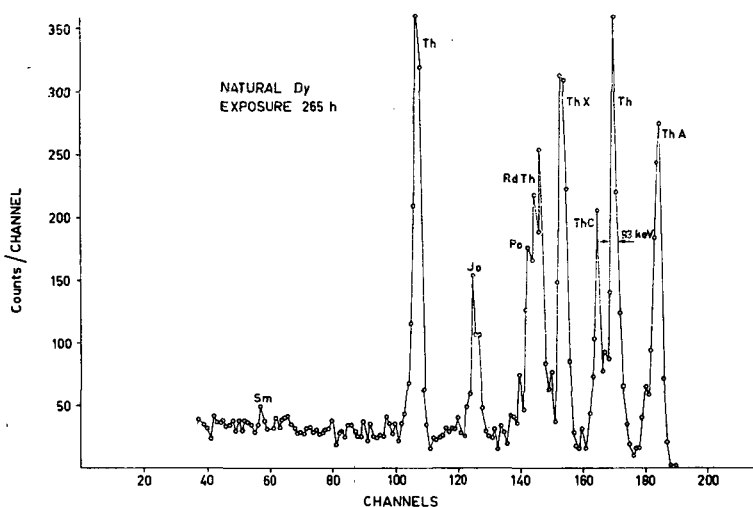


Fig. 3

Alpha spectrum of a natural Dy source

The line-width obtained is about 100 keV and partial resolution of the two RdTh lines with a separation of 84 keV is observed. It is interesting to note that the major Th lines in the spectrum correspond to an activity of about 3 counts/h while the Sm line contains only about 0.1 count/h.

V. The study of small alpha branchings

It has been found possible to operate the ion chambers under the presence of several tens of microcuries of beta and gamma activity in the source. By decreasing the pulse rise and clipping times to about 1 μ s and using an electronic pulse analyser as much as

200 μC can be tolerated. Under these conditions the line-width deteriorates to 200 or 300 keV but it is still possible to detect alpha activities amounting to a few counts per hour.

An example of this kind of study is provided by the measurement of the alpha branching of RaD with a result of $(1.8 \pm 0.5) \times 10^{-8}$ alpha particles per disintegration [3]. It is estimated that an alpha branching of 10^{-9} or less could be detected under favourable conditions.

VI. The limits of the present technique

The limit of lowest alpha activity detectable is set by the amount of source material that can be used, the background of the chamber, the energy resolution, and the stability of the system.

If no special precautions are taken the small chambers exhibit a background of 0.1 count/channel-hour (40-keV channels; see Fig. 3), while sources chemically purified from the Th series yield a background of only 0.04 count/channel-hour in the large chamber with ten times larger source area.

The thickness of the source is usually about 100 $\mu\text{g}/\text{cm}^2$ which will make a contribution of about 80 keV in the line width. On the other hand extremely thin Po sources have yielded a total line width in a small chamber of 42 keV measured with a discriminator.

The stability of the equipment makes it possible to carry out measurements of virtually unlimited duration with a line width of about 100 keV in the small chambers and 150 keV in the large chambers. Thus it may be estimated that an activity corresponding to a few disintegrations per day in a gram of material could be detected with the present equipment under optimum conditions. This corresponds to a half-life of 10^{18} years.

It might be possible to extend the limit still somewhat by the use of "infinitely thick" sources, i.e. sources thicker than the range of alpha particles in the material. This type of source emits a continuous spectrum with a sharp upper limit at the alpha energy of the material; the much larger amount of source material contributing to the spectrum makes it possible to accumulate statistically significant data in a relatively short time if the problem of radioactive impurities can be solved [4].

ACKNOWLEDGEMENTS

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DISCUSSION

M. Forte (European Atomic Energy Community): What proportion of the activity is due to the natural content of alpha-active elements in the source-holder, and of what material is the source-holder made?

M. Nurmia (Finland): We have been using source-holders made of brass and stainless steel and the parts used have to be carefully selected—they have first to be tried in the chambers for a few hours or a day. I do not think it is possible beforehand to say that a holder will not contain any active material regardless what it is made of. One way* is to use an infinitely thick source which will then give rise to a spectrum which looks like a step function from the alpha energy concerned down to zero energy. In this way one avoids the use of any backing plate but the source material itself has to be extremely pure from alpha-active impurities. I would like to stress that usually most of the background comes from alpha-active materials like thorium in the source studied. It is relatively easy to eliminate all other sources of background.

M. Forte: May I suggest that a source-holder made of some organic material like lucite could be used?

M. Nurmia: Lucite seems to poison the gas filling in very long measurements. We have tried it and it is good for a few hours, but not for any longer period. On the other hand it appears quite possible to use glass, which can be purified. The surface of the glass plate can be purified very well. But we are now working with these rare earth elements and the difficulty is to purify the sample itself—not necessarily the backing.

M. Forte: There are a few gas mixtures which are not sensitive to organic contaminations. For instance we have used argon plus 2% nitrogen in an ionization chamber which had rubber gaskets and no great care was taken in cleaning the chamber before the measurement.

M. Nurmia: Yes, I agree it is possible to do that. We used argon and 10% methane and we have been using rubber gaskets and so on, but if you take a very long measurement you will observe that in about one hundred hours your pulse-heights will decrease by about 1% if there are any organic materials in the chamber.

* GRAEFFE, G. and NURMIA, M., *Ann. Acad. Scient. Fenn.*, A. VI, (1961) 77.

A NEW TYPE OF INSTRUMENT FOR THE STUDY OF THE ANGULAR DISTRIBUTION OF FISSION FRAGMENTS

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Abstract — Résumé — Аннотация — Resumen

A new type of instrument for the study of the angular distribution of fission fragments. A gas scintillation counter in combination with a gridded ionization chamber has been developed to determine the angular distribution of ionizing particles with respect to a fixed direction. The cathode of the ionization chamber is coated with a thin layer of source material which emits ionizing particles under investigation. Pure xenon serves as an ionization gas of the chamber as well as a scintillator. A photomultiplier incorporated in the chamber observes the light emitted along the track of the ionizing particle, and gives a zero time pulse. The subsequent rise of the ionization pulse from the gridded ionization chamber gives the delay which determines the projection of the track length on the electric field. From the pulse height of the ionization pulse, the range of the track is determined. From knowledge of the range of the track and its projection along a fixed direction, the angular distribution of the ionizing particles is determined.

To study the mechanism of prompt neutron emission in the fission process, this instrument has been used to determine the angular correlations of prompt neutrons of specified energies and fission fragments in the thermal neutron fission of U^{235} . A fast neutron time-of-flight spectrometer has been associated with the above to measure the energies of the prompt neutrons by the time-of-flight technique. The fast neutron detector was placed along the electric field direction of the ionization chamber. The angular correlations of light fission fragments and prompt neutrons of specified energies have been obtained with the above arrangement.

Nouveau type d'appareil pour l'étude de la distribution angulaire des fragments de fission. Les auteurs ont mis au point un compteur à scintillation à gaz combiné avec une chambre d'ionisation à grille, pour déterminer la distribution angulaire des particules ionisantes par rapport à une direction fixe. La cathode de la chambre d'ionisation est revêtue d'une mince couche de matière radioactive qui émet des particules ionisantes, sur lesquelles porte la recherche. Du xénon pur est utilisé dans la chambre d'ionisation et comme scintillateur. Un photomultiplicateur incorporé dans la chambre observe la lumière émise le long de la trajectoire de la particule ionisante et délivre une impulsion à t_0 . Le temps de montée de l'impulsion d'ionisation provenant de la chambre d'ionisation à grille détermine la projection de la trajectoire sur la direction du champ électrique. On détermine le parcours d'après l'amplitude de l'impulsion d'ionisation. Lorsqu'on connaît le parcours et sa projection sur une direction fixe, on peut déterminer la distribution angulaire des particules ionisantes.

On a utilisé l'appareil décrit ci-dessus, dans les études sur le mécanisme d'émission des neutrons instantanés au cours du processus de fission, pour déterminer les corrélations angulaires entre les neutrons instantanés d'énergie déterminée et les fragments de fission, en particulier dans la fission de l'uranium-235 par les neutrons thermiques. Un spectromètre de temps de vol pour des neutrons rapides a été associé à l'ensemble ci-dessus pour mesurer les énergies des neutrons instantanés par la méthode du temps de vol. Le détecteur de neutrons rapides a été placé dans la direction du champ électrique de la chambre d'ionisation. Le dispositif décrit a permis d'obtenir les corrélations angulaires entre fragments légers de fission et neutrons instantanés d'énergies déterminées.

Новый вид прибора для изучения углового распределения осколков деления. Был усовершенствован газовый сцинтилляционный счетчик в комбинации с решетчатой ионизационной камерой для определения углового распределения ионизирующих частиц в отношении установленного направления. Катод ионизационной камеры покрывается тонким слоем исходного материала, который излучает изучаемые ионизирующие частицы. Чистый ксенон служит в качестве ионизационного газа камеры, а так же и как сцинтиллятор. Фотоумножитель, соединенный с камерой, фиксирует свет, излучаемый вдоль следа ионизирующей частицы, и дает нулевое время импульса. Последующее возрастание ионизационного импульса от решетчатой ионизационной камеры создает задержку, которая определяет проекцию длины трека в электрическом поле. По амплитуде импульса ионизационного толчка определяется протяженность трека. Определение протяженности следа и его проекций вдоль установленного направления дает возможность определить угловое распределение ионизирующих частиц.

При изучении механизма излучения мгновенного нейтрона в процессе деления этот прибор был использован для определения угловых корреляций мгновенных нейтронов установленных энергий и для определения осколков деления в процессе деления на тепловых нейтронах U^{235} . Спектрометр времени пролета быстрых нейтронов был соединен с вышеуказанным прибором с целью измерения энергий мгновенных нейтронов методом времени пролета. Детектор быстрых нейтронов был помещен вдоль направления электрического поля ионизационной камеры. В результате вышеуказанных мер были получены угловые корреляции легких осколков деления и мгновенных нейтронов установленных энергий.

Nuevo tipo de instrumento para el estudio de la distribución angular de fragmentos de fisión. Los autores han montado un contador de centelleo gaseoso en combinación con una cámara de ionización con rejilla para determinar la distribución angular de partículas ionizantes con respecto a una dirección fija. El cátodo de la cámara de ionización está revestido de una capa muy delgada de la sustancia activa que emite las partículas ionizantes objeto del estudio. La cámara emplea xenón puro como gas de ionización y como centelleador. Lleva incorporado un fotomultiplicador que registra la luz emitida a lo largo de la traza de la partícula ionizante y da el impulso correspondiente al tiempo cero. La elevación subsiguiente del impulso en la cámara de ionización con rejilla da el retardo que determina la proyección de la longitud de la traza sobre el campo eléctrico. A partir de la amplitud del impulso de ionización se puede calcular la longitud de la traza, y ésta, junto con su proyección sobre una dirección fija, permite determinar la distribución angular de las partículas ionizantes.

Este dispositivo ha servido a los autores para determinar las correlaciones angulares entre neutrones rápidos de energías específicas y fragmentos de fisión por neutrones térmicos del ^{235}U y estudiar así el mecanismo de emisión de neutrones rápidos en el proceso de fisión. Acoplando a los instrumentos ya citados un espectrómetro de tiempos de vuelo para neutrones rápidos, pudieron medir las energías de los neutrones rápidos por la técnica del tiempo de vuelo. Colocaron el detector de neutrones rápidos en la dirección del campo eléctrico en la cámara de ionización. Con este dispositivo se han obtenido las correlaciones angulares entre fragmentos ligeros de fisión y neutrones rápidos de energías específicas.

Introduction

The ionization chamber technique has been used to develop several methods to determine the angular distributions of heavy ionizing particles such as fission fragments and alpha particles. BATCHELOR *et al.* [1] and RAMANNA *et al.* [2] have made use of the greater mobility of the negative ions as compared to that of the positive ions to study the angular distribution of fission fragments. ROY [3] has studied the angular and energy distributions of fission fragments by means of a multi-gridded ionization chamber utilizing the same principle. SHERR *et al.* [4] and GATTI *et al.* [5] have derived

the angle of the ionizing particle track from a study of the shape of the pulse. The present method uses a combination of a gridded ionization chamber in combination with a gas scintillation counter to determine the angular distribution of ionizing particles with respect to the electric field direction of the ionization chamber. This method has been applied to a study of the angular distributions of fission fragments of specified energies in coincidence with prompt neutrons of various energies in the thermal fission of U^{235} . The energies of the prompt neutrons are determined by the time-of-flight technique. This has the advantage that many angles in the laboratory system can be studied simultaneously for selected prompt neutron energies. The angular correlation determines the angular distribution of the prompt neutrons of various emission energies in the fission fragment system, which throws light on the mechanism of the prompt neutron emission in the fission process.

Principle of the method

The source of the ionizing particles is coated on the cathode of a gridded ionization chamber. If the track of an ionizing particle has a range R and makes an angle Φ with the electric field direction, the delay t between the instant of the formation of the track and the instant the electrons from the edge of the track cross the grid is given by

$$(L - vt) = R \cos \Phi$$

where L is the distance between the cathode and the grid, and v is the drift velocity of the electrons. This gives $(\alpha - \beta t) = \cos \Phi$ for a fixed range R . The delay distribution $N(t)$ per unit time interval is related to the angular distribution $n(\Phi)$ per unit solid angle by the equation

$$N(t) dt = \text{Const. } n(\Phi) \sin \Phi d\Phi$$

which gives

$$\begin{aligned} n(\Phi) d\Phi &= \text{Const. } N(t) \frac{dt}{d\Phi} \cdot d\Phi \\ &= \text{Const. } N(t) d\Phi \text{ for a fixed range } R \end{aligned}$$

i.e.

$$n(\Phi) = \text{Const. } N(t)$$

Hence the delay distribution $N(t)$ directly gives the angular distribution $n(\Phi)$ of the ionizing particles of a fixed range R .

To determine the delay t , a photomultiplier type 6810-A is incorporated in the chamber to observe the scintillations produced in the gas due to the passage of the ionizing particle and give the zero time pulse. The zero time pulse triggers an oscilloscope sweep and the ionization pulse is applied to the y-axis. The point of rise of the ionization pulse determines the delay t .

In the case of isotropic emission of the ionizing particles the angular distribution $n(\Phi)$ plotted against Φ and hence the delay distribution $N(t)$ plotted against t for a fixed range R should be rectangular. In the rectangular distribution $t_{\min}$ and $t_{\max}$ correspond to the angles of 0° and 90° respectively. This determines the constants α and β for the selected ranges. With α and β known, angles corresponding to other delays can be determined.

Description of the apparatus

GRIDDED IONIZATION CHAMBER—SCINTILLATION-COUNTER SYSTEM

The gridded ionization chamber—scintillation counter-system is shown in Fig. 1. The distance between the collector and the grid and the grid and the cathode was 0.7 cm and 2.1 cm respectively. The cathode of the ionization chamber was coated with a layer of U^{235} 0.5 mg/cm² thick. The grid-wire radius was 5×10^{-3} cm and the grid-wire separation 76×10^{-3} cm. From the theory of BUNEMAN *et al.* [6] in the design of a gridded ionization chamber, the inefficiency of grid shielding (σ) was found to be 1.5% and the minimum field ratio of the grid collector to grid-cathode region was 2.5 for no electron collection by the grid. The ionization chamber was filled with pure Xenon gas to a pressure of 1.3 atm. It is very necessary to maintain a high degree of gas purity since the resolution of the chamber, the drift velocity of the electrons and also the scintillation pulse height are very sensitive to small traces of impurities. Care was taken in choosing the materials inside the system so that the gas remained at a high degree of purity for long periods. Xenon gas was purified by passing it over a hot calcium purifier to remove any traces of moisture and it was alternately solidified in a liquid nitrogen trap and pumped on it so that all traces of gaseous impurities were removed. The ionization chamber was flushed several times by the Xenon gas before final filling to remove traces of any other electro-negative gas and the whole system was hermetically sealed. The electric field between both the cathode and the grid, while grid and collector were experimentally determined for the best performance of the chamber corresponding to no recombination in the cathode-grid region and no electron capture by the grid structure. A potential of -1100 V and -638 V was finally applied to both cathode and grid respectively and the collector was kept at the ground potential.

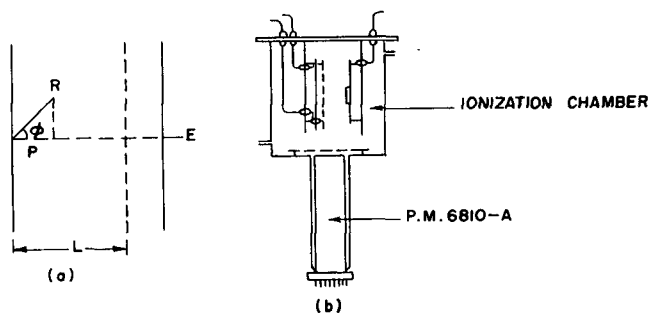


Fig. 1

- (a) Schematic diagram of ionization chamber
 (b) Ionization chamber—gas scintillation counter

The photomultiplier type 6810-A observes the scintillations produced in the Xenon gas by the passage of ionizing particles. In order to convert the ultra-violet light emitted by the Xenon gas into the region of photomultiplier sensitivity, the photomultiplier was coated with a very thin layer of p-quaterphenyl which acts as a wavelength shifter.

LINEAR AMPLIFIER

The time constants of the amplifier should be chosen to avoid the amplification factor depending upon the rise-time of the input pulses [7]. In the case of a gridded ionization chamber, the pulse rise-time T_R is given by $T_R = \frac{p}{v} + \frac{d_{gc}}{v'}$ where p is the projection of the length of the track in the field direction and d_{gc} is the grid-collector spacing and v, v' are the drift velocities of the electrons in the cathode-grid and grid collector regions respectively. Hence the input pulses of the same height may have different rise-times depending on the orientation angle of the track with the field direction. In the present case the rise-times of the pulses varied from about $1 \mu s$ to $3 \mu s$. To avoid the undesirable dependence of output amplitude on pulse rise-times a delay-line shaped amplifier was used having a flat top of $6 \mu s$ and rise-time of $0.2 \mu s$.

Experimental arrangements and results

This system has been used to measure the energy and angular distributions of the fission fragments in the thermal neutron fission of U^{235} . The whole assembly was placed before the thermal column of the Apsara reactor where the thermal neutron flux was of the order of $3 \times 10^6 \text{ n/cm}^2/\text{s}$. The energy distribution of the fission fragments as obtained with the present chamber is shown in Fig. 2. Fig. 3 shows the electronic arrangement, employing a time-to-pulse height converter for determining the delay distribution of fission fragments. Alternatively, these distributions have also been determined by photographing the fission-ionization pulses displayed on the vertical axis of an oscilloscope, triggering the sweep by the zero-time pulse. The oscilloscope was provided with a camera and film-moving device.

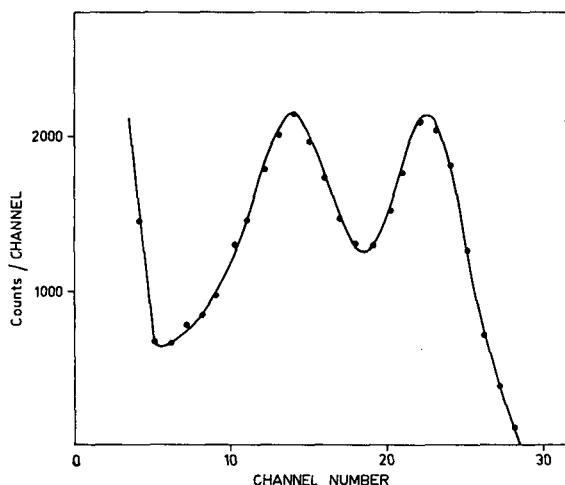


Fig. 2

Energy distribution of fission fragments in the thermal fission of U^{235} as obtained with the ionization chamber set-up

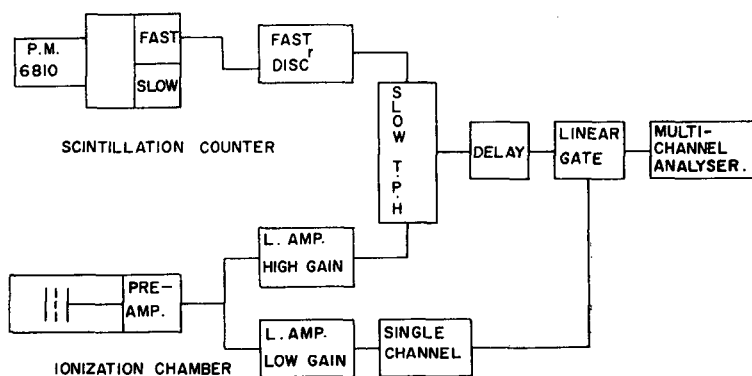


Fig. 3

Block diagram of the electronic set-up for determining the delay distribution of fission fragments

The delay distribution for the light-fragment peak is shown in Fig. 4 as obtained from the analysis of the photographs. For the fission fragments of a fixed range R , this should be a rectangular distribution. The departure of the experimental points from the rectangular distribution in the region of small and large delays is due to the following reasons. Firstly, as the U^{235} foil used in the work was not very thin, spread will occur in the ranges of the fragments selected for small energy width at the light-fragment peak. Secondly the ionization pulse for the fission-fragment track of fixed range R which is parallel to the electric field direction has a slow rise. Due to this reason slight uncertainty is caused concerning the fixing of the point where the fission-ionization pulse begins to rise. This in effect distributes the delays of zero-degree region over larger channels reducing the counts in each channel. The correction factor in the zero-degree region is determined from the departure of the experimental points from

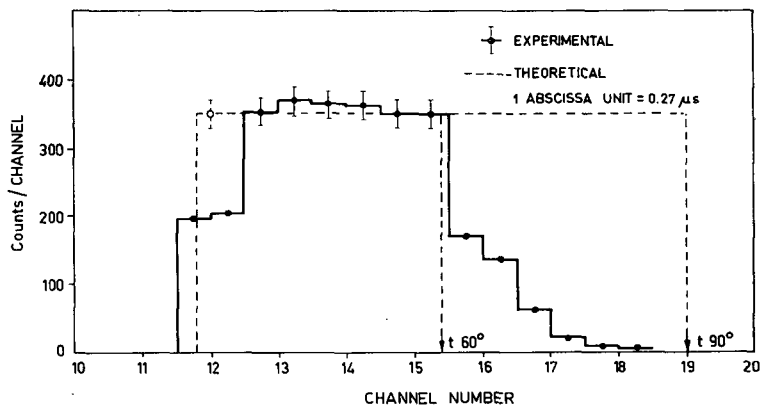


Fig. 4

Isotropic delay distribution of fragments selected at the light fragment peak having a very small spread in ranges

rectangular distribution and can be used to correct the other delay distributions which are not isotropic such as delay distributions of the fission fragments in coincidence with the prompt neutrons of specified energy groups detected along the electric field direction of the chamber. The fission fragments emerging at higher angles will lose some energy in the foil and appear with a smaller range. This results in the reduction of counts at larger delays.

The delay distribution for the fission-fragment spectrum including all the ranges is shown in Fig. 5. This gives an accurate determination of the maximum delay corresponding to the fragment angle of 90° , as maximum delay is independent of range. The constants α and β for the light fragment peak were obtained by determining t_{90° and t_{60° corresponding to the track angles of 90° and 60° respectively. t_{60° can be accurately determined as it divides the isotropic rectangular distribution corrected for foil thickness into two equal areas. With the present thickness of the foil, this method has been found good only up to 60° as higher angles are subject to errors due to foil thickness.

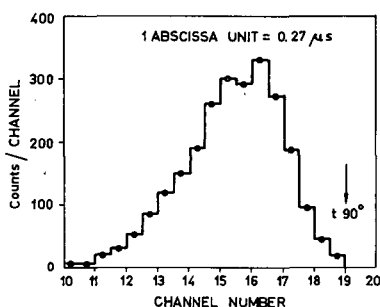


Fig. 5

Delay distribution of fragments for the total fission ionization spectrum. The maximum delay corresponds to the track angle of 90° with the field direction

Angular correlation of prompt neutrons and fission fragments

The above method has been used to obtain angular correlation of the fission fragments and prompt neutrons of specified energies. The fast neutron detector was a plastic scintillator of 10 cm diam. and 3 cm thickness, kept at a distance of 1 m from the U^{235} foil and along the direction of the electric field of the ionization chamber. The energy of the prompt neutrons was determined by time-of-flight technique. A time-to-pulse height-converter [8] was used to obtain pulse height proportional to the time difference between the fission scintillation pulse and the neutron counter pulse. A slow-fast coincidence system was used with discriminators in the side channel for pulse-height selection. In order to determine the zero time the prompt gamma peak in the time-of-flight spectrum was used. The events were photographed using a double-beam Tektronix 555 oscilloscope. The lower sweep, triggered by the zero-time pulse was intensity-modulated by the coincidence between the fission scintillation pulse (zero-time pulse) and neutron-counter pulse and the fission-ionization pulse was displayed on its vertical axis. This enabled us to record only those events where a prompt neutron is emitted along the electric field direction. The time-to-pulse height-converter output was displayed

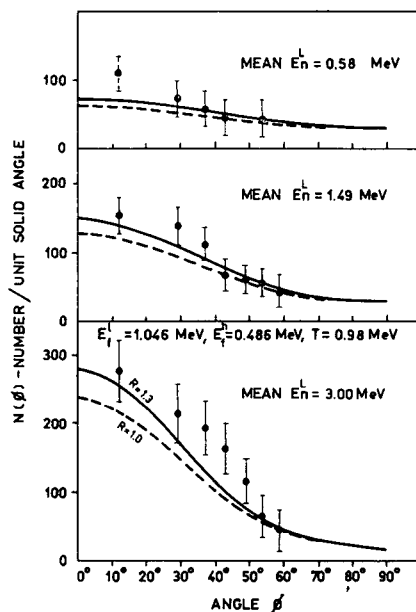


Fig. 8

Experimental angular distributions of prompt neutrons of different mean energies compared with the calculated distributions. Angle ϕ measured with the direction of motion of the light fragments

In the course of the experiments it was noted that, when the field in the grid-collector region was reasonably high, two pulses were observed in the scintillation counter (type 6810-A) for each ionizing event. The first pulse corresponds to the instant of the formation of the track and the second pulse begins to rise after a time which the electrons from the edge of the track take to cross the grid. It was found that the time separation of the second pulse from the first increased with the decrease in the field in the grid foil region and vice-versa. The rise-time of the second pulse was found to be less than the corresponding ionization pulse. It was also noticed that the pulse height of the second pulse increases with the increase of the field in the grid-collector region. The occurrence of the second pulse and the associated facts are explained on the basis that if the field in the grid-collector region is sufficiently high the electrons, just after crossing the grid, attain enough energies between successive collisions to excite the atoms of Xenon gas to a higher state which subsequently de-excites by the emission of photons. It is expected that proportionality between the energy of the ionizing particle and the pulse height of the second pulse can be obtained using the proper field in the grid-collector region. This point is being investigated. With the proportionality between the energy of the particle and the pulse height of the second pulse, a scintillation counter can be used for determining the angular distributions, since the first pulse gives the zero time and the second pulse contains the information about the projection of the length of the track in the field direction.

ACKNOWLEDGEMENT

We wish to thank Mr. B. R. Ballal for his assistance in the course of developing the system and to Mr. S. L. Raote for the construction of the electronic units.

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DISCUSSION

E. Gatti (Italy): I want to ask whether you have some means of controlling the drift velocity of your gas because it seems to me that the angle-measurement method you suggest is very sensitive to impurity in the gas.

G. Venkataraman (India): The gas used in the chamber was purified before filling by a process the details of which are described in the paper. However, in spite of the precautions taken, it is likely that there remained in the gas traces of impurities which affected electron mobility. Comparison of estimates of the electron drift velocities from rise times, delay times etc., with the values previously published by English and Hanna seem to confirm this. For the purposes of the experiment reported here however, this did not represent a serious obstacle. The actual experiment lasted four days or thereabouts during which period the performance of the chamber was continuously monitored and did not show any appreciable change.

СИСТЕМА УКАЗАНИЯ КООРДИНАТ ВХОДА ЧАСТИЦ В ЭМУЛЬСИОННУЮ КАМЕРУ (СЦУ-1)

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Н. С. ФРОЛОВ, В. А. КАЗАКОВ, И. И. СКРЫЛЬ
СССР

Abstract — Résumé — Аннотация — Resumen

A system of indicating the co-ordinates of particle entry into an emulsion chamber (scintillation counter СЦУ-1). Using the photoemulsion method it is very difficult to identify and separate particles of different types at energies of 10^9 eV and above. With Cerenkov scintillation counters it is possible to separate high energy particles, but not to observe the interaction of particles.

To overcome these drawbacks an apparatus has been designed, based on the specific effect of analysers and on the use of photoemulsion methods of investigating elementary particles. Apart from its main purpose (to facilitate the study of particle interactions), this СЦУ-1 scintillation counter gives a considerable saving in time as regards examination of the emulsion.

The paper gives the results of measurements with the apparatus and its technical characteristics as determined: e.g. the accuracy of determination of the co-ordinates of particle entry into the emulsion chamber is not worse than ± 0.5 mm; the efficiency of the apparatus is 90%.

Détermination des coordonnées à l'entrée des particules dans la chambre à émulsions (СЦУ-1). Le problème de l'identification et de la séparation des particules de natures différentes, ayant une énergie égale ou supérieure à 10^9 eV, est très difficile à résoudre par la méthode des émulsions photographiques. L'emploi de compteurs à scintillation Cerenkov rend possible le comptage de ces particules, mais ne permet pas d'observer leurs interactions.

Pour éliminer ces difficultés, on a construit un dispositif qui est fondé sur l'effet caractéristique des analyseurs et l'emploi d'émulsions photographiques dans l'étude des particules élémentaires. Ce dispositif permet, non seulement d'atteindre l'objectif principal (étude des interactions entre particules considérées), mais aussi d'abréger sensiblement la durée de l'examen des émulsions.

Le mémoire donne les résultats des mesures et les caractéristiques techniques du dispositif; par exemple, la précision avec laquelle sont déterminées les coordonnées à l'entrée des particules dans la chambre à émulsion comporte une marge d'erreur maximum de $\pm 0,5$ mm; le rendement du dispositif est de 90%.

Система указания координат входа частиц в эмульсионную камеру (СЦУ-1). Решение задачи идентификации и разделения частиц разных типов с энергией 10^9 эв и выше методом фотоэмульсий очень трудно. Применение черенковских сцинтилляционных счетчиков дает возможность разделить частицы высоких энергий, но не позволяет наблюдать взаимодействие частиц.

Для устранения этих трудностей был сконструирован прибор, основанный на принципе собственного действия анализаторов и фотоэмульсионной техники исследования элементарных частиц. Применение этой установки „СЦУ-1“ дает возможность, помимо основной цели (изучение взаимодействий интересующих частиц), получить существенный выигрыш во времени при просмотре эмульсий.

Будут представлены результаты измерений и полученные технические характеристики установки, как например — точность определения координат входа частицы в эмульсионную камеру не хуже $\pm 0,5$ мм; эффективность устройства составляет 90%.

Система de indicación de las coordenadas de entrada de las partículas en una cámara de emulsión (contador de centelleo СЦУ-1). Con el método de la fotoemulsión es muy difícil identificar y separar partículas de distintos tipos con energías superiores a 10^9 eV. Utilizando los contadores de centelleo de Cerenkov se pueden separar partículas de elevada energía pero no observar sus interacciones.

Para evitar estas dificultades los autores han construido un aparato basado en el efecto específico de los analizadores y en el empleo de la técnica de las fotoemulsiones para la investigación de partículas elementales. La utilización de este contador de centelleo СЦУ-1, no sólo cumple el propósito fundamental de facilitar el estudio de las interacciones, sino que permite realizar una economía de tiempo al hacer innecesario el examen de las emulsiones.

Los autores dan los resultados de las mediciones efectuadas y las características técnicas del aparato; la precisión en la determinación de las coordenadas de entrada de las partículas en la cámara de emulsión no es inferior a $\pm 0,5$ mm; la eficiencia del aparato es de 90 por ciento.

1. Введение

При наличии частиц с энергией 10^9 эв и выше методом фотоэмульсий (по ионизирующей способности) практически очень трудно, а иногда и невозможно решить задачу идентификации и разделения частиц разных типов.

Трудность заключается в том, что при высоких энергиях ионизирующая способность всех частиц (мезонов, нуклонов, гиперонов и др.) уравнивается и становится минимальной.

Однако применение эмульсионных камер позволяет наблюдать взаимодействие частиц высоких энергий с ядрами фотоэмульсии.

Другим способом идентификации частиц является разделение их по скорости с применением черенковских сцинтилляционных счетчиков и электронной аппаратуры. Этот способ дает возможность разделить частицы высоких энергий, но не позволяет наблюдать взаимодействие частиц.

Очевидно, что сочетание двух методов (фотоэмульсионного и электронного) может обеспечить разделение частиц и изучение их взаимодействий.

Система определения координат входа частиц в эмульсионную камеру (СЦУ-1) представляет собой прибор, основанный на принципе совместного действия анализаторов и фотоэмульсионной техники исследования элементарных частиц.

Применение установки „СЦУ-1“ дает возможность помимо основной цели (изучение взаимодействий интересующих частиц) получить существенный выигрыш во времени при просмотре эмульсий.

2. Блок-схема установки

Блок-схема установки СЦУ-1 приведена на рис. 1. Пролет нужной частицы через телескоп искровых счетчиков фиксируется анализаторами, выходные импульсы которых подаются на схему антисовпадений. Сигнал со схемы антисовпадений через переключатель рода работы подается на предварительный усилитель, который связан с генератором высоковольтных импульсов. Генератор высоковольтных импульсов имеет три отдельных выхода для питания искровых счетчиков. Искра, возникшая в промежутке искрового счетчика по следу пролетевшей частицы, фотографируется в двух проекциях на один кадр кинокамеры фото-регистратора. Перевод кадра кинокамеры осуществляется автоматически в случае возникновения искры хотя бы в одном искровом счетчике.

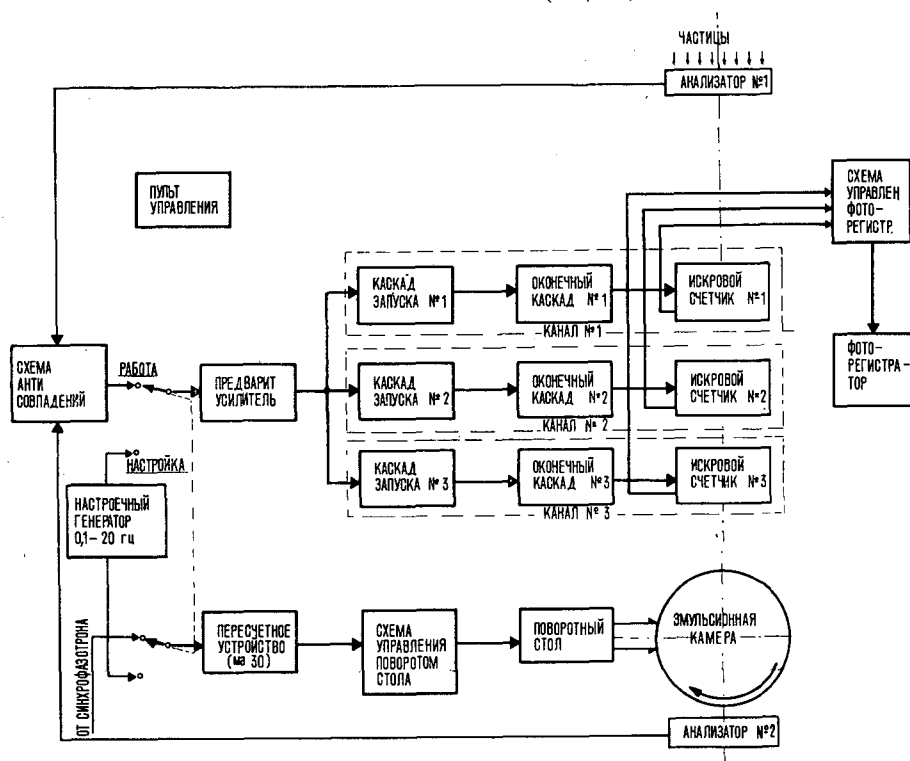


Рис. 1

Блок-схема установки СЦУ-1

3. Искровые счетчики

Конструкция. Искровой счетчик состоит из двух круглых плоско-параллельных электродов, разделенных газовым промежутком. Электроды изготовлены из медной фольги толщиной 0,05 мм, что позволяет сделать толщину рассеивания минимальной.

Важнейшая задача при конструировании искровых счетчиков — правильный подбор краев электродов искрового счетчика. Неправильная форма вызывает сильные локальные искажения поля на краях. Это искажение обуславливает „краевой эффект“, существенно влияющий на длину счетного „плато“ счетчика. Если искажения поля слишком большие, счетное „плато“ отсутствует совсем.

Форма электродов наших искровых счетчиков соответствует эквипотенциальной поверхности плоскопараллельного конденсатора конечной длины, рассчитанной таким образом, что напряженность поля в любой точке его неоднородной области всегда меньше напряженности однородного поля внутри разрядного промежутка.

Рабочая поверхность электродов тщательно отполирована механически и электролитически.

Телескоп искровых счетчиков состоит из трех искровых счетчиков, помещенных в отдельные газовые объемы. Камеры искровых счетчиков латунные, вакуум-плотные, позволяют откачку до давлений порядка 10 мм рт. ст.

4. Принцип действия и характеристики искровых счетчиков

Если на искровой счетчик за достаточно короткое время после пролета частицы подать импульс высокого напряжения достаточной амплитуды и длительности ($\tau_u \cong 10^{-7}$ сек), то при соответствующей величине „pd“ (один из основных параметров искрового счетчика) возникает стримерный пробой, локализованный вдоль следа ионизирующей частицы, или в прилегающей области. При этом искра имеет форму узкого ярко светящегося канала (ширина канала — несколько десятых мм). Изображение искр (путем фотографирования) получается достаточно хорошим — четким и ясным, которое затем можно обрабатывать.

В наших экспериментах исследовались газовые смеси, в которых вероятность образования отрицательных ионов достаточно велика. Изучались газовые смеси аргон-ацетон, аргон-осушенный воздух. Было выяснено, что искровой счетчик обладает высокой эффективностью при наполнении смесью аргон-осушенный воздух (400 мм рт. ст. Ag + 300 мм осуш. воздух).

Счетное плато наблюдается в интервале напряженностей (46 + 70) кв./см. (рис. 2).

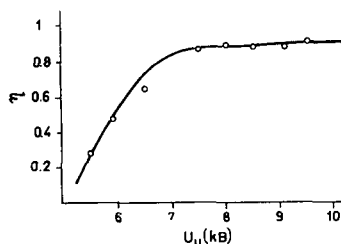


Рис. 2

Зависимость эффективности искровых счетчиков (η) от амплитуды питающих импульсов (U_u)

Длина разрядного промежутка $d = 1,5$ мм. Увеличением „pd“ можно довести эффективность до 100%.

Важным фактором существенно влияющим на „качество“ регистрации частиц высоких энергий является небольшое постоянное очищающее напряжение U_0 , постоянно наложенное на искровые счетчики. Оно позволяет в широком диапазоне регулировать время „памяти“ в диапазоне от 10 мксек. (при $U_0 \cong 0$) до 1 мксек (при $U_0 \cong 100$ в). Верхний предел U_0 (таким образом и разрешающее время) ограничен быстрым спадом эффективности при увеличении U_0 . Для вышеупомянутой смеси не наблюдается спада эффективности вплоть до $U_0 = 70$ в ($\eta = 90\%$), но при $U_0 = 200$ в эффективность понижается до 40%, при $U_0 = 500$ в $\eta \cong 10\%$ (рис. 3) таким образом, можно добиться разрешающего времени до 1 мксек за счет существенного уменьшения собственной задержки аппаратуры.

Совсем иную роль играет постоянное напряжение, наложенное на искровой счетчик, по величине несколько меньше чем статическое пробивное напряжение (режим предварительной ионизации).

В момент пролета частицы возникает таунсендовская лавина, создающая предварительную сильную ионизацию вдоль следа пролетевшей частицы. Если

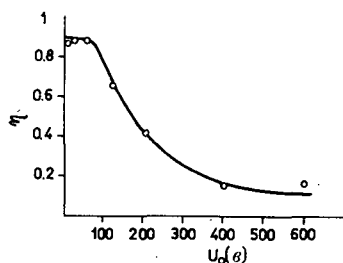


Рис. 3

Зависимость эффективности искровых счетчиков (η) от величины очищающего напряжения (U_0)

частица вызвала сигнал в анализаторе, то на искровые счетчики подается импульс высокого напряжения, амплитуда которого превышает статическое пробивное напряжение. В поле „зажигающего“ импульса высокого напряжения лавина достигает критической величины и превращается в искровой разряд.

Созданная нами аппаратура обеспечивает режим малых очищающих напряжений и режим предварительной ионизации.

Исследование работы искровых счетчиков данной конструкции показывает, что они обладают рядом положительных свойств:

А. Высокой эффективностью регистрации, которая зависит от

1. газовой смеси
2. величины „pd“
3. параметров высоковольтного импульса:
 - а. амплитуды импульса
 - б. длительности импульса
 - в. задержки импульса.

Б. Исключительно хорошей разрешающей способностью во времени, управляемой большим очищающим напряжением.

В. Хорошей разрешающей способностью в пространстве. Это свойство обусловлено стримерным механизмом разряда, зависящим от локализованных процессов, вызываемых единственным электроном.

5. Генератор высоковольтного импульса

Как следует из описания искровых счетчиков, лучшие характеристики системы в отношении разрешающего времени могут быть получены при минимальных задержках импульса высокого напряжения относительно момента пролета ионизирующей частицы. Применение специальной схемы запуска водородных тиратронов при скорости нарастания напряжения на сетке тиратрона от 10000 до 20000 вольт в микросекунду позволяет получить время задержки высоковольтного импульса не превышающее 200 наносекунд. При этом фронт нарастания напряжения высоковольтного импульса на искровом счетчике составляет 20 нсек.

В более позднем варианте генератора высоковольтных импульсов, с применением ламп с жестким вакуумом, удалось сократить время задержки высоковольтного импульса относительно импульса, поступающего с анализаторов до 50 нсек при фронте нарастания высоковольтного импульса на искровом счетчике в 30 нсек.

Схема генератора обеспечивает подачу на искровые счетчики импульсов длительностью в 100 нсек с регулируемой амплитудой от 1,5 кв. до 15 кв. при постоянном питании искровых счетчиков очищающим напряжением, регулируемых от 0 до 4,5 кв. от источника с внутренним сопротивлением не менее 150 мом.

6. Система индикации

Система индикации позволяет дистанционно, при местном дублировании, контролировать работу каждого искрового счетчика в отдельности и телескопа в целом, что дает возможность судить об эффективности системы, выражающейся как отношение зарегистрированных установкой частиц к общему количеству частиц, зарегистрированных анализатором.

7. Система управления фоторегистратором и эмульсионной камерой

Система управления фоторегистратором обеспечивает экспонирование на пленке служебных знаков (номер кадра, номер поворота стола эмульсионной камеры и реперную метку начала координат системы фоторегистратора), перевод кадра после каждого срабатывания хотя бы одного искрового счетчика и дистанционную аварийную сигнализацию и блокировку системы в случае неисправности в фоторегистрирующем устройстве.

Система управления положением эмульсионной камеры обеспечивает поворот стола эмульсионной камеры на 5° через каждые 30 циклов ускорителя и дистанционную сигнализацию конца облучения эмульсионной камеры.

8. Фоторегистратор

Оптическая схема регистратора (рис. 4) позволяет получить на одном кадре фотографии искр, возникающих в трех искровых промежутках с двух взаимно перпендикулярных направлений и служебных знаков.

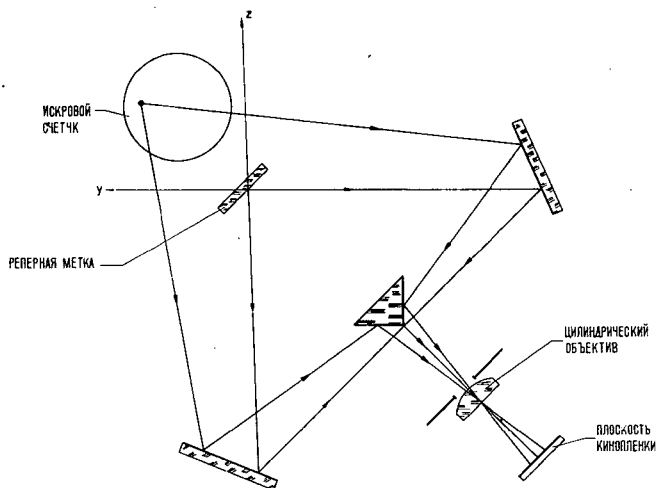


Рис. 4

Оптическая схема фоторегистратора установки СЦУ-1

Свет искры, возникшей в разрядных промежутках счетчиков, отразившись от плоских зеркал и зеркальной призмы попадает в цилиндрический объектив и дает два изображения на пленке кинокамеры. Этот же объектив проектирует на пленку изображение реперной метки начала координат в системе фоторегистратора.

С помощью дополнительного объектива осуществляется проектирование на тот же кадр служебных отметок: номера кадра и поворота стола.

9. Конструктивное выполнение установки

Установка СЦУ-1 конструктивно состоит из трех шкафов: (рис. 5)
а. шкафа электронной аппаратуры;

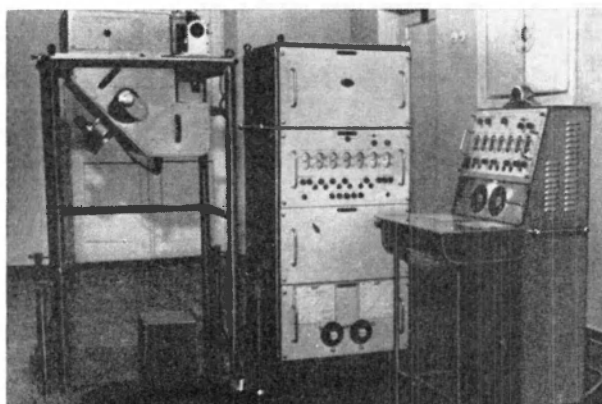


Рис. 5

Общий вид установки

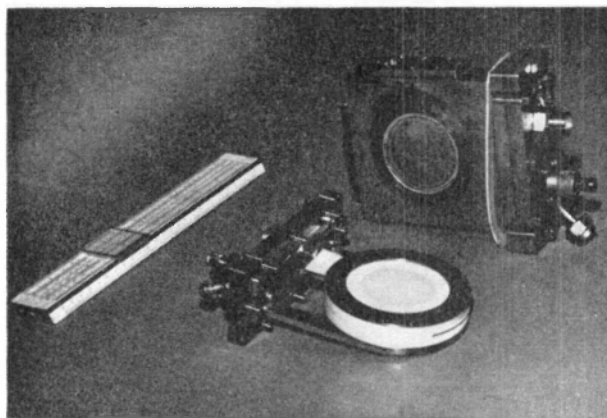


Рис. 6

Конструкция искрового счетчика

- б. шкафа фоторегистратора, искровых счетчиков (рис. 6) и эмульсионной камеры;
- в. пульта дистанционного управления.

Все шкафы установки мобильны, занимают немного места и удобны в эксплуатации.

10. Полученные технические характеристики установки

1. Точность определения координат входа частицы в эмульсионную камеру не хуже $\pm 0,5$ мм.
2. Число случаев выдачи ложных координат, вызванных случайными пробоями счетчиков не более 1 %.
3. Эффективность устройства составляет 90 %

Под эффективностью понимается отношение числа частиц вызвавших события, координаты которых зарегистрированы устройством, к числу частиц, вызвавших события, зарегистрированные анализатором.

SPARK COUNTER FOR NEUTRONOGRAPHIC RESEARCH

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Abstract — Résumé — Аннотация — Resumen

Spark counter for neutronographic research. A spark counter for neutronographic purposes has been constructed.

It is known that a spark counter with a suitable distribution of anodes and cathodes may be used to obtain diffraction patterns [1]. The high resolution and the possibility of measuring the intensity of diffraction peaks are made possible by means of a new, improved counting device.

Two moving electrodes of this counter explore a large area in order to obtain the diffraction patterns which are recorded mechanically.

Compteur à étincelles pour les recherches neutronographiques. Les auteurs ont construit un compteur à étincelles destiné aux recherches neutronographiques.

On sait qu'un compteur à étincelles dans lequel les anodes et les cathodes sont convenablement réparties peut servir à obtenir des diagrammes de diffraction des neutrons [1]. Un dispositif de comptage perfectionné donne un pouvoir de résolution élevé et permet de mesurer l'intensité des crêtes de diffraction.

Deux électrodes mobiles explorent une zone étendue et permettent de déterminer les diagrammes de diffraction, lesquels sont enregistrés par des procédés mécaniques.

Искровой счетчик для нейтронографических исследований. Был построен искровой счетчик для нейтронографических целей. Известно, что искровой счетчик с соответствующим распределением анодов и катодов может быть использован для получения дифракционных рисунков [1]. Новое усовершенствованное счетное устройство позволяет достигать высокой разрешающей способности и дает возможность измерять интенсивность дифракционных пиков.

Два подвижных электрода этого счетчика обследуют большую площадь для получения механически регистрируемых дифракционных рисунков.

Contadores de chispas para investigaciones neutronográficas. Los autores han construido un contador de chispa para realizar estudios neutronográficos.

Como es sabido, un contador de chispas cuyos ánodos y cátodos estén distribuidos de manera adecuada puede servir para obtener imágenes de difracción [1]. Un dispositivo nuevo de conteo permite alcanzar un alto grado de resolución y medir la intensidad de los máximos de difracción.

Dos electrodos móviles del contador exploran un área muy extensa para obtener las imágenes de difracción, que son registradas mecánicamente.

Introduction

In recent years, information concerning crystalline structures has been considerably widened by connecting X-ray and neutron diffraction methods.

The optic principle of neutron diffraction methods is identical with that of the X-ray method. But, with regard to laboratory techniques, the neutron diffraction equipment is considerably different from that used with X-rays. The determination of positions and intensities of the diffraction maxima in neutronographic research is usually made by means of scintillation or proportional counters, while in the X-ray field, an important

group of structure problems may be resolved by using the photographic method, the latter involving simpler working devices.

For methods using an incident beam of continuous spectrum, such as the Laue method, the necessity to reduce the background necessitates the construction of a diffractometer shield which, in neutronographic research, considerably exceeds the dimensions of that necessary for X-ray techniques.

This circumstance involves rather complex designs of neutron diffractometers. This difference is more noticeable when monochromatic neutron beams are used.

To obtain the Laue patterns for single-crystals by neutron diffraction, L. REIFFEL [1] used a spark counter. Thus, the recording techniques of Laue patterns became similar to those used in the X-ray field.

We built a spark counter for single-crystal studies which determine both the diffraction maxima positions and their intensities.

Description of the apparatus

The device consists of a metallic frame of $170 \times 170 \times 60 \text{ mm}^3$ containing grooves for guiding the two electrode holders. The plane of the two electrodes is normal to the neutron beam which is allowed to pass the counter through a circular hole 140 mm in diam. Each electrode holder may be moved with the aid of an endless screw coupled to the servomotor axis and thus effecting a remote control. The two electrodes are normal to one another. The electrode holders are made of perspex.

The anode is made from three wolfram wires of 0.1 mm diam. separated from one another by 2 mm. Two solutions were taken into account in making the cathode. In the first one the cathode was a copper wire of 1.5 mm diam. In this case, at a distance of 3 mm from the anode, a boron-coated aluminium plate, 0.5 mm thick, is mounted across the incident beam. Layers of boron coating of different thicknesses from 0.1 to 1 mm were used in order to obtain better efficiency. Good counting efficiency was thus obtained but the space resolution was poor.

In the second solution an aluminium electrode, semicircular in shape, was used as cathode and the boron filled the semicircular hole. The aluminium was 1 mm thick and the semicircular electrode's diam. was 3 mm. In this case the boron-coated aluminium plate was removed. The distance between the anode and cathode varied from 1.5 to 4 mm. The counter described above is shown in Fig. 1.

The high-voltage supply varied gradually from 2000 to 3000 V, corresponding to the distance between the electrodes. The best operation voltage was 2500 V, while the anode-cathode spacing was 2 mm.

The charge resistor was a resistance divider ($10 \text{ M}\Omega$, $10 \text{ k}\Omega$) by the aid of which the pulses were fed to an electronic scaler. The pulse-height was about 5 V with a width of $20 \mu\text{s}$ while the pulse rise-time was $0.1 \mu\text{s}$.

The thermal-neutron efficiency of the counter was estimated to be 2%. This value was found by accounting for the boron-layer transmission and for the solid angle under which the working volume sees the boron converter.

The γ -rays and fast neutron efficiency was found to be practically zero as was proved by removing the boron layer, or alternatively by removing the thermal neutrons with the aid of a boron filter placed across the beam.

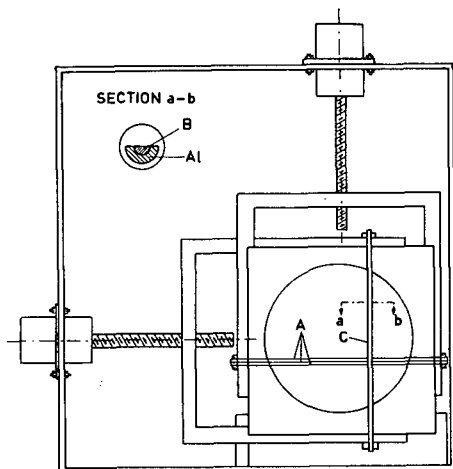


Fig. 1

The spark counter

A — anode

C — cathode

The results

Fig. 2 presents the experimental arrangement. In the experimental hole of the VVRS-2 reactor a Soller collimator with a 9-min divergence and a $20 \times 30 \text{ mm}^2$ aperture was introduced. In front of the collimator was placed a lead shutter 200 mm in length and with a 2.9-mm diam. aperture.

At 100 mm distance from the shutter opening the single-crystal holder was mounted, the counter being placed at 30 mm distance from the crystal-holder axis. The counter surface was perpendicular to the axis of the incident beam. The known geometry for an X-ray, Laue diffraction camera, was thus realized.

Laue patterns for a single crystal of Zn and calcite were obtained. Fig. 3 presents the diffraction pattern of a single crystal of Zn having the (0001) axis directed along the beam axis. The diffraction pattern was obtained in 7 h. The lack of an exact guidance device of the counter *versus* the beam direction did not allow a perfect hexagonal symmetry of the diffraction pattern to be obtained.

Background measurements gave 2 counts/min while the diffraction maxima gave 40 to 150 counts/min.

The apparatus proved to have a satisfactory space resolution, all the maxima being clearly separated, although their relative distances were small; thus, for a calcite single-crystal, maxima separated by 8 mm could be distinctly detected.

The results obtained so far show that the spark counter may be successfully used for single-crystal structure studies. With a corresponding modification of the electrodes shape this counter may be utilized for polycrystalline structure research.

The main advantage of the spark counters consist in their experimental facilities but their efficiency is at present too low to allow a convenient automatic operation.

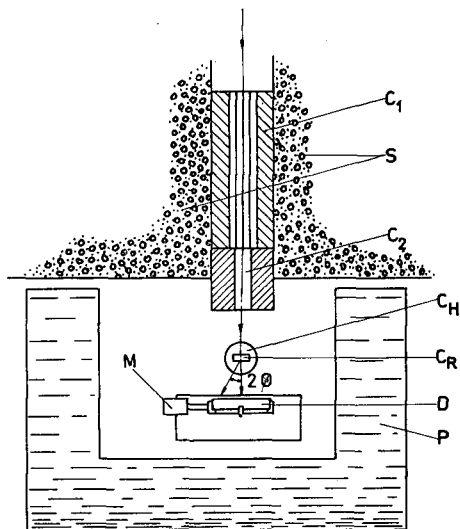


Fig. 2

The experimental arrangement

- C_1 — soiler colimator
- C_2 — lead colimator
- S — reactor shielding
- C_H — crystal holder
- C_R — crystal
- D — detector
- P — protection

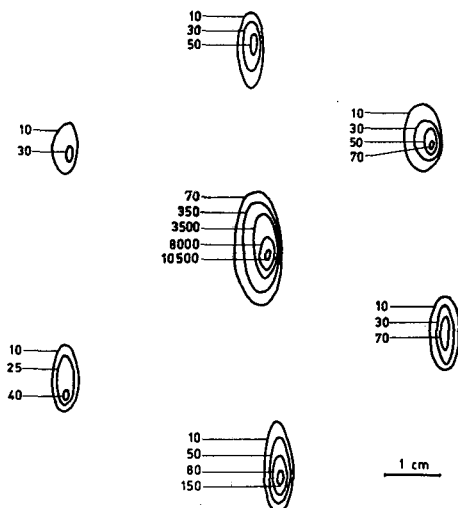


Fig. 3

The diffraction pattern of a single crystal of Zn

REFERENCES

- [1] REIFFEL, L., *Rev. Sci. Instr.* **29** (1958) 1151.

DISCUSSION

L. Reiffel (United States of America): I would like to hear in a few words the substance of Mr. Bally's paper on spark counters for neutronographic research. What method was employed?

N. Vylkov (Romania): It was a point-by-point system. We have a detailed description of this system and could explain it in private if you wish.

CARACTÉRISTIQUES ÉLECTRIQUES DE COMPTEURS A ÉTINCELLES DU TYPE SPHÈRE-PLAN

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Abstract — Résumé — Аннотация — Resumen

Electrical characteristics of sphere-plane type spark counters. The authors describe here the mechanical construction and operating characteristics of spark detectors using a small (0.30 mm) diameter sphere as anode, set opposite to a plane cathode and working by the "corona" effect, in air at atmospheric pressure.

Counting characteristics are very similar to those of Rosenblum-type anode wire detectors. However, the sphere counter has a certain superiority over the Rosenblum counter inherent in its geometry: (a) the residual current (background) is low and the release of ozone and nitrous oxides during the spark is not of great significance; (b) its self-capacity being very small, the detector gives a faster response; (c) unlike in the case of wire counters, efficiency is independent of particle incidence direction; (d) its sensitive volume, that of a solid of revolution around the axis of symmetry of the detector, amounts to a few cubic millimetres and, being very clearly defined, permits realization of accurate telescopic devices.

Caractéristiques électriques de compteurs à étincelles du type sphère-plan. Les auteurs décrivent la réalisation mécanique et les caractéristiques de fonctionnement de détecteurs à étincelles utilisant comme anode une sphère de petit diamètre (0,30 mm), disposée en regard d'une cathode plane, et fonctionnant en régime d'effet «couronne», dans l'air sous la pression atmosphérique.

Les caractéristiques de comptage sont voisines de celles des détecteurs à fil anodique, du type Rosenblum. Le compteur à sphère présente cependant sur le compteur de Rosenblum un certain nombre d'avantages liés à sa géométrie: a) le courant résiduel (bruit de fond) est faible, et le dégagement d'ozone et d'oxydes de l'azote lors des étincelles est peu considérable; b) sa capacité propre étant très petite, le détecteur présente une réponse plus rapide; c) l'efficacité est indépendante de la direction d'incidence de la particule, contrairement à ce qui a lieu pour les compteurs à fil; d) le volume sensible de révolution autour de l'axe de symétrie du détecteur, qui est de quelques millimètres cubes, est très bien défini, ce qui permet la construction de télescopes précis.

Электрические характеристики искровых счетчиков типа шар-плоскость. Авторы описывают механическую конструкцию и рабочие характеристики искровых счетчиков, в которых в качестве анода используется шар малого диаметра (0,30 мм), расположенный против плоского катода. Эти счетчики работают в режиме „кольцевого“ явления („короны“) в воздухе при атмосферном давлении.

Счетные характеристики близки к характеристикам счетчиков Розенблюма с анодным проводом. Шаровой счетчик имеет, однако, некоторые преимущества по сравнению со счетчиком Розенблюма, что связано с его геометрией: 1. остаточный ток (фон) слабый, а выделение озона и окиси азота во время искрения незначительно. 2. Поскольку его собственная емкость очень мала, счетчик дает более быстрый ответ. 3. Эффективность не зависит от направления падения частицы в противоположность тому, что характерно для проводных счетчиков. 4. Чувствительный объем вращения вокруг оси симметрии счетчика равняется нескольким кубическим миллиметрам; он очень точно определен, что позволяет сооружать точные телескопы.

Características eléctricas de los contadores de chispas del tipo esfera-plano. Los autores describen los detalles mecánicos y las características de funcionamiento de unos detectores de chispas en que se utiliza como ánodo una esfera de pequeño diámetro (0,30 mm), dispuesta frente a un cátodo plano y que funcionan en régimen de efecto «corona», en aire a presión atmosférica.

Las características de contaje son semejantes a las de los detectores de ánodo de alambre, de tipo Rosenblum. No obstante, el contador de esfera presenta, con respecto a dicho contador Rosenblum, cierto número de ventajas derivadas de su geometría: *a)* la corriente residual (ruido de fondo) es débil y el desprendimiento de ozono y de óxidos de nitrógeno, con las chispas, es poco considerable; *b)* como su capacidad propia es muy pequeña, el detector ofrece una respuesta más rápida; *c)* la eficiencia es independiente de la dirección de incidencia de la partícula, al revés de lo que ocurre con los contadores de alambre; *d)* el volumen sensible de revolución en torno del eje de simetría del detector es de algunos milímetros cúbicos y está muy bien definido, lo que permite la construcción de telescopios de gran precisión.

Introduction

GREINACHER a décrit en 1934 [1] des détecteurs de particules utilisant un phénomène d'effluve électrique; ils constituent les premières réalisations de compteurs à étincelles: la cathode, plane dans la plupart des cas, est séparée d'une anode de très faible rayon de courbure (pointe ou sphère) par une distance généralement inférieure à 1 mm. Par exemple, les compteurs à anode sphérique sont capables de détecter les rayons α , β , γ et même UV [2] [3] [4], mais on a été conduit à les abandonner parce que leur bruit de fond est très élevé et leur temps de résolution important, et que leurs caractéristiques varient beaucoup avec la tension.

En utilisant un fil anodique, tendu à quelques millimètres d'une cathode plane et parallèle à cette électrode, CHANG et ROSENBLUM [5] ont réalisé un détecteur beaucoup plus stable, de mouvement propre très faible, mais qui n'est sensible qu'aux particules lourdes (rayons α , fragments de fission). On trouvera la bibliographie de cette question dans [6].

Reprenant l'étude des compteurs à anode sphérique, nous les avons améliorés en tenant compte des résultats obtenus par Chang et Rosenblum sur les détecteurs à fil. Le but de cette communication est de donner les caractéristiques principales de nos compteurs.

Appareillage utilisé

DÉTECTEURS A ÉTINCELLES

L'anode est une sphère de 0,28 mm de diamètre, obtenue en fondant au chalumeau un fil de nickel-chrome à 20% de chrome; les sphères les plus régulières sont sélectionnées et polies électrolytiquement, ce qui élimine les aspérités et la couche d'oxyde qui s'est

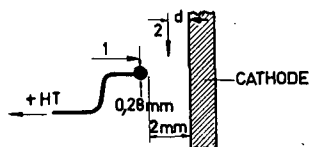


Figure 1

Disposition géométrique des électrodes du compteur à étincelles.

formée pendant la fusion. Cette anode est placée à 2 mm d'une plaque de rhodium soigneusement dressée. Par une vis micrométrique, on modifie à volonté la distance qui sépare les deux électrodes. Cette distance, ainsi que le diamètre de l'anode, est mesurée au moyen d'un viseur muni d'un micromètre oculaire.

Le détecteur fonctionne dans l'air, sous la pression atmosphérique; la pression partielle de la vapeur d'eau présente est toujours voisine de 1 cm de mercure.

CIRCUIT ÉLECTRONIQUE ASSOCIÉ

L'anode est liée à une source de haute tension stabilisée, par l'intermédiaire d'un circuit (résistance R — capacité C). La valeur de la résistance a été fixée à 5 M Ω , mais on peut faire varier C jusqu'à 7 pF.

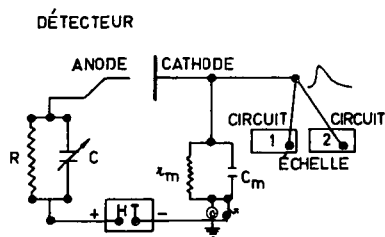


Figure 2

Circuit électronique associé au compteur à étincelles.

Les impulsions sont recueillies aux bornes du circuit (r_m — c_m) intercalé dans la branche cathodique. Leurs amplitudes, cinquante fois plus faibles environ que celles des impulsions que l'on recueille aux bornes du circuit (R - C) anodique, sont cependant de plusieurs volts. Ces impulsions positives passent dans deux circuits échelles de seuils modifiables à volonté disposés en parallèles; le galvanomètre G donne l'intensité du courant produit par l'effet «couronne» dans le détecteur.

SOURCES RADIOACTIVES

Le détecteur n'est sensible qu'à des particules très ionisantes: nous avons employé des sources de ^{210}Po , qui donnent des rayons α de 5,30 MeV; des sources presque ponctuelles ont été obtenues par dépôt sur la section polie d'un fil d'argent de 0,5 mm de diamètre du polonium venant d'une solution de nitrate. La source ainsi obtenue est disposée au sommet d'un cône, selon l'axe duquel on peut adapter des tubes d'acier cylindriques jouant le rôle de collimateurs. Dans les mesures décrites ici, nous utilisons un tube de 0,25 mm de diamètre; le faisceau de particules α avait un angle d'ouverture de 2,3°.

La source est disposée sur un montage micrométrique, ce qui permet de la déplacer parallèlement à elle-même dans un plan bien déterminé.

Effet permanent

En l'absence d'une source de particules α , une décharge «couronne» se produit pour des tensions d'alimentation supérieures à 2800 V environ. On trouvera sur la figure 3

les caractéristiques de cet effet permanent. La courbe 1 donne la différence de potentiel entre l'anode et la cathode en fonction de la tension appliquée; elle est toujours très voisine de la tension d'alimentation.

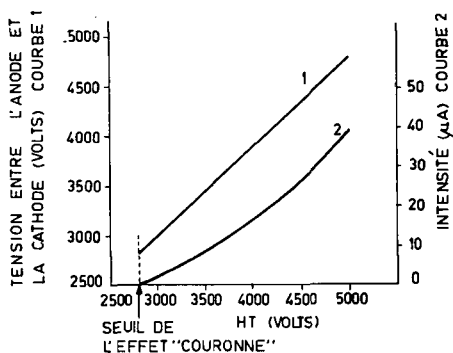


Figure 3

Caractéristiques de l'effet «couronne» permanent.

L'intensité du courant qui traverse le compteur, mesurée sur le galvanomètre G, est portée sur la courbe 2.

Caractéristique de comptage

ALLURE GÉNÉRALE DU PALIER

Pour obtenir des résultats reproductibles, il faut faire les mesures après vieillissement des électrodes, c'est-à-dire après que le détecteur a fonctionné un certain temps. Le bruit de fond est alors pratiquement nul.

L'effet «couronne» débute, comme le montre la figure 3, vers 2800 V, mais, comme dans le cas des compteurs à fil, notre compteur est sensible pour des tensions légèrement inférieures à ce seuil (fig. 4 et 5).

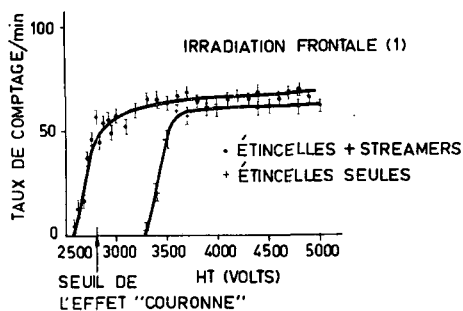


Figure 4

Caractéristiques de comptage pour une irradiation de front.

- Étincelles + streamers
- + Étincelles seules

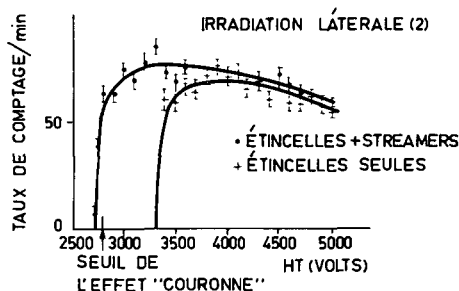


Figure 5

Caractéristiques de comptage pour une irradiation latérale.

- Étincelles + streamers
- + Étincelles seules

Entre 2800 et 3500 V (environ), les impulsions ont des amplitudes variables (de l'ordre de 1 V aux bornes de ($r_m - c_m$), de 50 V aux bornes de ($R - C$)). Dans cette région, le passage d'une particule ionisante déclenche un canal prédisruptif (ou «streamer»), mais ce canal n'atteint pas la cathode, et aucune étincelle ne se produit.

Au-dessus de 3500 V, tous les «streamers» atteignent la cathode: on observe des étincelles visibles et audibles. Si l'on fixe les seuils des deux circuits échelles à 0,5 et 10 V, respectivement, la première échelle permet de dénombrer la somme du nombre d'étincelles et de «streamers», la seconde le nombre des étincelles seulement. Les deux caractéristiques obtenues sont parallèles au-dessus de 4000 V bien que le nombre des «streamers» reste toujours supérieur, de quelques pour cent, à celui des étincelles.

INFLUENCE DE LA DIRECTION D'INCIDENCE DE LA PARTICULE α

Nous avons irradié le détecteur en utilisant deux directions d'incidence perpendiculaires (fig. 1):

- a) De front, selon 1, c'est-à-dire parallèlement à l'axe de révolution du système;
- b) Latéralement, selon 2, c'est-à-dire normalement à l'axe de révolution.

La figure 4 donne la caractéristique obtenue pour les irradiations de front: la pente du palier est légèrement positive. Le palier a une forme identique à celui que l'on obtient pour un compteur à fil lorsque la distance entre les deux électrodes a une valeur suffisamment élevée [7].

Pour les irradiations latérales, par contre (fig. 5), la courbe présente un maximum dans la région des tensions les plus faibles, et sa forme semble dépendre beaucoup de la répartition de la charge d'espace.

Volume sensible

IRRADIATION DE FRONT

Nous avons déplacé la source parallèlement à la cathode, dans un plan de symétrie du compteur; la figure 6 donne la variation du taux de comptage en fonction de la position de la source. Cette courbe montre que le volume sensible est plus important que celui des compteurs à fil [6] [7]. On remarquera enfin (fig. 4) que ce volume augmente un peu avec la tension d'alimentation.

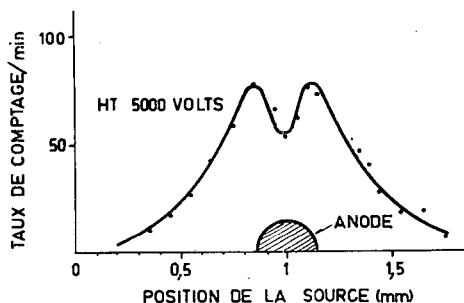


Figure 6

Variation du taux de comptage pour un déplacement de la source parallèlement à la cathode (irradiation de front). HT = 5000 V.

IRRADIATION LATÉRALE

Nous avons déplacé la source, entre l'anode et la cathode, selon l'axe de révolution du détecteur: le taux de comptage est maximal au tiers environ de la distance qui sépare la cathode de l'anode. Un résultat analogue est obtenu quand on utilise des compteurs à un fil, ou à plusieurs fils électriquement indépendant [7]. La figure 7 montre que, malgré la diminution du champ électrique quand on se rapproche de la cathode, la largeur du volume sensible est maximale dans cette région.

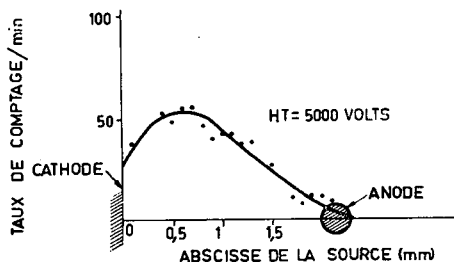


Figure 7

Variation du taux de comptage pour un déplacement de la source selon l'axe de révolution du compteur (irradiation latérale). HT = 5000 V.

Nous fixant $d = 0,5$ mm, nous avons déplacé la source parallèlement à la cathode, dans la direction normale à celle du faisceau de particules α : le taux de comptage suit la courbe de la figure 8. On peut ainsi estimer l'ordre de grandeur du volume sensible: il possède la forme générale donnée sur la figure 9.

Conclusion

En résumé, le compteur à sphère possède sur le compteur à fil les avantages suivants:

1. Le courant permanent est plus faible.
2. Le dégagement d'ozone et la formation d'oxydes de l'azote dans l'étincelle sont moins importants.

3. Sa capacité propre étant très faible, le temps de résolution est plus faible: pour le détecteur étudié ici, ce temps est inférieur à 50 μ s.

4. L'efficacité est indépendante de la direction d'incidence de la particule, alors que, pour un compteur à fil, cette condition n'est remplie que lorsque les deux électrodes sont très rapprochées [7].

5. Le volume sensible est de révolution autour de l'axe du détecteur; il est de quelques millimètres cubes; bien défini, il doit permettre l'emploi de ces détecteurs dans des télescopes précis.

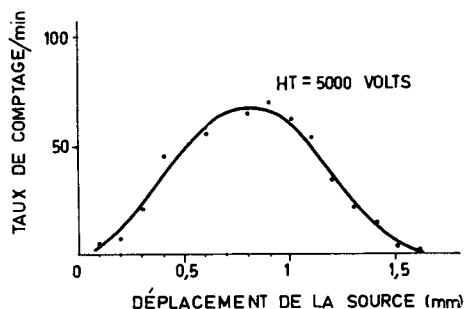


Figure 8

Variation du taux de comptage pour un déplacement de la source parallèlement à la cathode (irradiation latérale). HT = 5000 V ($d = 0,5$ mm).

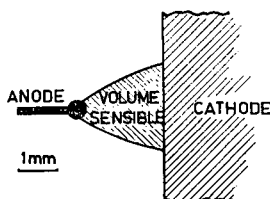


Figure 9

Volume sensible du compteur (sphère — plan).

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A PROPORTIONAL COUNTER WITH REDUCED WALL EFFECT

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Abstract — Résumé — Аннотация — Resumen

A proportional counter with reduced wall effect. A proportional counter, using gaseous sources, in which the wall effects are considerably reduced, is described. The counter is fitted with a ring of internal shielding counters in anti-coincidence, separated from the main central counter only by a number of cathode wires. The counter can be readily assembled, giving flexibility in research investigations. Applications to a measurement of the L/K capture ratio in A^{37} and Fe^{55} are described.

Compteur proportionnel à effets de paroi réduits. Les auteurs décrivent un compteur proportionnel, utilisant des sources gazeuses, dans lequel les effets de paroi sont considérablement réduits. Ce compteur est muni d'une couronne de compteurs montés en anticoincidence, qui ne sont séparés du compteur central que par un certain nombre de fils cathodiques. Ce compteur est d'un montage facile, ce qui permet une grande souplesse dans les recherches.

Les auteurs décrivent ensuite les modalités d'utilisation de ce compteur dans la mesure du rapport de capture L/K pour ^{37}A et ^{55}Fe .

Пропорциональный счетчик с ослабленным влиянием стенок. Описывается пропорциональный счетчик с газовыми источниками и со значительно ослабленными эффектами стенки. Счетчик снабжен расположенным кольцом и работающими в несовпадении счетчиками с внутренним экранированием, отделенными от главного центрального счетчика только небольшим числом катодных проводов. Счетчик может быть легко смонтирован, что дает гибкость при исследовательских работах. Дается описание применения счетчика для измерения соотношения захватов L/K в A^{37} и Fe^{55} .

Contador proporcional con efecto de pared reducido. La memoria describe un contador proporcional que emplea fuentes gaseosas y en el que los efectos de pared han quedado considerablemente reducidos. El contador va rodeado de un anillo de contadores en anti-coincidencia, con blindaje interno, separados de él únicamente por una serie de cátodos de alambre. El montaje del contador es muy sencillo, por cuyo motivo se adapta fácilmente a necesidades experimentales muy diversas. La memoria describe su aplicación a la medición de la razón de captura L/K en el ^{37}As y el ^{55}Fe .

In all investigations involving low-energy measurements with proportional counters, effects due to the wall of the counter must be considered. For example, the low-energy part of a beta spectrum may be distorted and other low-energy phenomena obscured. In the cases of X-ray sources the radiation may escape from the counter and the interpretation of the results becomes very complicated. Wall effect can, in principle, be reduced by filling the counter with an absorbing gas under a high pressure. However, practical limitations are set by impurity of the gas, the high voltage required and the background. In connection with a programme of electron-capture investigation we adopted an anti-coincidence-type proportional counter in which the wall effects are considerably reduced. This system can be usefully exploited in other fields of study.

The arrangement consists of two co-axial proportional counters, the axial measuring counter being in anti-coincidence with the annular counter. This approach has been

suggested by DREVER *et al* [1]. Their method consists in counting only the pulses from the axial counter which are not in coincidence with the K pulses from the peripheric counter. The intensity of the L peak is then associated with L capture only. The K peak is due partly to the events in the ordinary counter and partly to the K photons coming from the outer counter which compensate for the K photons that escape from the central counter.

The cross-sectional diagram of the counter assembly is shown in Fig. 1. The end plates are made of 2-cm thick lucite plastic which are held apart by supporting rods. A 0.1-mm harmonic steel centre wire is mounted between teflon stoppers. The 32 cathode wires of the inner circle are harmonic steel 0.1 mm in diam. Their number seems sufficient to remove the coupling effect between the central and the ring counters. Twelve wires, 0.2 mm in diam., define the volume of each shielding counter. The cathode wires are arranged so that the field distribution around the 8 counting wires is not much distorted. The surrounding counters are proportional in operation and they can operate at the

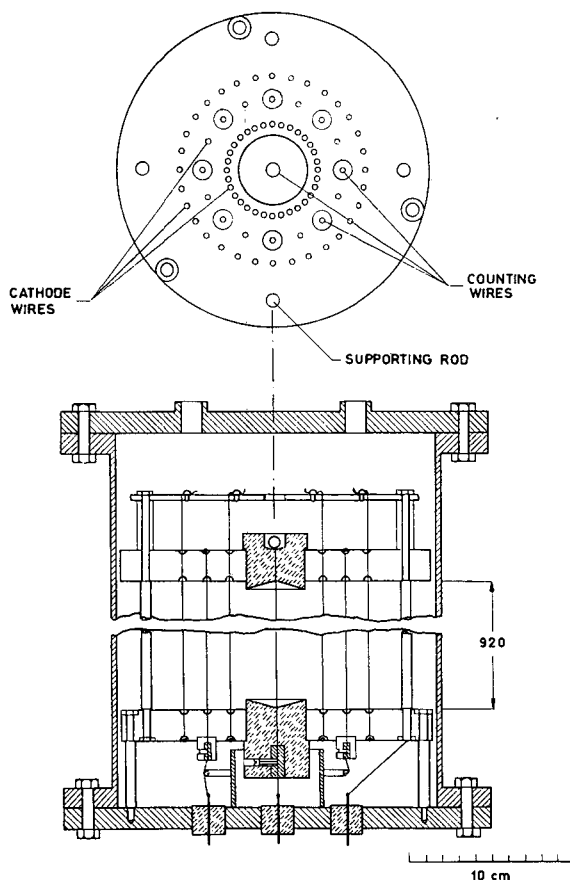


Fig. 1
Multi-wire counter assembly

same voltage as the main counter. The counter has been constructed without field tubes. A large fraction of the 92-cm-long counter, however, operates with maximum resolution because of the relatively small distortion of the electric field by the non-conducting lucite end plates. The whole system can be removed as a unit from the containing cylinder

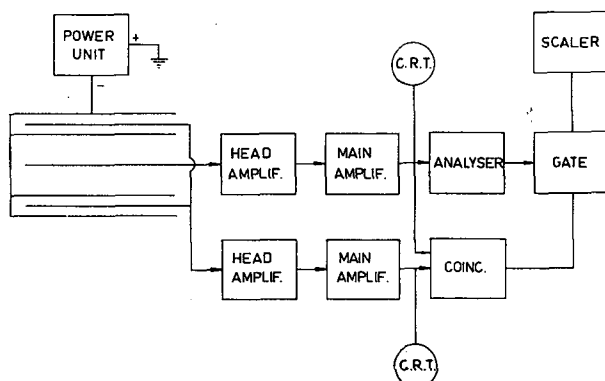


Fig. 2
Block diagram of the electronic equipment

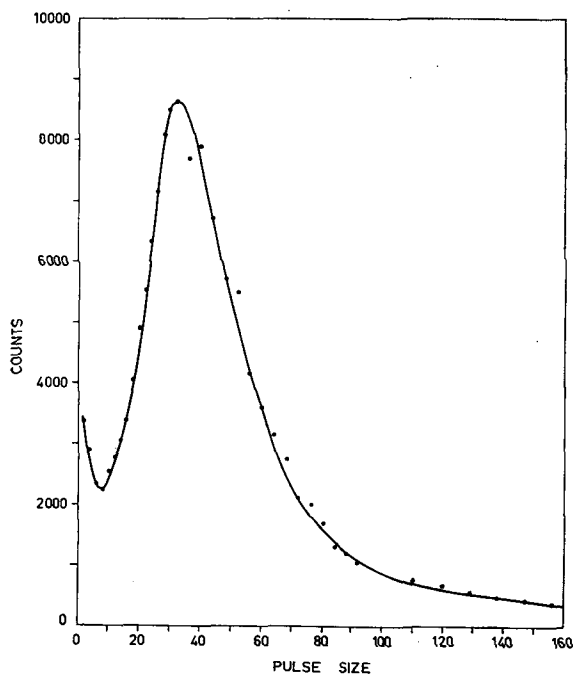


Fig. 3
A³⁷ L peak from the central counter in anti-coincidence with the ring counter

and it can be readily assembled. The limit of pressure set by the mechanical strength of the counter is 10 atm.

Either anode or cathode wires can be operated at earth potential. This facilitates the operation of the counter, giving flexibility in research investigation.

The signals from the central counter are fed through a non-overloading linear amplifier to a conventional analyser. Pulses from both the central and the ring counters, after amplification, pass through a pulse-height selector to the coincidence circuit. The coincidence pulses are fed to an anti-coincidence gate of the scaler. The block diagram is shown in Fig. 2. With the electronic system designed, the high counting rate in the ring counter does not greatly affect the efficiency of gating. Figs. 3 and 4 show typical spectra obtained with a gas filling of 3 atm of tank argon with a small amount of methane. The gases are not purified.

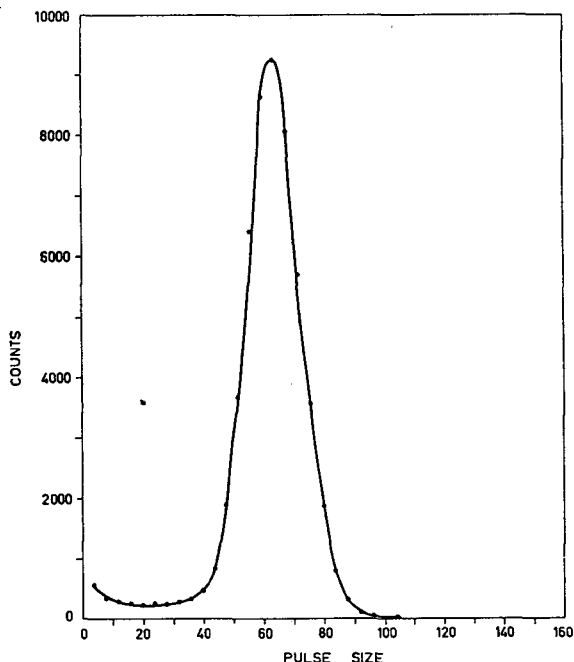


Fig. 4

A^{37} K peak from the central counter in anti-coincidence with the ring counter

The wall-less counter has been used to re-investigate the decay of A^{37} and Fe^{55} . Measurements were carried out with argon-filling at various pressures and methane at a pressure of 200 torr was used as quenching gas. The iron compounds used as gaseous sources were ferrocene (bicyclopentadienyl iron) and penta-carbonyl iron. The results agree satisfactorily with the theoretical calculations and will be published elsewhere.

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CONSTRUCTION AND OPERATING CHARACTERISTICS OF FLEXIBLE GEIGER COUNTERS

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Abstract — Résumé — Аннотация — Resumen

Construction and operating characteristics of flexible Geiger counters. A method has been developed for constructing flexible Geiger counters in a wide range of lengths and diameters. The counters are quite flexible: a 3-cm diam. counter can be bent to a circle of 5 cm radius. Using Q-gas (98.3% helium, 1.7% n-butane) as the counting medium, plateaux are several hundred volts long with 3% slopes and are independent of the counter configuration.

Counters are constructed from tubing having a polyvinyl-chloride formulation (PVC-744 - Alpha Wire Corp.). Short segments of the plastic tubing (length ~ 3 times the tube diameter) are slipped over a coarsely threaded aluminium mandrel. Wire is wrapped tightly in the threads and the whole is placed in a 110°C oven for 20 min. After cooling, the corrugated plastic segment is removed from the mandrel. This corrugation prevents the collapse of the tubing when it is coiled.

A polystyrene disk, perforated with relatively large holes near the periphery for gas flow and having a 0.6-mm hole in the centre for the anode, is fastened in one end of each segment. By threading the segments thus prepared on a 3-mil tungsten anode and slipping one end of each segment over the adjacent segment and securing them with an adhesive, a counter of any desired length can be built up. Glass end-pieces for attaching the anode ends and for admitting and exhausting the flow gas are attached. A bare copper wire spiralled in the grooves of the counter makes a satisfactory external cathode which operates in the manner observed by MAZE [1].

A 3-cm diam. counter, 1 m long, either linear or coiled, has a plateau beginning at 1400 V and extending beyond 1750 V with a 2.9% slope. Counting rates in excess of 300000 counts/min with little coincidence loss have been observed. Since the counter is actually a series of short Geiger counters and the discharge does not spread beyond the polystyrene spacer disks, adjacent counter segments operate independently. Pulse heights are greater than 50 mV.

Caractéristiques de construction et d'utilisation de compteurs Geiger flexibles. On a mis au point une méthode de construction de compteurs Geiger flexibles ayant des dimensions très variées.

Les compteurs sont très flexibles: un compteur de 3 cm de diamètre peut être plié avec un rayon de courbure de 5 cm. En utilisant du gaz Q (98,3% d'hélium et 1,7% de n-butane) comme milieu de comptage, les paliers ont une longueur de plusieurs centaines de volts avec une pente de 3% et sont indépendants de la configuration géométrique du compteur.

Les compteurs sont construits avec des tubes en chlorure de polyvinyle (PVC-744 - Alpha Wire Corp.). De courts segments du tube (longueur égale à environ 3 fois le diamètre) sont glissés sur un mandrin d'aluminium grossièrement fileté et entourés d'un fil fortement serré. Le tout est placé dans un four à 110°C pendant 20 minutes. Après refroidissement, le segment de matière plastique ainsi cannelé est dégagé du mandrin. Ce traitement du tube empêche sa rupture lorsqu'il est enroulé.

Un disque de polystyrène, perforé de trous relativement grands à la périphérie pour l'écoulement du gaz et d'un trou central de 0,6 mm pour le passage de l'anode, est attaché à une extrémité de chaque segment. En enfilaient les segments ainsi préparés sur une anode en tungstène de 3 mm, en glissant une extrémité de chaque segment sur le segment adjacent et en les fixant solidement avec un adhésif, on peut construire un compteur d'une longueur quelconque. On attache aux

extrémités des pièces en verre pour la fixation de l'anode et pour l'admission et l'évacuation du gaz. Un fil de cuivre nu, entouré en spirale dans les cannelures du compteur, donne une cathode externe satisfaisante, qui fonctionne suivant le mode observé par Maze.

Un compteur de 3 cm de diamètre et de 1 mètre de longueur, linéaire ou enroulé, possède un palier commençant à 1400 volts et allant jusqu'à 1700 volts avec une pente de 2,9%. On a enregistré des taux de comptage de plus de 300 000 coups par minute, avec peu de pertes par coïncidences. Comme le compteur est en fait une série de compteurs Geiger courts et que la décharge ne s'étend pas au-delà des disques d'espacement en polystyrène, les segments de compteur adjacents fonctionnent indépendamment. Les hauteurs d'impulsions dépassent 50 mV.

Конструкционная и оперативная характеристики гибких счетчиков Гейгера. Был разработан метод изготовления гибких счетчиков Гейгера различной длины и диаметра. Счетчики являются совершенно гибкими; счетчик диаметром 3 см можно согнуть в круг радиусом 5 см. При использовании Q-газа (98,3% гелия и 1,7% n-бутана) в качестве счетной среды, плато имеют несколько сот вольт напряжения с 3-процентным скачком и не зависят от конфигурации счетчика.

Счетчики изготовлены из пластмассовой поливинил-хлоридной трубки (PVC-744-Альфа Уайр Корп.). Короткие сегменты пластмассовой трубки (длина составляет примерно 3 диаметра трубки) проходят через грубо нарезанный алюминиевый сердечник. Провод плотно обертывается в нарезках и все вместе помещается на 20 минут в печь с температурой 110° С. После охлаждения рифленый пластмассовый сегмент снимается с нарезки. Это рифление предохраняет трубку от разрушения при наматывании.

Полистироловый диск, перфорированный относительно большими отверстиями около окружности для перехода газа и имеющий отверстие 0,6 мм в центре для анода, крепится на одном конце каждого сегмента. Натягивая подготовленные таким образом сегменты на вольфрамовый анод в 3 мм и пропуская один конец каждого сегмента поверх соседнего сегмента с одновременным креплением, можно создать счетчик любой желаемой длины. Для присоединения концов анода и для впуска и выпуска потока газа придаются стеклянные наконечники. Оголенный медный провод, проходящий змеевиком в вырезах счетчика, представляет собой удовлетворительный внешний катод, действующий по принципу Мейза.

Счетчик диаметром 3 см и длиной 1 м (линейного или катушечного типа) имеет плато, начиная с 1400 вольт и кончая более 1750 вольт с 2,9-процентным скачком. Счетчик регистрирует свыше 300 000 отсчетов в минуту с незначительной потерей при совпадении. Поскольку счетчик относится фактически к серии коротких счетчиков Гейгера, а разряд не выходит за пределы полистироловых разделительных дисков, то примыкающие сегменты счетчика работают независимо. Амплитуды импульсов превышают 50 милливольт.

Construcción y características de funcionamiento de contadores Geiger flexibles. Los autores describen el método que han usado para construir contadores Geiger flexibles, de muy diferentes longitudes y diámetros. Estos contadores son efectivamente muy flexibles: un contador de 3 cm de diámetro puede doblarse hasta formar un círculo de 5 cm de radio. Utilizando gas Q (98,3% de helio y 1,7% de n-butano) se obtienen «plateaux» de varios centenares de voltios con pendientes de 3%, que son independientes de la configuración del contador.

Estos contadores están hechos de tubos de material plástico a base de cloruro de polivinilo (PVC-744 - Alpha Wire Corp.). Sobre un mandril de aluminio de rosca gruesa se enchufan segmentos cortos de tubo de dicho material plástico (de una longitud aproximadamente 3 veces mayor que el diámetro del tubo). Los filetes de la rosca se envuelven con alambre bien apretado y la pieza entera se coloca en un horno a 110° C durante 20 minutos. Después de enfriar, el segmento de material plástico así ondulado se retira del mandril. Esta ondulación evita que el tubo se aplaste cuando se le enrolla.

En un extremo de cada segmento va sujeto un disco de poliestireno, en el que se han practicado orificios relativamente grandes próximos a la periferia, para permitir la circulación del gas; el disco lleva además un orificio de 0,6 mm en el centro, para el ánodo. Roscando los segmentos

preparados en esta forma sobre un ánodo de tungsteno de 3 milésimas de pulgada (75 micrones), enchufando el extremo de cada segmento sobre el segmento siguiente y sujetándolos con un material adhesivo, se puede dar al contador la longitud que se desee. Se adjuntan piezas terminales de vidrio para sujetar los extremos del ánodo y para dar entrada y salida a la corriente de gas. Un alambre de cobre desnudo encajado en espiral en las ranuras del contador constituye un cátodo externo satisfactorio que funciona en la forma observada por Maze.

Un contador de 3 cm de diámetro y 1 m de largo, por ejemplo, sea extendido o enrollado, presenta un «plateau» que comienza a los 1400 V y se extiende a más de 1750 V con una pendiente del 2,9%. Se ha contado a más de 300000 impulsos por minuto, con escasa pérdida por coincidencia: como el contador consiste prácticamente en una serie de contadores Geiger cortos y la descarga no se extiende más allá de los discos espaciadores de poliestireno, los segmentos de contador adyacentes trabajan independientemente. Las amplitudes de los impulsos superan a los 50 mV.

MAZE [1] constructed a Geiger-Mueller counter by painting colloidal graphite on the outside of a thin soft glass tubing which contained an axial tungsten wire. On filling the tube with a counting gas and applying a voltage between anode and cathode, the device behaved similarly to a regular metal-cathode Geiger-Mueller counter. Although subsequent literature presents conflicting data, it appears as if external cathode ionization chambers, proportional counters, and Geiger-Mueller counters can be constructed from Pyrex and quartz [2] [3] [4], the latter operating only above about 200°C.

It occurred to us that the Maze principle might be applied to the construction of flexible Geiger-Mueller counters. Many uses can be foreseen for long G-M tubes which can be coiled, wrapped, or placed in non-linear configurations. We have succeeded in finding a plastic material having satisfactory conductivity, which permits us to construct external cathode flexible G-M tubes of any desired length or diameter.

None of the many "plastics" is a perfect insulator—all will conduct some quantity of electricity under the proper conditions. Some are better conductors than others. The early part of our work consisted in testing various industrial plastic tubings to determine whether any would indeed conduct satisfactorily the minute currents which make up the Geiger pulse. Table I lists those materials which were tried.

Whereas many "plastic tubings" have not been investigated, it is interesting to note that all those which have been found sufficiently conductive for the purpose are vinyl-chloride polymers. However, poly-vinyl-chloride in itself is not sufficient, since Nalgon and Tygon R-2400 are poly-vinyl-chloride formulations and were found to have too high a resistance to conduct the G-M currents. The co-polymer material undoubtedly plays an important part in the process. The most satisfactory results have been achieved with PVC-744 and subsequent discussion will be concerned chiefly with this material.

Early experiments were carried out in the following manner: PVC-744 sleeving, as received from the vendor, was slipped over a long-threaded rod of diameter slightly less than that of the sleeving. Wire was wrapped around the plastic (in the threads of the rod) and kept taught while the assemblage was heated at 110°C for 20—30 min. After cooling, the plastic tubing was removed from the threaded mandrel, whereupon it now maintained a corrugated tubular shape. The corrugations allowed it to be bent in relatively short radii without collapsing. A 3-mil molybdenum wire containing polystyrene disks fastened at intervals with adhesive was carefully slipped into the corrugated tubing. A bare copper wire spiralled in the grooves on the outside of the tubing acted as a cathode. When Q-gas (98.7% helium, 1.3% butane) was flowed through the tubing, the result was found to be a satisfactory G-M counter.

TABLE I
TUBINGS INVESTIGATED FOR USE AS FLEXIBLE G-M COUNTERS

Tubing	Manufacturer	Conducts G-M Current
SLY-105	Illumitronic Engineering, Sunnyvale, California	Yes
Tygon R3603	United States Stoneware Company, Tallmadge, Ohio	Yes
PVC-744	Alpha Wire Corporation, New York, N. Y.	Yes
PVC-105	Alpha Wire Corporation, New York, N. Y.	Yes
Dacron-Tygon	*	Yes
Tygon R2400	United States Stoneware Company, Tallmadge, Ohio	No
Nalgon	Nalge Corporation, Rochester, New York	No
Polyethylene		No
Silicone Rubber	Bentley, Harris Co., Conshohocken, Pa.	No
Natural Rubber		No
"Conductive" Tubing	Bittner Corporation, New York, N. Y.	Yes - No**

* Knitted dacron (methyl terephthalate-ethylene glycol polyester fibre, DuPont Company) cloth tubing made gas tight with Tygon paint containing colloidal graphite.

** Conducts G-M currents, but no plateau could be obtained with this material.

This method of forming flexible tubings has two severe limitations. First, the length of counter which can be made is limited to the length of threaded rod which can be accommodated in the heat-treating oven. Furthermore, removing the formed tubing from a long rod is found to be very tedious. Second, fastening disks to a thin anode wire and slipping this into the corrugated tubing is difficult and exasperating since no really satisfactory adhesive was ever found.

A much better technique has been devised. Short segments of corrugated PVC-744 (7 cm) are formed on an aluminium mandrel, shown in Fig. 1, by wire-wrapping and heat-treating as described above. The ends of the mandrel are of slightly different diameters, such that the end of one formed segment can be slipped loosely over the end of another segment. A polystyrene disk, 0.5 cm thick by 2.3 cm diam. (Fig. 1) containing a 25-mil central hole and three peripheral holes to permit passage of gas, is fastened with adhesive in the smaller end of each PVC-744 segment. Any desired length of flexible counter can thus be built up by threading the required number of segments on to a molybdenum or tungsten anode wire. Bare copper wire spiralled in the grooves on the outside of the counter serves as cathode. Fig. 2 shows an experimental tube, about 1 m long, fitted with glass end-pieces to maintain the anode taut and to admit the Q-gas mixture. The smallest radius of curvature possible with this particular diameter of tubing (3 cm) is about 2 cm.

The operating characteristics of these flexible counters, made from PVC-744, are superior in two respects to those made from rigid metallic cathodes. First, the plateaux of 2–4% slope can be up to 1000 V long and second, counting rates of the whole counter can be many hundreds of thousands of counts per minute with little coincidence loss.

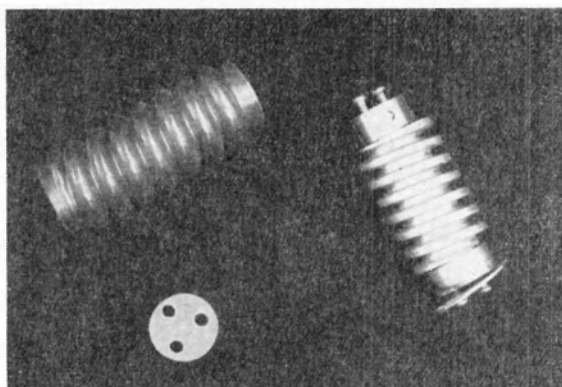


Fig. 1

7-cm segment of corrugated PVC-744, formed by RTI technique (right side)
A polystyrene disk (0.5 cm thick by 2.3 cm diam.) containing a 25-mil central hole and three peripheral holes to permit passage of gas, is shown above. It is fastened with adhesive tape in the smaller end of PVC-744 segment (left side)

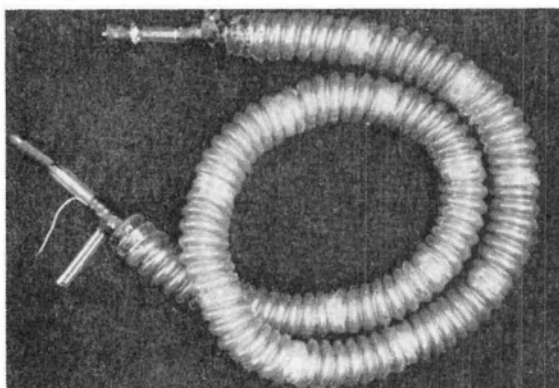


Fig. 2

View of an experimental 3-cm diam. tube, fitted with glass end-pieces to maintain the anode taut and to admit the Q-gas mixture. The smallest curvature-radius possible is about 2 cm

The long plateaux observed with these flexible counters probably result directly from the "semi-conducting" property of the plastic tubing. The wall material produces a situation which acts as if there were a parallel resistance-capacitance network between the place where positive ions are collected and the electrical ground [2]. The high voltage applied between anode and cathode is therefore distributed partly between anode-and-wall and wall-and-cathode. The actual electrical field which an electron just formed in the counting gas experiences is thus less than that indicated by the measured potential between anode and cathode. How this is distributed has not been studied. Another possible reason for the long plateau is that the production of secondary electrons by positive ions at the plastic wall is much lower than with metal cathodes, partly

because no conduction electrons are available for multiple emission processes, and partly because the work function of the plastic surface is high [5].

Counting rates of flexible counters can be very high because of their segmented construction. Geiger pulses are not propagated beyond insulating obstructions placed on the anode. Glass beads, for example, when attached to anodes, stop the discharge along the wire [6]. Flexible counters with their polystyrene spacers, therefore, are a series of short, independent G-M counters, any one of which can operate irrespective of the recovery of its neighbours. Long flexible counters made up of many segments will thus be limited in counting rate by the resolving time of scaler circuitry rather than that of the counter itself.

As the counting rate is increased on our flexible G-M counters, by bringing a distant radioactive source up close, it is possible with an oscilloscope to watch the discharge pulse-heights decrease markedly in size. This phenomenon has been reported before [4] [5]. It is due probably to what can be called a "sheath effect". An electrostatic charge collects on the interior wall of the counter from the Geiger discharges and is only slowly drained off to the exterior cathode. If sufficiently high radioactivity decay-rates are encountered, this charge can build up to such values that an ion pair just created in the counter gas sees a reduced potential on the anode. The resulting smaller output pulses may not trigger the scaler. However, with PVC-744, counting rates up to 100000 counts/min have been observed on a single segment and the pulse heights were still above 50 mV. The "sheath effect", therefore, cannot be a serious drawback to PVC-744 external-cathode counters.

We have thus developed a method for constructing highly flexible Geiger-Mueller counters with lengths and diameters limited only by the requirements of the application. They are stable, durable, exhibit remarkably long plateaux and are capable of high counting rates. We are now investigating their suitability as anti-coincidence coils and gamma counters.

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MISE AU POINT DE COMPTEURS GEIGER-MÜLLER FONCTIONNANT A HAUTE TEMPÉRATURE

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Abstract — Résumé — Аннотация — Resumen

Development of Geiger-Müller counters for operation at high temperatures. Counters of this type are necessary for radioactive logging at great depths; they have to operate normally at temperatures up to 180°C.

In order to preserve their characteristics under such conditions, the work function of the cathode has been improved by a special treatment. Tests have been made on counters with graphite, copper and wolfram cathodes in a glass envelope.

The method is simple, and can easily be employed in industry.

Mise au point de compteurs Geiger-Müller fonctionnant à haute température. De tels compteurs sont nécessaires pour le sondage radioactif aux grandes profondeurs; ils doivent fonctionner dans des conditions normales jusqu'à la température de 180°C.

Afin qu'ils puissent conserver leurs caractéristiques jusqu'à cette température, on a agi sur le travail de sortie de la cathode par un traitement adéquat. On a fait l'essai sur des compteurs avec cathode de graphite, de cuivre ou de tungstène, dans un ballon de verre.

La méthode proposée est simple et peut être appliquée facilement dans l'industrie.

Разработка счетчиков Гейгера-Мюллера, работающих при повышенной температуре. Подобные счетчики необходимы для радиоактивного кароттажа на больших глубинах; они должны функционировать в нормальных условиях при температуре до 180° С.

Наконец, для того, чтобы они могли сохранять свои особенности при этой температуре, было обращено внимание на работу катодного выхода при помощи соответствующей обработки. Был проведен опыт на счетчиках с графитовым, медным или вольфрамовым катодом в стеклянном сосуде.

Предлагаемый метод прост и может быть легко использован в промышленности.

Contadores Geiger-Müller que funcionan a temperaturas elevadas. Se requiere este tipo de contador para la determinación de la radiactividad a grandes profundidades; debe ser capaz de funcionar normalmente a temperaturas hasta de 180°C.

A fin de que sus características se conserven inalteradas hasta tales temperaturas, se ha modificado la función de trabajo del cátodo mediante un tratamiento adecuando. Se han ensayado contadores con cátodo de grafito, de cobre o de wolframio en un balón de vidrio.

El método propuesto es simple y puede aplicarse fácilmente en la industria.

Introduction

Pour les besoins de la recherche pétrolière, nous avons réalisé un compteur Geiger-Müller avec autoextinction qui fonctionne jusqu'à 180°C au moins sans changer ses caractéristiques. Pour cela, il a été nécessaire d'analyser les causes qui provoquent les modifications des caractéristiques de ces compteurs lorsque la température à laquelle ils fonctionnent augmente, et de prendre les mesures nécessaires afin de les éviter.

Le problème est depuis longtemps débattu dans la littérature technique, mais jusqu'à présent on n'a pu tirer de conclusions précises sur les phénomènes qui y ont lieu.

Les causes qui provoquent la modification des caractéristiques des compteurs Geiger-Müller avec la température peuvent être groupées selon les données connues dans trois catégories:

a) Adsorption-désorption des gaz de remplissage dans les parois d'un compteur, processus qui influence la concentration du gaz autocuiseur du compteur [2] [13] [18].

b) Chimiadsorption, aux températures élevées, du gaz autocuiseur à la cathode, processus qui provoque une modification de la concentration et de la composition de ce gaz [2].

c) Emission thermique, soit par le champ des électrons ou des ions [10] [14] [15] de la cathode, soit par une émission secondaire accrue due à l'augmentation de l'énergie moyenne et du nombre des ions positifs qui bombardent la cathode [5] [8].

Afin de combattre ces effets, on recommande soit une augmentation du travail de sortie de la cathode et la réduction de l'adsorption par la formation d'une pellicule de gaz autocuiseur sur la cathode [3] [4] [6] [9] [19], ou d'une couche aux caractéristiques convenables, obtenue par oxydation, polissage, etc., soit le choix d'une pression convenable du gaz, selon la température à laquelle les compteurs vont fonctionner.

Résultats expérimentaux

Nous avons d'abord fait des mesures sur nos compteurs ordinaires, dont les données constructives sont les suivantes: ballon de verre, cathode de graphite, anode de tungstène de 0,1 mm $\varnothing$, gaz de remplissage obtenu d'un mélange d'argon et d'isopentane 10% sous la pression totale de 40 à 100 mm Hg. La caractéristique (nombre d'impulsions comptées en fonction de la tension) se modifie selon la température (fig. 1).

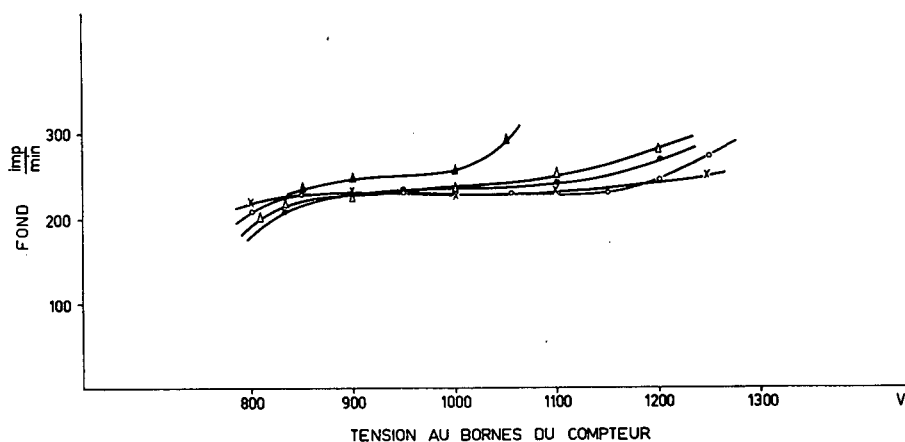


Figure 1

Caractéristique de comptage d'un compteur ordinaire.
x 26°C, o 60°C, ● 80°C, Δ 100°C, ▲ 100°C après 150 min.

Au-dessus de 80°C, le compteur n'est pratiquement plus utilisable. L'effet est le même pour les compteurs avec cathode d'un autre métal (formation d'une pellicule), mais la température à laquelle le compteur devient inutilisable diffère (tungstène, 140°C; tungstène oxydé, 80°C; cuivre, 100°C, etc.).

Les résultats ne dépendent pas de la pression du gaz de remplissage, dans les limites mentionnées.

On obtient une certaine amélioration en remplissant les compteurs à 100—150°C, sans tout de même obtenir des résultats satisfaisants.

Nous avons essayé alors d'agir sur la surface de la cathode, pour augmenter le travail de sortie et pour réduire l'adsorption. On a obtenu de bons résultats en utilisant une des deux méthodes suivantes:

- a) Traitement thermique du compteur;
- b) Formation d'une pellicule stable du gaz autocuiseur sur la cathode.

Nous allons décrire brièvement les résultats obtenus sur les compteurs ainsi réalisés.

TRAITEMENT THERMIQUE DU COMPTEUR

Les compteurs réalisés suivant les procédés mentionnés sont maintenus quelques heures aux températures de 75, 100 et 150°C. Après ce traitement, ils peuvent fonctionner dans des conditions normales au moins jusqu'à 180°C. Cela a été vérifié sur vingt compteurs à différentes cathodes surveillées à cette température au cours d'un fonctionnement de 20 heures.

Par ce traitement, le seuil G.M. baisse de 50 V par rapport au seuil G.M. des compteurs non traités.

On a constaté qu'autour de la température de 200°C les compteurs ont une augmentation du nombre des impulsions de fond, qui va en croissant exponentiellement avec la température, et on ne peut plus définir de plateau. Le seuil G.M. se maintient à la même valeur jusqu'à cette température (que nous appellerons «seuil thermique»), après quoi il s'élève brusquement de 50—100 V.

Lorsque la température s'abaisse sous ce seuil thermique, les compteurs reviennent aux caractéristiques initiales (impulsions de fond, plateau, pente du plateau, seuil G.M.).

Relevons le fait que, pendant le traitement, on observe qu'après un chauffage de près de 2 heures à 100°C le nombre des impulsions de fond augmente de presque 50%, pour revenir après quelques heures à la valeur initiale.

Ces résultats sont satisfaisants du point de vue des performances, mais le processus technologique est trop long.

FORMATION D'UNE PELLICULE STABLE DU GAZ AUTOCUPEUR SUR LA CATHODE

Pour la création de cette pellicule, il est important d'introduire dans le compteur l'isopentane d'abord. Nous avons essayé plusieurs méthodes pour remplir les compteurs, et les résultats obtenus sont identiques. Les compteurs obtenus gardent leurs caractéristiques initiales jusqu'aux températures de 180° à 300°C. Ces résultats ont été vérifiés sur deux cents compteurs (10% des compteurs obtenus deviennent inutilisables avant d'atteindre 180°C; 15% ont fonctionné normalement à la température de 180°C moins de 20 heures, et 75% plus de 20 heures).

Le seuil G.M. de ces compteurs reste constant jusqu'à une température de 20—30°C au-dessus du seuil thermique, après quoi il baisse brusquement de 100—200 V; par refroidissement, les compteurs reviennent à la valeur initiale du seuil G.M.

COMPORTEMENT ET STABILITÉ EN FONCTION DE LA TEMPÉRATURE

Nous allons analyser maintenant le comportement et la stabilité avec la température des caractéristiques principales des compteurs obtenus par les procédés décrits; nombre d'impulsions de bruit de fond, plateau, pente du plateau, seuil thermique.

Nombre d'impulsions de bruit de fond

Les mesures ont été effectuées sur des compteurs soumis à une variation de température entre 1 et 2,5°C par minute, d'une part par l'enregistrement continu du nombre des impulsions, les compteurs étant soumis à une tension de 100 V au-dessus du seuil G.M. (contrôle effectué sur dix compteurs), d'autre part par le contrôle de 25 en 25°C du nombre des impulsions à une tension de 100 V au-dessus du seuil G.M. (75 compteurs contrôlés).

La figure 2 donne les résultats obtenus sur l'un des compteurs. Ils démontrent, comme nous avons déjà dit, que le nombre des impulsions de bruit de fond reste constant jusqu'à la température critique t_0 , après quoi il augmente exponentiellement. Si ce seuil thermique est dépassé de plus de 20–30°C, ou si le compteur fonctionne longtemps (30–40 minutes) au-dessus de la température t_0 , il résulte une déformation irréversible de cette caractéristique, le retour ayant lieu selon la ligne 2. Le seuil thermique d'un compteur qui a subi cette transformation baisse jusqu'à t_0 .

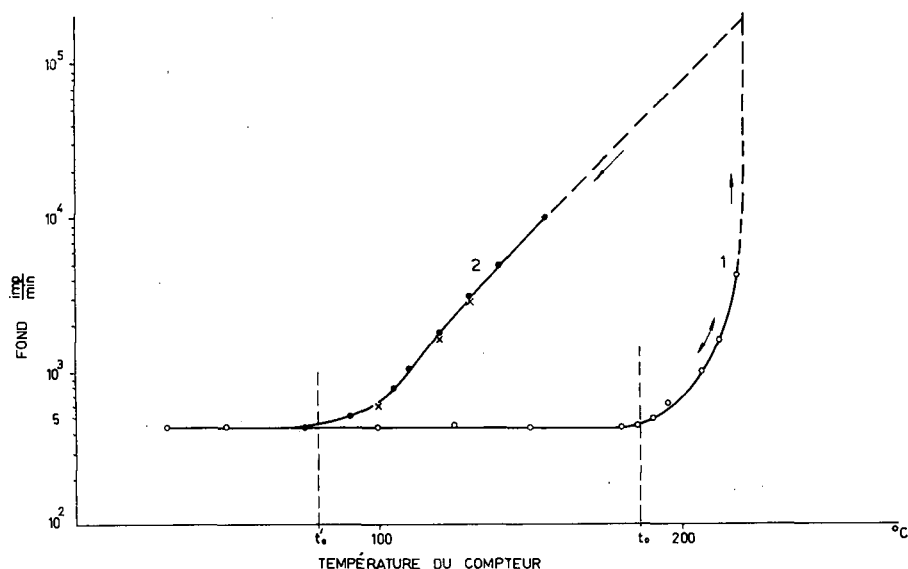


Figure 2

Dépendance du nombre d'impulsions de bruit de fond d'un compteur par rapport à la température.

- Fond mesuré quand la température s'élève
- Fond mesuré quand la température baisse
- x Fond mesuré quand la température s'élève pour la deuxième fois.

On a constaté que tout dépassement du seuil thermique (jusqu'à 350°C) sans tension appliquée au compteur ne lui cause aucune détérioration irréversible.

Plateau et pente du plateau

Les variations du plateau et de la pente du plateau des compteurs avec la température sont illustrées dans la figure 3.

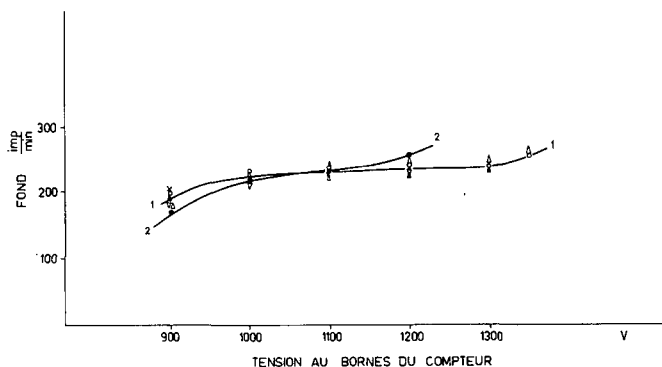


Figure 3

Caractéristiques de comptage d'un compteur pour températures élevées.

▲ 26°C ○ 75°C × 100°C △ 150°C ▽ 180°C

Courbe 1: palier à différentes températures

Courbe 2: après 20 heures de fonctionnement à 180°C

Seuil thermique

Pour déterminer le seuil thermique, on a contrôlé quatre-vingts compteurs, soumis à une variation de température entre 1 et 2,5°C par minute.

La distribution des compteurs sur différentes valeurs du seuil thermique est la suivante:

t_0	inférieur à 180°C	185°C	200°C	225°C	250°C	275°C	300°C	supérieur à 300°C
Compteurs	9	10	10	19	14	13	4	1

Résistance à la température

On a effectué les vérifications suivantes. *Preuve de durée:*

Température à laquelle on a fait le contrôle ($t < t_0$)	180°C	200°C	250°C
Compteurs			
{ expérimentés	54	19	19
{ résultats positifs	48	13	9
Durée de l'expérience après laquelle les compteurs continuent de fonctionner (h)	20	10	1

Résistance au choc de température: dix-sept compteurs ont été vérifiés après une élévation brusque (10 minutes) de température. Les résultats obtenus sont:

Température du choc	180°C	200°C	250°C	300°C
Compteurs				
{ expérimentés	6	8	2	1
{ résultats positifs	5	1	—	—
Observations	Après quelques minutes, le compteur fonctionne en régime de «décharge»		Après le refroidissement, le bruit de fond croît de 20%	

Il résulte que le choc de température ne doit pas dépasser 180°C. Les compteurs chauffés brusquement au-dessus de cette température sont dégradés; une expérience ultérieure pour déterminer le seuil thermique nous a montré que tous ces compteurs ont le seuil thermique au-dessous de 180°C.

La pression du gaz de remplissage et le matériau constituant la cathode n'ont eu aucune influence. Les compteurs réalisés d'après la technologie mentionnée avaient les mêmes qualités, dans les limites mentionnées, quelle que soit la pression et la composition du gaz de remplissage et quel que soit le matériau employé pour la cathode (graphite, tungstène, tungstène oxydé, cuivre).

Discussions

Nous estimons que par les procédés technologiques appliqués aux compteurs nous avons agi sur le travail de sortie de la cathode et pour vérifier cette hypothèse nous avons mesuré la dépendance de la photosensibilité du compteur avec la température.

Dans ce but nous avons utilisé des sources monochromatiques de lumière [20]. Le verre dont est fabriqué le ballon d'un compteur laisse passer les radiations lumineuses avec $\lambda > 3100 \text{ \AA}$. Les filtres de lumière monochromatique que nous avons utilisés se situent entre 3500 et 11000 $\text{\AA}$.

Il en résulte:

a) Les compteurs ordinaires sont sensibles aux ondes lumineuses ayant λ_{max} de 3650 à 4077 $\text{\AA}$ et à la fin de leur vie sont sensibles à λ_{max} de 4077 à 5000 $\text{\AA}$. Si cet effet de photosensibilité est dû à la cathode, il correspond à un travail de sortie de celle-ci entre 3,42 et 3,06 eV, et à la fin de la vie entre 3,06 et 2,5 eV.

b) Les compteurs qui fonctionnent aux températures élevées ne sont pas du tout photosensibles, c'est-à-dire qu'ils sont insensibles aux ondes lumineuses avec $\lambda > 3100 \text{ \AA}$ que laisse passer le ballon du compteur et qui correspondent, dans les mêmes hypothèses, à un travail de sortie de plus de 4,2 eV.

Les compteurs qui deviennent photosensibles pendant l'usage ne sont plus capables de fonctionner aux températures élevées.

On constate que le seuil thermique est un point de saut brusque de la photosensibilité, qui croît rapidement et, après 20—30° C, le compteur est sensible à 11000 $\text{\AA}$. Dans les mêmes hypothèses, cela correspond à un travail de sortie inférieur à 1,13 eV.

Si le seuil thermique est trop dépassé, on obtient une dégradation irréversible (fig. 3) du compteur, qui, refroidi, reste photosensible pour λ_{max} compris entre 3650 et 5000 $\text{\AA}$. La nouvelle valeur du seuil thermique du compteur est en corrélation avec λ_{max} pour laquelle le compteur est sensible. Dans la figure 4, qui illustre ces effets, on a tracé par une ligne interrompue la courbe au dessus de 11000 $\text{\AA}$ et au-dessous de 3100 $\text{\AA}$, faute de valeurs précises.

En analysant les impulsions de bruit de fond, aux températures qui dépassent le seuil thermique, nous avons constaté que ces impulsions ne sont pas des impulsions fausses résultant d'une ionisation primaire et que leur nombre dépend logarithmiquement de la température.

Nous avons voulu vérifier si le nombre d'impulsions de bruit de fond obéit à la loi d'émission de Richardson [10] [14], selon laquelle l'émission thermique d'une cathode est

$$I = AST^2 e^{-\frac{\phi}{kT}}.$$

Nous avons tracé la courbe (fig. 5)

$$\log \frac{N - N_0}{T^2} = f \left(\frac{1}{T} \right)$$

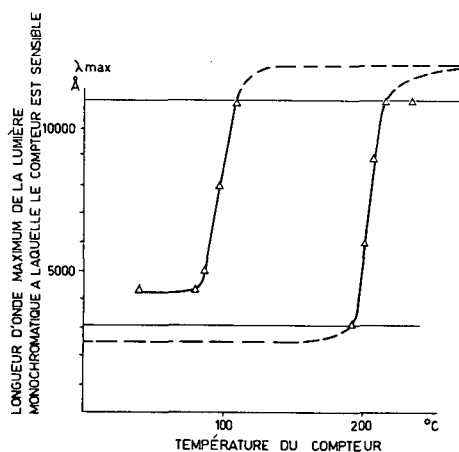


Figure 4

Dépendance de la photosensibilité d'un compteur pour températures élevées par rapport à la température du compteur.

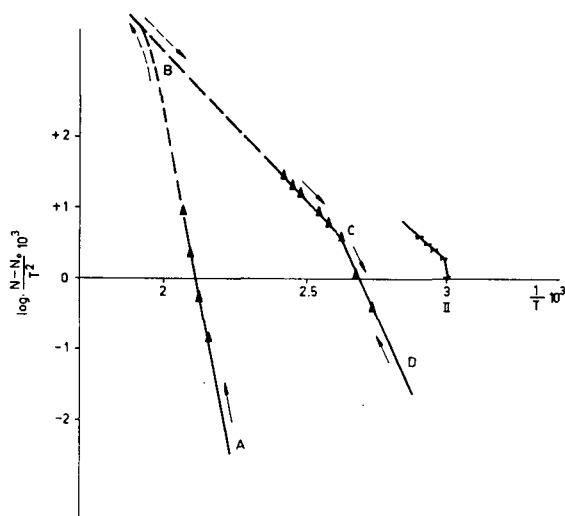


Figure 5

Dépendance du nombre d'impulsions d'un compteur par rapport à la température.

I Compteur fonctionnant à haute température
II Compteur ordinaire

où N_0 est le nombre d'impulsions de bruit de fond, et N le nombre d'impulsions à la température T . Il en résulte des droites et la valeur des pentes de ces droites donne le travail de sortie de la cathode. Dans la figure 5 sont indiqués les résultats pour un compteur dont on a mesuré le nombre d'impulsions de bruit de fond en fonction de la température jusqu'à 215°C, le seuil thermique étant à 185°C.

Lorsque la température croît, la loi de variation du nombre d'impulsions est donnée par la droite AB, de laquelle on déduit un travail de sortie de 4,2 eV; si la température croît encore, le compteur se dégrade, la pente de la droite change et on trouve un travail de sortie de 0,7 eV, qui se maintient quand la température baisse (droite BC), jusqu'à un nouveau point de transformation, après lequel nous avons la droite CD qui correspond à un travail de sortie de 2 eV. Le compteur a maintenant le seuil thermique à 80°C.

Pour un travail de sortie de 0,7 eV, que nous avons observé, le coefficient AS de la relation Richardson est de $5 \cdot 10^{-6}$ A/degré². Ces résultats quoique curieux, nous semblent être en concordance avec ceux qu'on a obtenus par l'effet de photosensibilité.

Conclusions

Nous estimons que nos expériences confirment l'hypothèse que le comportement d'un compteur avec la température est déterminé par l'état de la surface de la cathode. On a établi que dans la région du seuil thermique la photosensibilité du compteur se modifie rapidement en ce qui concerne la longueur d'onde maximum de la radiation lumineuse à laquelle il est sensible.

Les résultats concernant la validité d'une émission Richardson de la cathode restent à vérifier.

Pour obtenir des compteurs fonctionnant aux températures élevées, on a mis au point deux procédés technologiques pour la formation d'une couche stable de gaz autocoupeur sur la cathode, dont le plus simple est basé sur l'introduction, dans le compteur vide, du gaz autocoupeur et ensuite du gaz noble.

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УПРАВЛЯЕМАЯ ИСКРОВАЯ КАМЕРА — ПРИБОР ДЛЯ НАБЛЮДЕНИЯ СЛЕДОВ ЗАРЯЖЕННЫХ ЧАСТИЦ

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СССР

Abstract — Résumé — Аннотация — Resumen

Controllable spark chamber—an apparatus for observing the tracks of charged particles. The authors present a new type of detector—"a spark chamber", which is similar, in its principle of operation, to the spark counter. Unlike the latter, the spark chamber has a pulse-feed. The detector is simple in design and easy to operate; it can be used for following particle trajectories;— it possesses high time and space resolution; finally, it can be made to large dimensions.

Chambre réglable à étincelles pour observer les traces de particules chargées. Les auteurs proposent un nouveau type de détecteur appelé «chambre à étincelles» qui fonctionne selon un principe semblable à celui du compteur à étincelles. Contrairement à ce dernier, la chambre à étincelles est alimentée par impulsions. Elle est d'une construction simple, facile à employer, permet de suivre la trajectoire d'une particule et dispose d'un pouvoir de résolution élevé dans le temps et dans l'espace; en outre, on peut construire des chambres de grandes dimensions.

Управляемая искровая камера — прибор для наблюдения следов заряженных частиц. Авторами настоящей работы предложен новый тип детектора — „искровая камера“, сходный по принципу действия с искровым счётчиком. В отличие от последнего искровая камера питается импульсно. Детектор прост по конструкции, удобен в эксплуатации, даёт возможность следить за траекторией частицы и обладает высоким временным и пространственным разрешением, при этом он может быть сделан больших размеров.

Cámara de chispa regulable para observar las trazas de partículas cargadas. Los autores describen un nuevo tipo de detector: una «cámara de chispa» cuyo principio de funcionamiento es análogo al del contador de chispa. A diferencia de este último, la cámara de chispa se alimenta por impulsos. Este detector, de construcción sencilla y manejo cómodo, puede utilizarse para seguir las trayectorias de las partículas y tiene un alto poder de resolución en el tiempo y en el espacio. Es posible construir modelos de grandes dimensiones.

За последние годы для определения траектории движения частицы, всё более широкое применение находят различного вида детекторы разрядного типа. К числу таких детекторов относятся годоскопы, в которых в виде датчиков применяются счётчики Гейгера-Мюллера как в режиме постоянного, так и импульсного питания [1], безэлектродные разрядные трубки Конверси [2], искровые счётчики [3] и разрядная камера [4]. Все они обладают хорошим временным и пространственным разрешением, а также высокой эффективностью регистрации заряженных частиц. Однако при применении этих устройств в системе с большой светосилой возникает ряд трудностей, связанных с ростом числа используемых элементов.

1. Принцип работы и конструкция искровой камеры

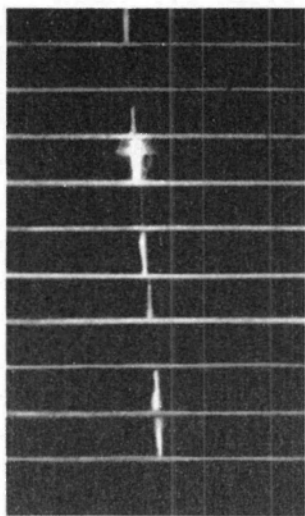
Искровая камера представляет собой ряд разрядных промежутков, образованных проводящими пластинами. Если после прохождения частицы приложить к пласти-

нам высоковольтный импульс достаточной амплитуды и длительности $\sim 10^{-7}$ сек, то в промежутке между пластинами в месте прохождения частицы возникает стримерный разряд, который представляет собой узкий $\sim 2-3$ мм светящийся канал, ориентированный примерно по направлению поля (рис. 1а и рис. 1б). Интенсивность разряда достаточна для его фотографирования. По наблюдаемой последовательности стримеров можно определить траекторию движения заряженной частицы.

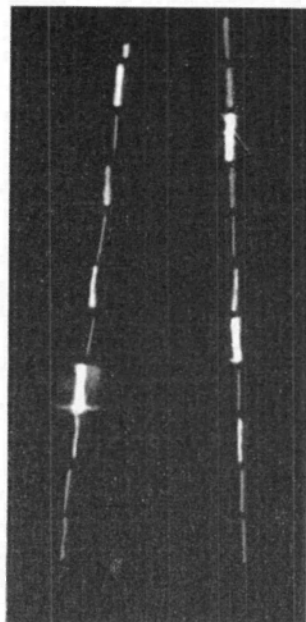
Нами были сконструированы и испытаны три камеры. В этих камерах искровые промежутки образовывались конденсатором, представляющим собой набор параллельных пластин, соединённых через одну. В двух случаях конденсатор помещался в стеклянный цилиндр, зажатый с двух сторон металлическими фланцами. В третьей камере конденсатор монтировался в коробке из органического стекла, склеенного дихлорэтаном. Конденсаторы собирались из латунных пластин толщиной 1—2 мм и размером 11×14 см², с искровыми промежутками $d = 8$ мм, $d = 9$ мм и $d = 10$ мм соответственно. В качестве рабочего газа нами использовался неон „особой чистоты“ при давлении 1,1 атм. Выбор неона в качестве рабочего газа обеспечивает возможность наблюдения за несколькими траекториями одновременно (рис. 1в) и облегчает конструктивное выполнение камеры из-за сравнительно низкого значения рабочего напряжения.

Рис. 1

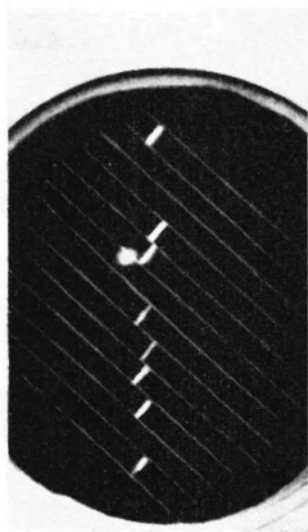
Типичные фотографии, полученные в искровой камере:



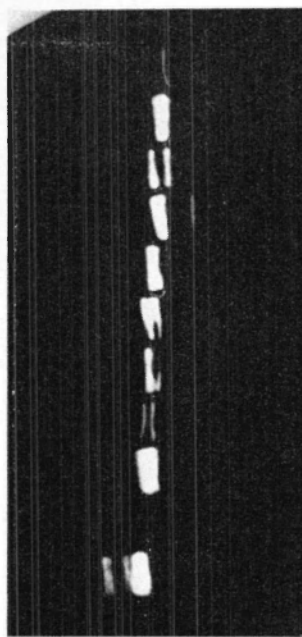
а) фотография проникающей частицы в камере ($d = 1$ см, $E = 9$ кв/см, $T_3 = 0,7$ сек, $\tau_n \sim RC = 10^{-7}$ сек)



б) случай наклонного прохождения частицы (угол $\sim 45^\circ$, $d = 8$ мм)



в) случай одновременного прохождения двух частиц



г) фотография одиночной частицы при $T_3 = 12 \mu\text{сек}$

2. Характеристики камеры

Экспериментальная установка для изучения характеристик искровой камеры показана на рис. 2.

μ -мезоны космического излучения, проходя через искровую камеру и 3 ряда счётчиков Гейгера-Мюллера, включенных на совпадение, вызывают срабатывание

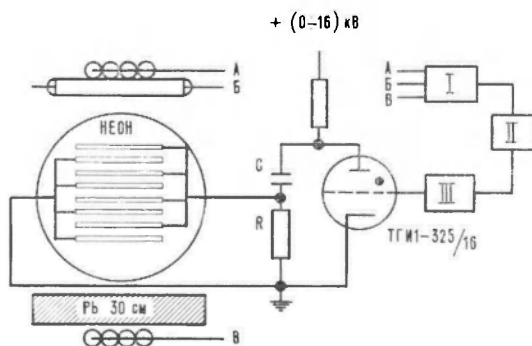


Рис. 2

Экспериментальная установка: I — схема совпадения, II — линия задержки, III — спусковой блокинг-генератор $R = 50 \text{ см}$, $C = 2000 \text{ пф}$

схемы 3-х кратного совпадения. Сигнал совпадения запускает водородный тиратрон ТГИ1 — 325/16 и к пластинам конденсатора прикладывается высоковольтный импульс длительностью $\sim 10^{-7}$ сек.

Одной из основных характеристик искровой камеры является эффективность одного искрового промежутка, которая определяется по формуле $R = \frac{n}{N}$, где N — число проходов частицы через промежуток, а n — число его зажигания.

Эффективность искрового промежутка, зависит от: а) рода и давления рабочего газа; б) давления остаточного газа; в) величины искрового промежутка — d ; г) параметров высоковольтного импульса: амплитуды — u , длительности — $T_{и}$; д) времени задержки — T_3 между прохождением частицы через искровую камеру и прикладыванием к нему высокого напряжения.

Для выяснения роли остаточного газа камеры эвакуировались до различных давлений в интервале 10^{-1} — 10^{-3} мм Рг. При этом не было замечено сколько-нибудь существенного изменения их эффективности.

На рис. 3 приведены кривые зависимости эффективности камеры от времени задержки питающего импульса. Кривая I снималась без очищающего поля, а кривая II — при значении постоянного очищающего поля 50 вольт/см. Как видно из рис. 3, очищающее поле резко улучшает временное разрешение детектора. На рис. 4 приведена зависимость эффективности детектора от величины очищающего поля при постоянной задержке питающего импульса 0,7 мсек.

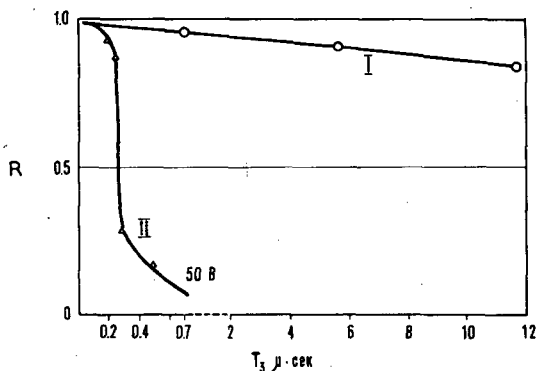


Рис. 3

Кривая I — зависимость эффективности камеры от времени задержки питающего импульса в отсутствие постоянного очищающего поля. Кривая II — зависимость эффективности камеры от времени задержки питающего импульса при значении напряженности постоянного очищающего поля 50 вольт/см

Следует отметить, что при задержках $T_3 \sim 12$ мс стримера расщепляются (рис. 1г), что можно объяснить отходом электронов от траектории частицы, вызванным диффузией.

С увеличением искрового промежутка (при давлении рабочего газа $\sim 1,1$ атм) эффективность возрастает почти до полной. Надо отметить, что при зазоре между

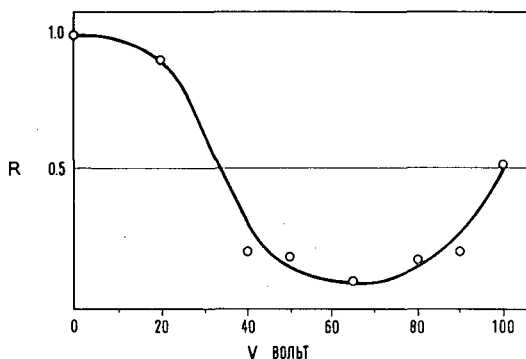


Рис. 4

Зависимость эффективности камеры от величины очищающего поля при постоянном значении времени задержки $T_3 = 0,7 \mu\text{сек}$

пластинами равно 6 мм, стримерные разряды, коррелированные с прохождением частицы через камеру, не наблюдались вплоть до больших напряжённостей поля $E = 11 \text{ кВ/см}$, когда начинаются случайные разряды. Видимо, значение $Pd \sim 450 \text{ мм Нг/см}$ критично для искровой камеры с неоновым наполнением.

Зависимость эффективности от величины высоковольтного импульса показана на рис. 5. Как видно из рис. 5, в интервале напряжённости поля 6—11 кВ/см у камеры имеется плато.

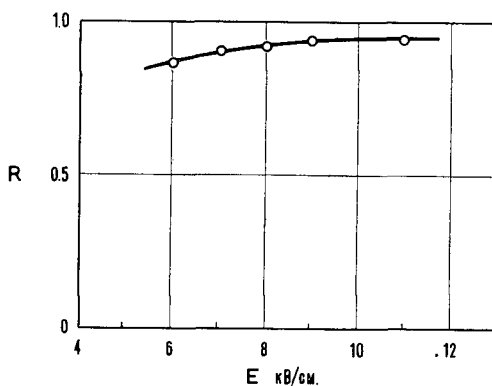


Рис. 5

Зависимость эффективности камеры от амплитуды прикладываемого импульса

3. Точность определения координат и углов

Вследствие того, что стример развивается в промежутке конденсатора примерно вдоль направления электрического поля (рис. 1), следует ожидать, что ошибка

в определении координат траектории частицы тем больше, чем больше угол между направлением движения частицы и направлением электрического поля.

Измерения проводились при двух положениях искровой камеры относительно выделяющей системы. В первом случае пластины камеры были перпендикулярны к оси системы выделения (при этом направление движения частицы составляло малый угол с направлением электрического поля), а во втором случае угол между пластинами и осью системы выделения был $\sim 45^\circ$.

В первом случае методом наименьших квадратов проводилась прямая через центр стримеров (измерения координат производились на плёнке с помощью микроскопа УИМ-21), и находились отклонения этих центров от аппроксимирующей их прямой.

На рис. 6 приведено распределение наблюждённых отклонений. Полученное распределение уже нормального распределения. Среднеквадратичное отклонение центра стримера (для частицы, движущейся примерно перпендикулярно к пластинам камеры) от аппроксимирующей прямой составляет $b = 0,22$ мм. Для наклонных следов отклонения центров стримеров от прямой, проведенной вышеуказанным способом, гораздо больше и составляют величину $b = 1,6$ мм. Анализ экспериментальных данных показывает, что в этом случае наиболее близко к истинной траектории расположены точки стримера, находящиеся на расстоянии $\ell = 0,16 d$ (d -длина стримера) от отрицательного электрода (при этом $b = 0,44$ мм). Этот факт, а также расщепление стримеров при больших временах задержки, вероятно, подтверждают электронный механизм „памяти“ камеры.

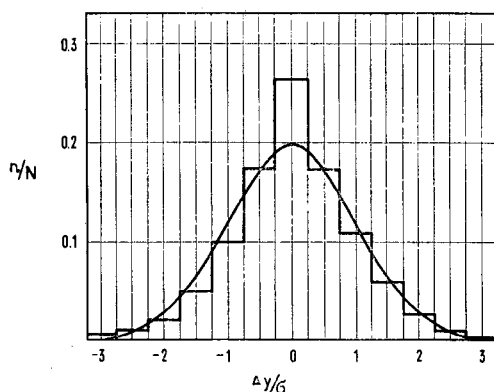


Рис. 6

Нормированное дифференциальное распределение отклонений центров стримеров от траектории движения частицы. Гистограмма — наблюдаемое распределение (среднеквадратичное отклонение $\sigma = 0,22$ мм). Сплошная кривая — нормальное распределение

Ошибка в определении направления движения частицы, когда оно определялось с помощью двух камер, разнесённых на расстояние 50 см, составляла $5 \cdot 10^{-4}$ радиан.

Благодаря высокому временному и пространственному разрешению и относительной простоте конструкции, описанный прибор может быть использован для решения круга задач как в исследованиях космических лучей, так и на ускорителях.

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IV.

SEMICONDUCTOR DETECTORS AND THEIR APPLICATION IN DETECTION

(SESSION 4)

КРИСТАЛЛИЧЕСКИЕ СЧЕТЧИКИ ИЗ СУЛЬФИДА КАДМИЯ

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БОЛГАРИЯ

Abstract — Résumé — Аннотация — Resumen

A study of the possibilities of using cadmium-sulphide crystal counters. The paper gives the results of research on polarization effects in cadmium-sulphide crystal counters.

The kinematics of polarization effects and the dependence of the maximum value of the polarization potential on the working potential were studied. It was shown that in some scintillators the maximum polarization potential is below that of the working potential. The influence of infra-red light on the polarization effect was also ascertained and investigated.

To eliminate the influence of polarization effects, it is proposed to use a high-frequency potential instead of a constant one. The counting efficiency was compared for different crystals using constant and high-frequency potentials. Even crystals which apparently do not polarize for a constant potential were shown to have a higher counting efficiency when they are used with a high-frequency potential.

Some work was done on the relation between pulse amplitude, α -particle energy and working potential.

The mechanism of pulse formation in cadmium-sulphide crystal counters was also studied.

With a view to the practical applications of cadmium-sulphide crystal counters, measurements were made to determine their useful life and their counting efficiency for different parts of a given crystal. Practical methods were worked out for using them as α -particle counters and in certain other types of apparatus.

Etude sur les possibilités d'emploi de détecteurs cristallins en sulfure de cadmium. Le mémoire expose les résultats de recherches effectuées sur les phénomènes de polarisation dans les détecteurs cristallins en sulfure de cadmium.

Les auteurs ont étudié la cinématique des phénomènes de polarisation et cherché à établir dans quelle mesure la valeur maximum de la tension de polarisation dépend de la tension de régime. Ils montrent que pour certains détecteurs cristallins, la tension de polarisation maximum est inférieure à la tension de régime. En outre, ils ont déterminé et étudié l'effet de la lumière infrarouge sur les phénomènes de polarisation.

Pour neutraliser l'effet des phénomènes de polarisation, il est proposé d'utiliser une tension haute fréquence au lieu d'une tension continue. Les auteurs comparent le rendement de comptage effectué au moyen de divers cristaux en employant une tension continue et une tension haute fréquence. Ils montrent que même au moyen de cristaux dans lesquels il ne semble se produire aucun phénomène de polarisation, lorsque la tension est continue, on obtient un comptage plus efficace en utilisant une tension haute fréquence.

Les auteurs ont exécuté plusieurs travaux sur l'interdépendance de l'amplitude des impulsions, de l'énergie des particules alpha et de la tension de régime.

Ils ont procédé à certaines recherches sur le mécanisme de formation des impulsions dans les compteurs cristallins en sulfure de cadmium.

Pour permettre une application pratique des compteurs cristallins en sulfure de cadmium, ils ont effectué des mesures en vue de déterminer leur durée d'utilisation et le rendement de comptage dans diverses parties du cristal considéré. En outre, ils ont mis au point plusieurs schémas pratiques permettant de les utiliser pour le comptage des particules alpha et d'en équiper certains instruments.

Исследования возможности применения кристаллических счетчиков из сернистого кадмия. В докладе приводятся результаты исследований поляризационных явлений у кристаллических счетчиков из сульфида кадмия.

Исследованы кинематика поляризационных явлений и зависимость максимальной стоимости поляризационного напряжения в отношении рабочего напряжения. Показано, что у некоторых кристаллических счетчиков максимальное поляризационное напряжение ниже рабочего. Установлено также и исследовано влияние инфракрасной подсветки на поляризационные явления.

Для устранения влияния поляризационных явлений предлагается использовать высокочастотное напряжение вместо постоянного такого. Проведено сравнение эффективности счета для различных кристаллов при использовании постоянного и высокочастотного напряжений. Показано, что даже у кристаллов, которые видимо не поляризуют при постоянном напряжении, эффективность счета выше, когда они используются с высокочастотным напряжением.

Проведены некоторые исследования существующей зависимости между амплитудой импульсов и энергией альфа-частиц и рабочего напряжения.

Сделаны некоторые исследования механизма образования импульсов у кристаллических счетчиков из сульфида кадмия.

В целях практического применения кристаллических счетчиков из сульфида кадмия проведены измерения в отношении их срока службы и их эффективности счета на различных участках данного кристалла. Разработаны также некоторые практические схемы их использования в качестве счетчиков альфа-частиц, а также их применения в некоторых устройствах.

Estudio de las posibilidades que ofrecen los contadores de cristal de sulfuro de cadmio. En este informe se exponen los resultados de la investigación de los efectos de la polarización en los contadores de cristal de sulfuro de cadmio.

Se estudia la cinemática de los efectos de polarización y la relación entre la tensión de trabajo y el valor máximo de la tensión de polarización. Se demuestra que, en algunos contadores de cristal, la máxima tensión de polarización es inferior a la de trabajo. También se determina e investiga la influencia de iluminación infrarroja sobre los fenómenos de polarización.

Para eliminar la influencia de los fenómenos de polarización, se propone aplicar una tensión de alta frecuencia en lugar de la tensión continua. Se efectúa una comparación de los rendimientos del recuento obtenido con diversos cristales utilizando, respectivamente, la tensión continua y la de alta frecuencia. Se demuestra que, aun en los cristales que no producen una clara polarización bajo tensión continua, la eficacia del recuento es mayor cuando se les aplica una tensión de alta frecuencia.

Se investigan las relaciones existentes entre la amplitud de los impulsos y la energía de las partículas alfa y la tensión de trabajo.

Se ha investigado el mecanismo de generación de los impulsos en los contadores de cristal de sulfuro de cadmio.

Con miras a la aplicación práctica de los contadores de cristal de sulfuro de cadmio, se hicieron mediciones relativas a su duración en servicio y al rendimiento del recuento, con diferentes secciones del cristal. Se proyectaron también algunos circuitos prácticos para utilizarlos como contadores de partículas alfa, así como para aplicarlos en algunas instalaciones.

Возможность использования кристаллов сернистого кадмия для счета альфа- и бета-частиц была установлена впервые Кальманном и Верминским [1]. Впоследствии свойства кристаллических счетчиков из сернистого кадмия были исследованы в нескольких работах Гольдшмидта и Ларк-Хоровитца [2], Гертсена и Кольба [3], Рывкина с сотрудниками [4] и др. Однако, все еще остается ряд невыясненных вопросов в связи со свойствами этого типа кристаллических счетчиков и механизмом формирования импульсов в них. Также не получил еще окончатель-

ного разрешения вопрос о возможностях их практического использования. Кристаллические счетчики и, в частности, счетчики из сернистого кадмия все еще не стали стандартным прибором в руках экспериментатора. Одной из причин этого является отсутствие технологии для получения монокристаллов и изготовления из них кристаллических счетчиков, обладающих стандартными свойствами. Кроме этого, как обычно отмечается в литературе, существенным недостатком кристаллических счетчиков вообще является поляризация, возникающая в кристаллах во время их работы как кристаллические счетчики. Поляризация непрерывно изменяет свойства кристаллического счетчика в процессе его работы, причем у алмазных кристаллических счетчиков, где она сравнительно лучше всего исследована [5], через некоторое время обычно ведет к полному затуханию счета. С целью устранения поляризации предложены были ряд мер, но они вообще не разрешают этот вопрос, т. к. либо являются слишком сложными, либо ведут к значительному понижению эффективности счетчика [6].

Целью нашей работы было исследовать поляризационные явления у кристаллических счетчиков из сернистого кадмия и поискать способы устранения влияния поляризации на работу кристаллического счетчика; исследовать некоторые свойства кристаллических счетчиков из сернистого кадмия и некоторые явления в них, имеющие значение для выяснения механизма формирования импульсов; постараться найти некоторые возможности практического использования кристаллических счетчиков из сернистого кадмия. Часть экспериментальных результатов, главным образом по первому разделу настоящей работы, опубликованы в некоторых предварительных сообщениях [7]. Большая часть из них, однако, сообщается впервые.

Использованные нами кристаллические счетчики изготовлялись из монокристаллов сернистого кадмия, полученных методом Фрерихса из паров кадмия и сероводорода, с толщиной не более 0,1 мм. На противоположные широкие грани кристалла, площадью около десяти квадратных миллиметров, наносились путем катодного распыления золотые электроды, как это показано на рис. 1.

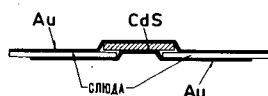


Рис. 1

Схема кристаллического счетчика с золотыми электродами

1. Исследования поляризационных явлений у кристаллических счетчиков из сернистого кадмия

До сих пор в литературе не имеется данных исследования поляризационных процессов в кристаллических счетчиках из сернистого кадмия.

При достаточно тонких кристаллах, используемых как альфа-счетчики, которые работают при так называемом режиме проводящего канала, т. е. у которых альфа-частица пронизывает весь кристалл, поляризации не наблюдается. Однако, у кристаллов, толщина которых больше пробега альфа-частиц в них, после приложения рабочего напряжения к счетчику и начала его бомбардировки альфа-частицами амплитуда импульсов обычно постепенно убывает. Это можно объяснить возникновением в кристалле некоторого поляризационного напряжения, которое

противоположно направлено приложенному к кристаллу рабочему напряжению. Измерение поляризационного напряжения производилось следующим образом (рис. 2). В данный момент к кристаллу прилагалось известное рабочее напряжение и начиналась его бомбардировка альфа-частицами из данного источника с постоянной интенсивностью. Импульсы от этих альфа-частиц наблюдались на экране осциллографа при максимальном усилении его усилителя. У использованных нами кристаллических счетчиков с рабочим сопротивлением в 1 мегаом, импульсы, до возникновения поляризации в кристаллах, начинали замечаться на осциллографе при напряжении от 0,2 до 0,3 вольт. Для измерения поляризационного напряжения кристалла, после того, как он работал в течение промежутка времени t как альфа-счетчик, мы понижали приложенное напряжение к счетчику до исчезновения импульсов на экране осциллографа. Последнее напряжение с точностью до 0,2—0,3 вольт представляет поляризационное напряжение, возникнувшее в кристалле в данный момент.

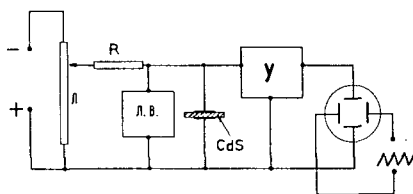


Рис. 2

Схема измерения поляризационного напряжения

Таким образом были произведены исследования зависимости поляризационного напряжения при различных рабочих напряжениях от времени. На рис. 3 приведены кривые зависимости поляризационного напряжения от времени для кристалла при шести рабочих напряжениях. В начале работы счетчика число импульсов было около 30 шт./сек. Видно, что при данном рабочем напряжении поляризационное напряжение клонит к насыщению. Промежуток времени, в течение которого достигается это насыщение, зависит от напряжения и от интенсивности источника (числа альфа-частиц, попадающих за единицу времени на кристалл), а также еще от тока кристалла в темноте. Насыщенное значение поляризационного напряжения, со своей стороны, возрастает с увеличением рабочего напряжения, клоня к одному максимальному значению — максимальному поляризационному напряжению. Это видно из рис. 4, где представлена зависимость насыщенного значения поляризационного напряжения от рабочего напряжения. Выше определенного значения рабочего напряжения насыщенное значение поляризационного напряжения снова начинает убывать, и дальнейшее увеличение напряжения ведет к электрическому пробое и разрушению счетчика. Многие кристаллы сернистого кадмия со слабым током в темноте (подобно использованному нами при измерениях, результаты которых показаны на рис. 3 и рис. 4) могут работать как счетчики при значительно более высоких напряжениях, чем максимальное поляризационное напряжение. Таким образом у них, после наступления максимальной поляризации, число импульсов перестает изменяться, при чем эффективность понижается в несколько раз.

Существование максимального значения поляризационного напряжения в кривой, изображающей зависимость насыщенного значения поляризационного

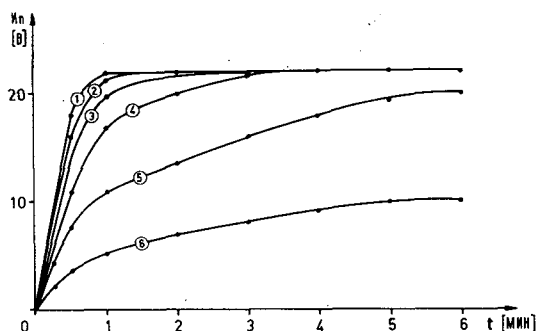


Рис. 3

Кривые снимались при рабочем напряжении, как следует:

- 1 — 60 вольт
- 2 — 50 вольт
- 3 — 40 вольт
- 4 — 30 вольт
- 5 — 20 вольт
- 6 — 10 вольт

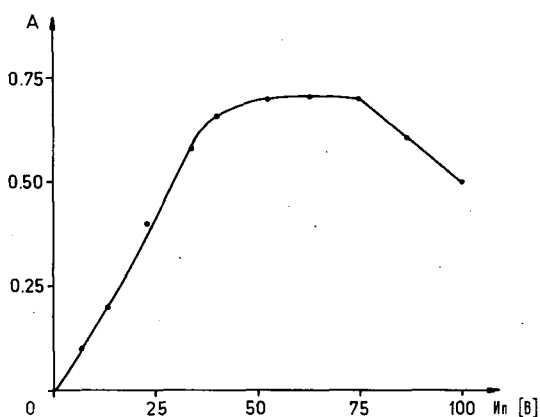


Рис. 4

Зависимость насыщенного значения поляризационного напряжения от рабочего напряжения

напряжения от рабочего напряжения, может объясняться наличием двух конкурирующих процессов в формировании поляризационного напряжения в кристалле. С одной стороны, в кристалле под действием приложенного рабочего поля освобожденные альфа-частицами противоположные заряды разделяются и захватываются ловушками; с другой стороны, самое электрическое поле может освобождать часть захваченных зарядов. Кроме от рабочего напряжения эти два процесса и их равновесие, соответственно насыщенное значение поляризационного напряжения, будут зависеть еще от температуры, как и от дополнительной подсветки кристалла видимым или инфракрасным светом. Две типичные кривые хода насыщенного значения поляризационного напряжения в зависимости от

температуры показаны на рис. 5. Как это видно, для некоторых кристаллов поляризационное напряжение в температурном интервале от 0 до 100° С непрерывно понижается с ростом температуры; для других кристаллов оно сначала, в температурном интервале от 0 до около 40° С, слабо повышается, после чего снова убывает.

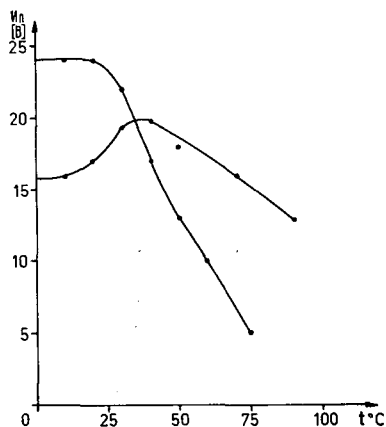


Рис. 5

Кривые хода насыщенного значения поляризационного напряжения в зависимости от температуры

При освещении счетчика во время его работы инфракрасным светом (полученным через эбонитовый фильтр толщиной 0,3 мм, пропускающий лучи с длиной волны больше 7500 Å, не причиняющие использованным кристаллам заметного фотоэффекта) поляризационные явления в нем изменяются. При освещении счетчика инфракрасным светом наблюдается сокращение времени, в течение которого достигается насыщенное значение поляризационного напряжения при данном рабочем напряжении (рис. 6). Зависимость этого времени от интенсив-

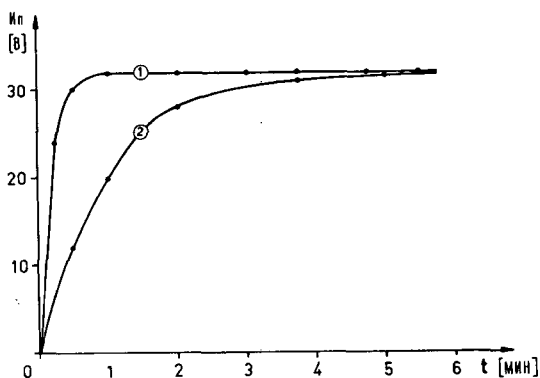


Рис. 6

1 — при освещении образца инфракрасным светом
2 — при отсутствии инфракрасного освещения

ности инфракрасного света представлена на рис. 7. На рис. 8 показано, как у одного сравнительно более толстого кристалла максимальное поляризационное напряжение падает при облучении инфракрасным светом.

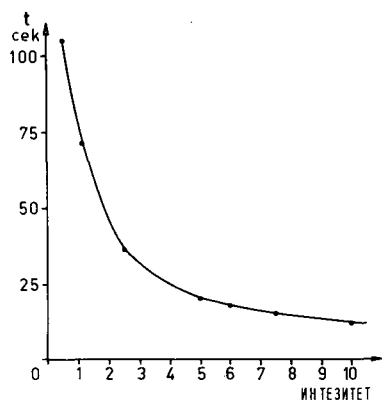


Рис. 7

Влияние инфракрасного света на время достижения насыщенного значения поляризационного напряжения

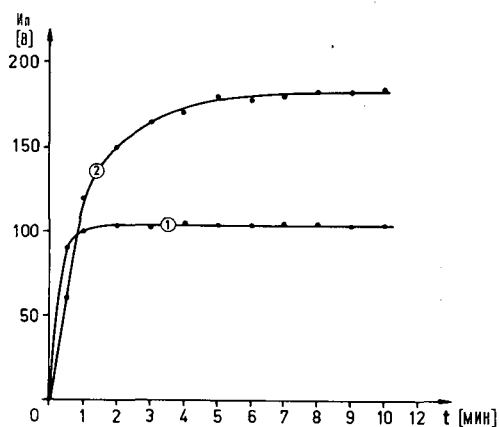


Рис. 8

- 1 — при освещении образца инфракрасным светом
2 — при отсутствии инфракрасного освещения

В случае, если кристаллический счетчик будет поляризован до насыщения при данном рабочем напряжении, а после этого выключится напряжение и прекратится бомбардировка альфа-частицами, то поляризационное напряжение убывает в течение минут, как это показано для двух кристаллов на рис. 9. Этот процесс деполяризации при подсветке альфа-частицами, инфракрасным или видимым светом происходит гораздо быстрее.

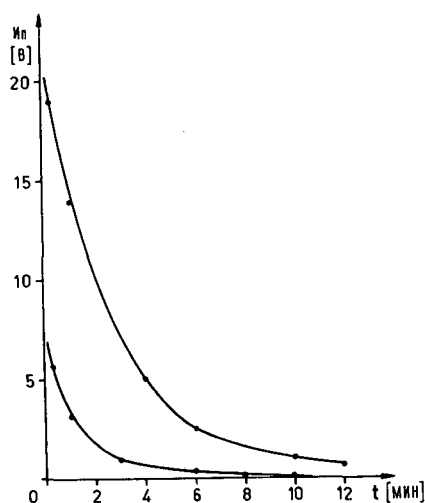


Рис. 9

Процесс деполяризации в двух кристаллах

С целью устранения поляризационных явлений были произведены некоторые исследования работы кристаллических счетчиков из сернистого кадмия при высокой частоте. Для регистрации импульсов в этом случае был применен метод реакции лампового осциллятора при изменении потерь в его колебательном контуре. Рабочая схема приведена на рис. 10.

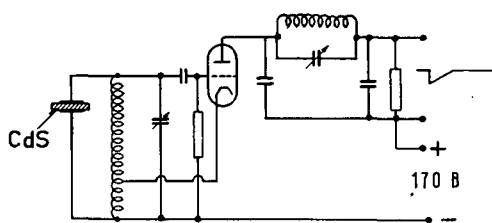


Рис. 10

Рабочая схема лампового осциллятора

При высокой частоте не наблюдаются никакие поляризационные явления. Более того, даже у кристаллов, у которых при работе с постоянным напряжением не наблюдается с течением времени уменьшения амплитуды импульсов вследствие поляризации, при высокой частоте эффективность счета значительно выше, чем при постоянном напряжении. Это видно на рис. 11. При измерении, результат которого приведен на рис. 11, как постоянное напряжение, так и высокочастотное имели достаточно высокие значения, при которых число импульсов при постоянной интенсивности альфа-источника не зависит от напряжения.

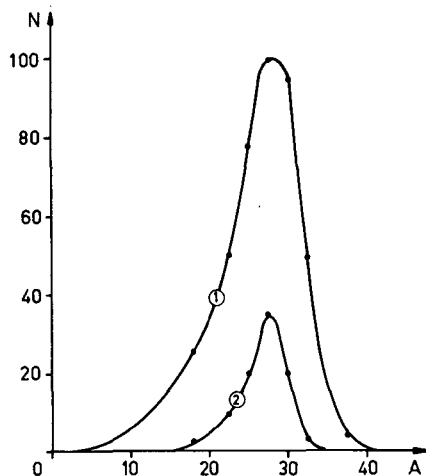


Рис. 11

1 — при высокой частоте
2 — при постоянном напряжении

2. Исследования некоторых других свойств кристаллических счетчиков из сернистого кадмия и явлений, связанных с механизмом формирования импульсов.

У использованных в настоящей работе кристаллических счетчиков были произведены некоторые измерения зависимости амплитуды импульсов от рабочего напряжения. На рис. 12 приведена одна типичная кривая этой зависимости. Как это наблюдали также некоторые другие авторы [8], величина амплитуды импульсов выше определенного напряжения остается постоянной. У некоторых кристаллов при еще более высоких напряжениях наблюдается дальнейший спад амплитуды, что, повидимому, связано с уменьшением сопротивления кристаллов при высоких напряжениях.

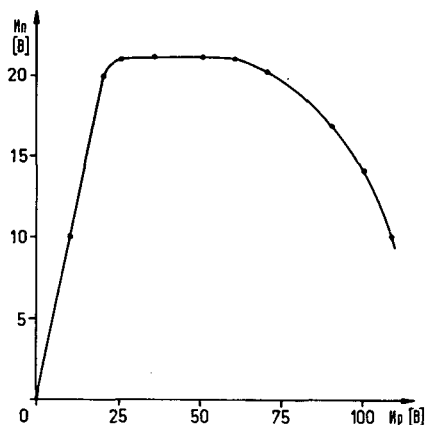


Рис. 12

Зависимость амплитуды импульсов от рабочего напряжения

Параллельно с этим были произведены также некоторые измерения зависимости амплитуды импульсов от энергии попадающих в кристалл альфа-частиц при постоянном рабочем напряжении, большим максимального поляризационного напряжения. Для этой цели альфа-источник отдалялся от кристалла, вследствие чего изменялся остаточный пробег альфа-частиц в нем. У использованных кристаллических счетчиков измерения показали, что в весьма широком интервале энергий альфа-частиц (соответственно остаточного пробега этих частиц в кристалле) амплитуда импульсов остается постоянной. На рис. 13 приведены три кривые распределения импульсов по амплитуде для одного и того же кристалла при трех различных значениях остаточного пробега альфа-частиц в нем.

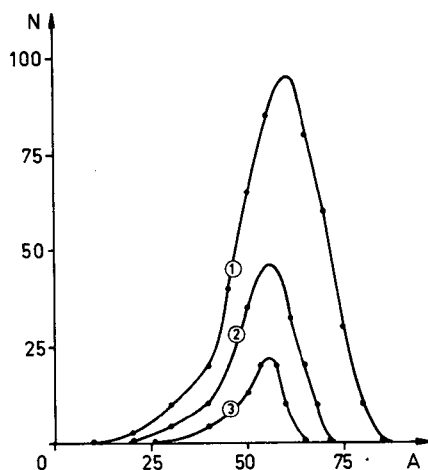


Рис. 13

- 1 — полный пробег альфа-частиц
- 2 — 2/3 полного пробега
- 3 — 1/3 полного пробега

Аналогичные измерения предстоит сделать также с кристаллическими счетчиками из сернистого кадмия с различными электродами, как при работе с высокой частотой, так и с постоянным напряжением.

Использованные нами кристаллические счетчики обычно хорошо считали при низком напряжении, только когда альфа-частицы проникали в кристалл через катод. Форма импульсов в этом случае не отличалась существенно от формы импульсов, когда кристаллический счетчик работал при режиме проводящего канала (4). Как видно из осциллограммы на рис. 14, в этом случае импульсы имеют сравнительно крутой фронт и пологий спад в течение обычно около 1 миллисекунды (расстояние между отметками на рис. 14 составляет 20 микро-секунд).

У многих кристаллов наблюдались, однако, импульсы и тогда, когда альфа-частицы проникали в кристалл через анод. В этом случае кристаллы вообще начинали считать при более высоком напряжении. Импульсы были вообще меньшими и приблизительно одним порядком более длинными. Это видно на рис. 15, где продолжительность развертки составляет 20 миллисекунд. Фронт импульсов

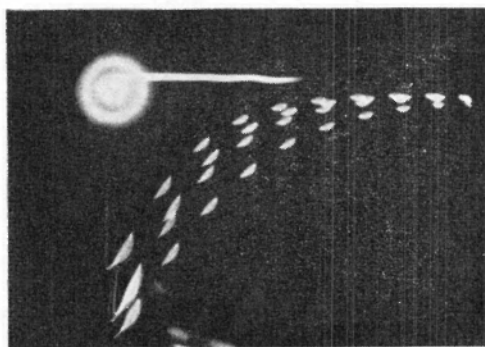


Рис. 14

Форма импульсов при проникновении альфа-частиц через катод

в этом случае становится также значительно более пологим. Вообще в нем можно наблюдать одну более крутую и одну более пологую части, соотношение между которыми зависит от глубины, до которой альфа-частица проникает в кристалл.

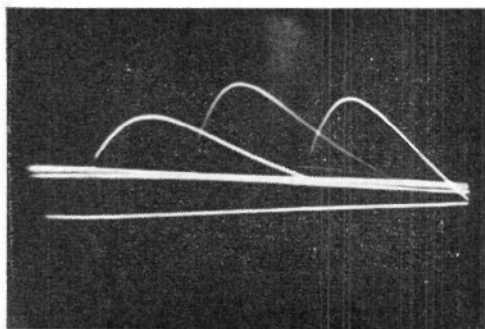


Рис. 15

Форма импульсов при проникновении альфа-частиц через анод

Эти результаты показывают, что при формировании импульсов, как и при протекании фототока через кристаллы из сернистого кадмия, важную роль играют вторичные процессы инжекции электронов катодом. Последние процессы, со своей стороны, зависят от движения и распределения дырок в кристалле.

Важным вопросом при формировании импульсов в кристаллических счетчиках из сернистого кадмия является роль диффузии токовых носителей, полученных от альфа-частицы на больших расстояниях. Для экспериментального изучения этого вопроса были изготовлены кристаллические счетчики (рис. 16а), у которых электроды были нанесены один против другого только до половины широких сторон кристалла. Облучение альфа- частицами производилось на некотором расстоянии от электродов-х с помощью одного сильно коллимированного альфа-источника. Результат одного такого измерения показан на рис. 17. Аналогичные

результаты некоторые авторы получают также при освещении кристалла на некотором расстоянии от электродов посредством светового зонда [9]. В дальнейшем было установлено, однако, что получение импульсов при бомбардировке кристалла альфа-частицами на некотором расстоянии от электродов обязано поверхностной проводимости кристалла. Для этой цели на верхнюю поверхность того же кристалла, которым было произведено измерение (результат которого показан на рис. 17), был нанесен еще один электрод *a* на расстоянии около 0,1 мм от катода счетчика (рис. 16 б). Когда электрод *a* соединен с *b* или свободен, характер кривой на рис. 17 не изменяется. Однако, если соединить электрод *a* с *c*, т.е. заземлить его, то кристаллический счетчик перестает считать в случае, когда кристалл бомбардируется на некотором расстоянии от электродов счетчика. На основании этого можно считать доказанным, что в процессе формирования импульса диффузия носителей тока, созданных альфа-частицей, не играет роли на расстояниях, больших по крайней мере 0,1 мм.

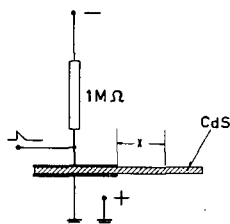


Рис 16 а

Схема кристаллического счетчика с нанесением электродов до половины кристалла

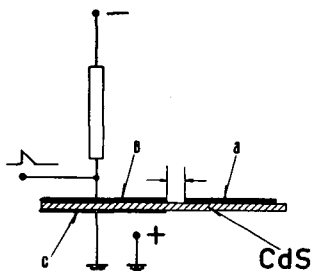


Рис. 16 б

Схема счетчика с добавлением электрода *a*

3. Некоторые исследования возможностей практического использования кристаллических счетчиков из сернистого кадмия

С целью практического использования кристаллических счетчиков из сернистого кадмия были произведены измерения зависимости эффективности счета от места попадания альфа-частиц на кристалл. Было установлено, что у тонких кристаллов, работающих в условиях проводящего канала, эффективность по всем местам рабочей площади кристалла одинакова.

Важной характеристикой при практическом использовании счетчиков является срок их службы. Для кристаллических счетчиков из сернистого кадмия было

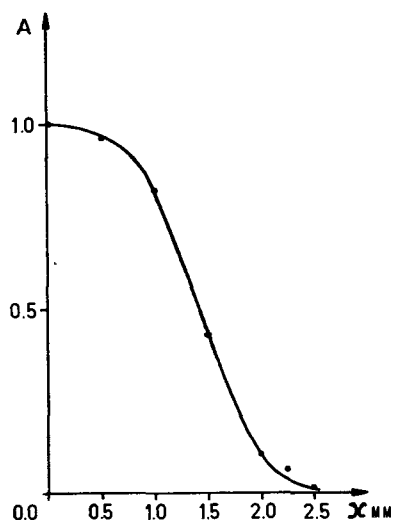


Рис. 17

Кривая распределения импульсов при удалении альфа-источника от электродов

установлено, что после регистрации импульсов порядка $5 \cdot 10^9$, полученных от альфа-частиц или электронов, никаких изменений в свойствах и параметрах счетчика не замечается. Таким же образом длительное облучение кристаллических счетчиков гамма-лучами не ведет к заметным изменениям их свойств.

Были осуществлены несколько схем для практического использования кристаллических счетчиков из сернистого кадмия. На рис. 18 показана одна простая схема сконструированного нами детектора альфа-частиц с кристаллическим счетчиком из сернистого кадмия с телефонными трубками. Примененный в нем кристалл (или мозаика из кристаллов) работал или при режиме проводящего канала или при рабочем напряжении, более высокого максимального поляризационного напряжения. Из-за простоты своей конструкции и своих малых размеров этот детектор очень удобен для поиска альфа-активных крупинок в скальных породах.

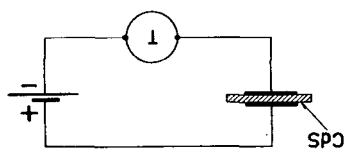


Рис. 18

Схема детектора альфа-частиц с кристаллическим счетчиком

На рис. 19 дана схема изготовленного и испытанного нами альфа-реле с кристаллическим счетчиком из сернистого кадмия, которое с успехом может использоваться в многих случаях для регулировки и контроля различных процессов, например в терморегуляторе. Из-за миниатюрности детектора, низкого рабочего напряжения, малого потребления энергии и вследствие того, что здесь требуется

альфа-источник со слабой активностью (достаточно попадания на кристалл 2—3 импульсов в секунду), такое реле имеет большие преимущества перед известными до сих пор радиоактивными реле, использующими бета- или гамма-источники, а также перед существующими реле, которые используют альфа-источники, работающие с ионизационными камерами. На рис. 20 дан снимок разработанного таким образом реле, по сравнению со спичечной коробкой.

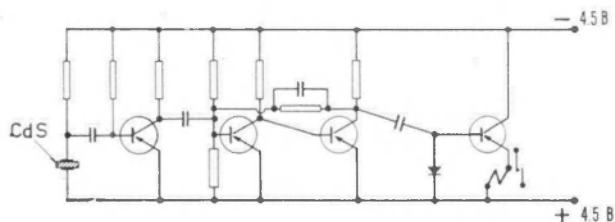


Рис. 19

Схема альфа-реле с кристаллическим счетчиком из сернистого кадмия

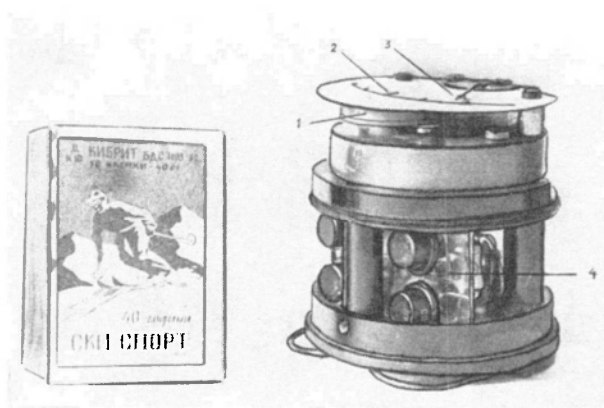


Рис. 20

- 1 — кристаллический счетчик
- 2 — отверстие, через которое на счетчик попадают альфа-частицы
- 3 — стрелка измерительного амперметра, которая на своем конце носит радиоактивный альфа-источник
- 4 — электронная схема

В заключение позволим себе выразить надежду, что дальнейшее изучение свойств кристаллических счетчиков из сернистого кадмия и выяснение механизма формирования импульсов в них позволят в будущем этим счетчикам, наравне с другими полупроводниковыми счетчиками, занять полагающееся им место среди других типов детекторов ядерных излучений.

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DISCUSSION

L. Costrell (United States of America): What percentage of the crystals that you try do you find you are able to use without appreciable alteration of your circuit?

M. Borisov (Bulgaria): Several dozen crystals could be used per hundred without a great change in the circuit.

C. G. Clayton (United Kingdom): I would very much like to know what effect the impurity concentration has on the performance of the crystal and whether or not any specific doping of the crystal is undertaken and I should also be interested to know why the author chose gold electrodes.

M. Borisov: The crystals that we used were not specially processed, and were not activated. They were just as originally obtained by the Frerichs method. Of course we did not use all the crystals we obtained by this method: we graded them according to their photoelectric sensitivity and selected those that were best, for counting.

H. E. Wegner (United States of America): Could you characterize your crystals according to an ohm-centimeter rating? Also, do you have any information about carrier lifetime in these crystals?

M. Borisov: The lifetime of the carrier in these cadmium-sulphide crystals is about 1 ms. We have not measured the relation between the counting characteristics of these crystals and the electron lifetime.

G. L. Miller (United States of America): It seems, since you get pulses by injecting alpha particles both through the cathode and through the anode, that you should be able to determine the hole lifetime as well. Can you express this in quantitative terms?

M. Borisov: We have made measurements when the alpha particles entered through the anode, and the pulses are then obtained at a higher voltage as described in the paper; they also have a different shape, and their width is larger by an order of magnitude. This is described in the document, and an oscillogram is also given. Conduction in the CdS crystals used was electronic. Secondary processes associated with the injection of electrons at the cathode, however, have a considerable effect on the pulse shape, and these processes depend on the movement and distribution of holes in the crystal.

SILICON SURFACE-BARRIER NUCLEAR-PARTICLE DETECTORS

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UNITED STATES OF AMERICA

Abstract — Résumé — Аннотация — Resumen

Silicon surface-barrier nuclear-particle detectors. Silicon surface-barrier detectors with sensitive areas of 25 mm² and 1 cm² have given a resolution of 13.5 keV (FWHM) and 17 keV, respectively, for alpha particles of 5.5 MeV. Detectors made from an entire ingot section and having a sensitive area of 2.6 cm² have given a resolution of $\sim 1\%$ which was limited by noise due to diode current.

Barrier depths approaching 1 mm have been achieved using diodes made from 3500 Ω -cm n-type silicon with 1000-V bias. At 500 V the reverse current was $< 10^{-6}$ A/cm². These barrier depths permit the detection of 10-MeV protons with good energy linearity. Silicon surface-barrier detectors have been used to measure electron, β , p, d, t, α , heavy-ion and fission-fragment energies. Fast-neutron spectrometry has been performed by using a Li⁶ radiator and a 4π detector geometry.

Thin silicon surface-barrier detectors suitable for dE/dX applications have been made with areas ranging from 1/10 to 2 cm² and thicknesses down to 75 μ . Alpha-particle resolution of 22 keV is typical of $\frac{1}{2}$ -cm² units, and the sensitive region can be extended to within approximately 10 μ of the rear surface.

An amplifier system has been designed specifically for use with silicon diode detectors to achieve the optimum pulse-height resolution. The noise with a capacitive load of 20 pF and 180 pF on the amplifier input is ~ 3.5 and 10 keV, respectively. A built-in window amplifier allows a small portion of the pulse-height spectrum to be spread out over the entire capacity of multichannel pulse-height analyser. The system, including window amplifier, has a drift of < 300 eV/h and a line-voltage sensitivity of < 250 eV/line volt, when analysing a charge pulse on the input equivalent to 5.5 MeV.

Détecteurs à barrière de surface au silicium pour particules nucléaires. Des détecteurs à barrière de surface au silicium possédant des surfaces sensibles de 25 mm² et de 1 cm² ont des pouvoirs de résolution de 13,5 keV (largeur totale à mi-hauteur du maximum) et de 17 keV respectivement pour des particules alpha de 5,5 MeV. Des détecteurs ayant une surface sensible de 2,6 cm² et réalisés à partir d'une section de lingot entier ont un pouvoir de résolution d'environ 1%, limité par le bruit de fond du courant de diode.

En utilisant des diodes constituées par du silicium de type n de 3500 Ω -cm avec une tension de polarisation de 1000 volts, on a pu atteindre des profondeurs de barrière approchant 1 mm. A 500 volts, le courant inverse était inférieur à 10^{-6} A/cm². On a pu grâce à ces profondeurs de barrière détecter des protons de 10 MeV avec une bonne linéarité en énergie. On a utilisé des détecteurs à barrière de surface au silicium pour mesurer l'énergie d'électrons de particules bêta, de protons, de deutérons, de tritons, de particules alpha, d'ions lourds et de fragments de fission. On a réalisé la spectrométrie des neutrons rapides en utilisant une couche de ⁶Li comme milieu radiatif et une géométrie du détecteur en 4π .

On a construit des détecteurs à barrière de surface au silicium pouvant être appliqués aux mesures de dE/dX , avec des surfaces allant de 0,1 cm² à 2 cm² et des épaisseurs dont certaines ne dépassaient pas 75 microns. La résolution des particules alpha de 22 keV est caractéristique

des appareils de $0,5 \text{ cm}^2$ et la région sensible peut être étendue jusqu'à à peu près 10 microns de la surface postérieure de la barrière.

Les auteurs ont conçu un système d'amplification spécial pour les détecteurs à diode au silicium en vue de permettre une résolution optimum des amplitudes d'impulsion. L'amplitude du bruit de fond d'une charge capacitive de 20 pF et de 180 pF placée à l'entrée de l'amplificateur est d'environ 3,5 keV et de 10 keV respectivement. Un amplificateur fenêtre permet d'étaler une faible partie du spectre des amplitudes d'impulsion sur la capacité totale de l'analyseur d'amplitude multicanaux. Le système, y compris l'amplificateur fenêtre, a un glissement inférieur à 300 eV/h et est sensible à des tensions de secteur inférieures à 250 eV/volt de ligne, lorsqu'il analyse une impulsion de charge à l'entrée équivalente à 5,5 MeV.

Барьерные детекторы ядерных частиц с кремниевой поверхностью. Барьерные детекторы с кремниевой поверхностью, обладающие зонами чувствительности в 25 мм^2 и 1 см^2 , показали разрешающую способность соответственно 13,5 кэВ (fwhm) и 17 кэВ для альфа-частиц в 5,5 мэВ. Детекторы, сделанные из цельной секции и обладающие зоной чувствительности в $2,6 \text{ см}^2$, показали разрешающую способность приблизительно в 1%, которая была ограничена шумом, вызываемым током диода.

Толщина барьеров, приближающаяся к 1 мм, была достигнута при использовании диодов, изготовленных из кремния типа n в 3500 ом-см со смещающимся напряжением в 1000 вольт. При 500 вольт обратный ток был менее 10^{-6} ампер/см². Эти толщины барьеров позволяют обнаружить протоны в 100 мэВ с хорошей энергетической линейностью.

Барьерные детекторы с кремниевой поверхностью использовались для измерения энергии электронов, бета- и альфа-частиц, протонов, орбитального момента, тритонов, тяжелых ионов и осколков деления. Была проведена спектрометрия быстрых нейтронов при помощи радиатора лития-6 и детекторной геометрии 4π .

Были созданы барьерные детекторы с тонкими кремниевыми поверхностями, подходящие для определения dE/dX с зонами от $1/10$ до 2 см^2 и толщинами до 75 микрон. Разрешение альфа-частиц в 22 кэВ является типичным для установок в $0,5 \text{ см}^2$, и зона чувствительности может быть расширена приблизительно до 10 микрон задней поверхности.

Была спроектирована специальная система усиления для использования с кремниевыми диодовыми детекторами для получения оптимального разрешения амплитуды импульса. Шум со способностью к загрузке в 20 pF и 180 pF на входе усилителя составляет около 3,5 и 10 кэВ соответственно. Усилитель с вмонтированным каналом позволяет распространить небольшую часть спектра амплитуды импульсов на всю мощность многоканального анализатора амплитуды импульсов. Система, включая каналовый усилитель, обладает дрейфом в менее 300 эВ/час и чувствительностью напряжения сети менее 250 эВ/вольт сети при анализе импульса нагрузки при входном эквиваленте на 5,5 мэВ.

Detectores de barrera superficial de silicio para partículas nucleares. Con detectores de silicio de barrera superficial, de superficies sensibles de 25 mm^2 y 1 cm^2 se han obtenido poderes de resolución de 13,5 keV y 17 keV respectivamente, para partículas alfa de 5,5 MeV. Con detectores hechos de la sección completa de un lingote, de una superficie sensible de $2,6 \text{ cm}^2$, se ha alcanzado un poder de resolución de 1 por ciento, aproximadamente, limitado por el ruido causado por la corriente del diodo.

Utilizando diodos hechos de silicio tipo n, de una resistividad de 3500 Ωcm , con una polarización negativa de 1000 V, se logró establecer espesores de barrera próximos a 1 mm. A 500 V, la corriente inversa fue de menos de 10^{-6} A/cm^2 . Con tales espesores de barrera, es posible detectar protones de 10 MeV con una característica lineal de energía. Se han usado detectores de barrera superficial de silicio para medir la energía de los electrones, partículas β , protones, deuterones, tritones, partículas α , iones pesados y fragmentos de fisión. Se ha conseguido espectrometría de neutrones rápidos usando un radiador de ^6Li , con una geometría del detector de 4π .

Los autores han preparado detectores de barrera superficial delgada de silicio apropiada para determinaciones de dE/dX , con superficies desde $0,1 \text{ cm}^2$ hasta 2 cm^2 y espesores de

75 micrones como mínimo. Para unidades de $0,5 \text{ cm}^2$, es típico un poder de resolución de 22 keV para partículas α , y la región sensible puede extenderse hasta distancias de 10 micrones, aproximadamente, de la superficie posterior.

Los autores han proyectado un sistema amplificador especial para usar con detectores de diodo de silicio a fin de lograr una óptima resolución en amplitud de impulsos. Con una carga capacitiva de 20 pF y 180 pF en la entrada al amplificador, el ruido es de aproximadamente 3,5 y 10 keV, respectivamente. Un amplificador de ventana incorporada permite que una pequeña parte del espectro de amplitud de los impulsos se disperse en todo el margen de entrada del analizador multicanal de amplitud de impulsos. El sistema, incluyendo el amplificador de ventana, tiene una deriva de menos de 300 eV/h y una sensibilidad a la tensión de línea de menos de 250 eV/v de línea, cuando se analiza un impulso de carga a la entrada equivalente a 5,5 MeV.

I. Introduction

The silicon surface-barrier detector is used as a reversed biased diode whose sensitive volume is the charge-depletion region plus a part of one-carrier diffusion length [1] [2]. The operation of silicon surface-barrier detectors is highly analogous to a gas-filled ionization chamber: electron-hole pairs produced by ionizing radiation are swept out by the electric field which is present in the charge-depletion region. The operation of these devices has been described more fully elsewhere [3] [4] [5].

Silicon surface-barrier detectors can be used as spectrometers for determining the energy of α [6], β [7], fission fragments [8], protons [9], and heavy ions [10] [11]. With suitable radiators, fast and slow neutrons may also be measured [12] [13].

II. Performance of surface-barrier diodes

Three parameters which concern the user of these detectors are energy resolution, useful area, and sensitive depth. Noise, and therefore energy resolution spread, is dependent upon the area and sensitive depth. If a diode is made small enough and operated at low bias voltages (thus a shallow sensitive depth), the alpha-particle resolution is not limited by noise due to the diode.

Silicon surface-barrier detectors with a useful area of 25 mm^2 have given a resolution of $13\frac{1}{2}$ keV full-width half maximum (FWHM) for Cm^{244} (5.801 MeV) (Fig. 1), when cooled to 77° K to reduce the noise due to the reverse current and operated at 100 V reverse bias. Under these circumstances, the total electronic noise was ~ 5 keV. At room temperature this detector gives an energy resolution of 15 keV (Fig. 2), when operated over a bias range from 100 to 500 V. The sensitive depth was ~ 0.7 mm at 500 V bias. At 1000 V bias the energy resolution increased to 20 keV due to the increase in diode noise. A detector with 1 cm^2 useful area gave 17-keV resolution for Cm^{244} , as shown in Fig. 3. Detectors made from an entire ingot section and having a useful area of 2.6 cm^2 have given ~ 40 keV resolution.

According to [14], long carrier lifetimes should yield low space-charge generated currents and, since the fabrication process for surface-barrier detectors involves, in principle, no elevated temperature, the space-charge generated current should be lower than that of diffused junction detectors. Heating silicon to high temperatures invariably reduces the charge carrier lifetime. Fig. 4 illustrates voltage-current curves typical of a good surface-barrier diode.

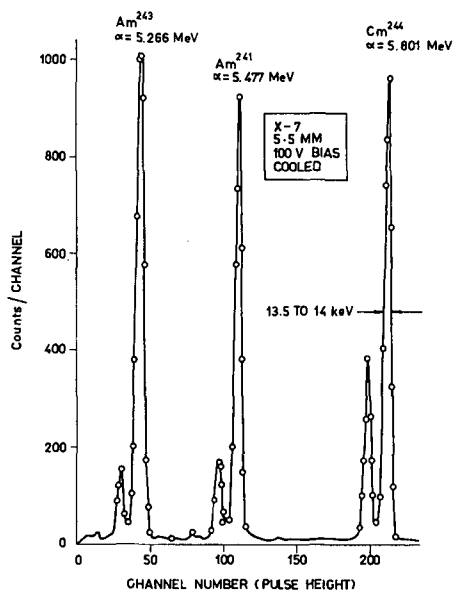


Fig. 1

Pulse-height spectra of Am^{243} , Am^{241} , and Cm^{244} taken with a detector of 25 mm^2 sensitive area. Temperature is 78° K , and bias is 100 V

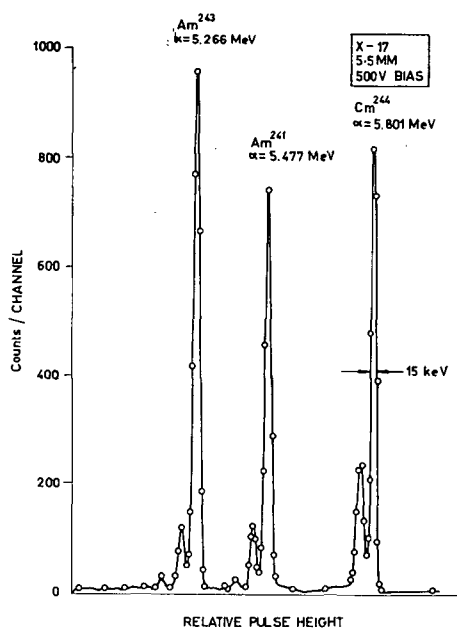


Fig. 2

Pulse-height spectra of Am^{243} , Am^{241} , and Cm^{244} taken with a detector of 25 mm^2 sensitive area. Temperature is 23° C and bias is 500 V

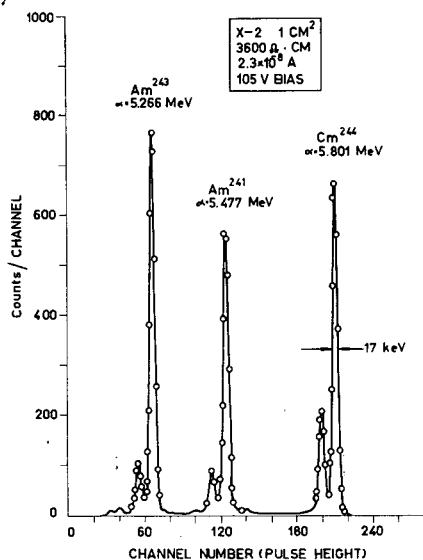


Fig. 3

Pulse-height spectra of Am^{243} , Am^{241} , and Cm^{244} taken with a detector of 1 cm^2 sensitive area. Bias is 105 V

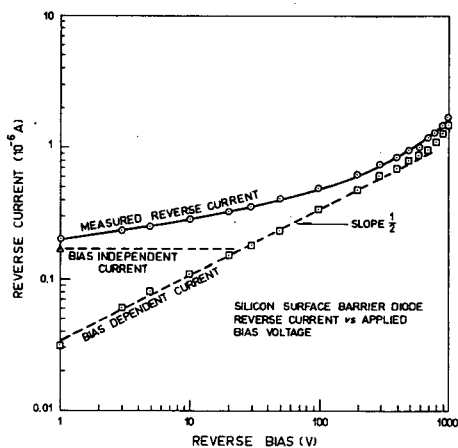


Fig. 4

Reverse current as a function of bias voltage for a detector of 1 cm^2 sensitive area

III. Edge treatment

At ORNL and elsewhere, silicon surface-barrier detectors are often constructed by potting an etched silicon wafer in a room-temperature curing epoxy resin and depositing a continuous film of gold over both the etched silicon and the adjacent epoxy

(Fig. 5). When excessive bias voltage is applied to such a junction (typically several hundred volts) breakdown occurs, and one or more small spots of light can usually be observed at Q, the edge of the epoxy. Severe electrical noise is, of course, associated with these microplasmas.

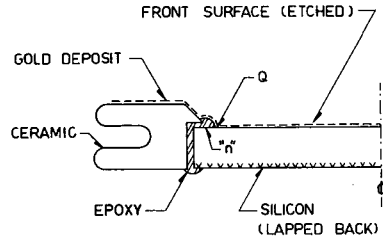


Fig. 5

Conventional front contact for surface-barrier detectors

To better understand this persistent edge breakdown, measurements were made of the surface conductivity σ_s of a silicon surface in contact with epoxy. The surface was found to be strongly "n" type (Table I) evidently as a result of the amine-type epoxy curing agent (Ciba No. 951) used. Consequently, regarding the gold film as the "p" half of a p-n junction, the junction must, in effect, terminate on the surface of the silicon very near Q. The location of the microplasmas further justifies this assumption.

TABLE I
SURFACE CONDUCTIVITY OF SILICON IN CONTACT WITH VARIOUS MATERIALS

Test Ring Number	Bulk Resistivity of Ring (ohm cm)	Material in Contact with Silicon	Surface Conductivity observed σ_s ($10^{-9} \Omega/\text{sq}$)
1	2000 "n" type	Ciba No. CN502 epoxy mixed 10:1 with Ciba No. 951 hardener (amine type)	13 "n" type
2	2000 "n" type	Ciba No. CN502 epoxy mixed 5:1 with Epoxylite No. 204-B hardener* (amine-free)	1.7 "n" type
3	2000 "n" type	Ciba No. CN502 epoxy + 1% iodine mixed 5:1 with Epoxylite No. 204-B hardener	13 "p" type
4	3300 "p" type	Arsenic glass: 24% As; 67% S; 9% I§	3.7 "n" type

* Suggested and supplied by: K. O. Neville, Project Engineer, Epoxylite Corp., El Monte, California.

R. J. Fox at ORNL has been able to reduce the steep potential gradient at the edge by the following procedure: an amine-free epoxy was doped with iodine, and a 1/32-in wide ring of this resin was placed around the edge of a diode (Fig. 6) before the gold

film was deposited. The iodine-doped epoxy produces a "p"-type surface on silicon so that the junction will still be at Q, but the edge of the gold film at R is now removed from the electric field.

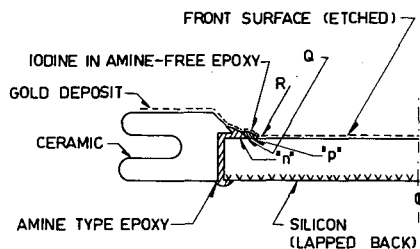


Fig. 6

Modified front contact to surface-barrier detector

Diodes produced in this manner typically withstand greater than 4000 V (using 6000 Ω cm silicon) without breakdown or damage, and reverse currents as low as 1.5 μ A/1.5 cm² have been observed at 1500 V. At 2500 V the reverse current increased to 2.5 μ A and at 3500 V to 5 μ A. The sharp increase in current at 3700 V may have been due to the depletion region extending into the lap damage at the ohmic contact 4 mm from the surface.

The 0.97-MeV conversion electron in Bi²⁰⁷ was resolved as can be seen in Fig. 7. No subtraction of the Compton electrons from the γ -rays was made in this spectrum. The spectrum was taken with a surface-barrier detector having an effective area of

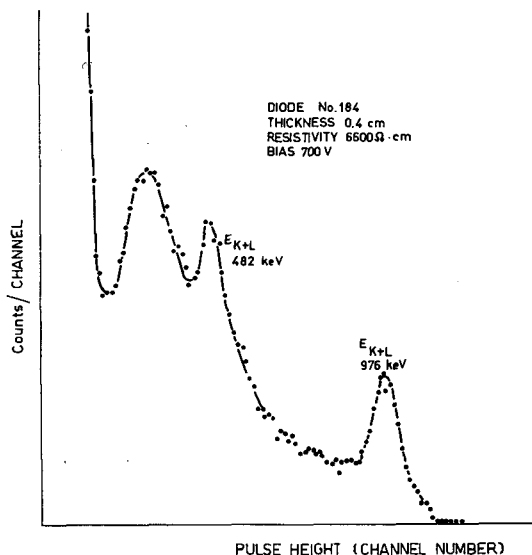


Fig. 7

Bi²⁰⁷ spectra, diode area 1.5 cm²

1.5 cm² and a thickness of 4 mm. The increased resolution for electron spectra obtainable with a smaller area (15 mm²) detector is shown in Fig. 7a.

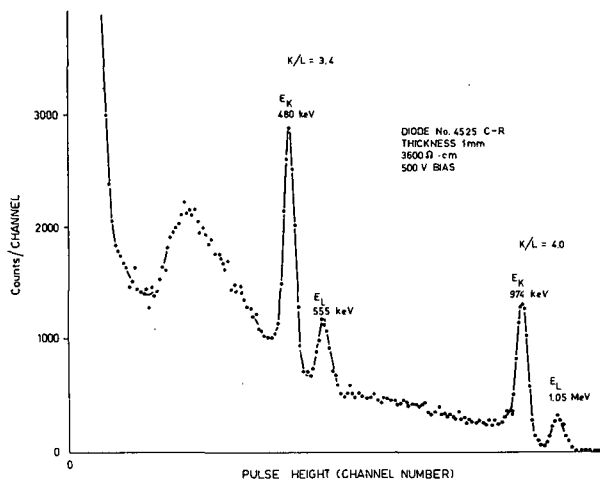


Fig. 7a
Bi²⁰⁷ spectra, diode area 15 mm²

IV. Experimental method used to determine semiconductor surface conductivities

The annular ring-structure shown in Fig. 8 is convenient for the measurement of surface conductivity, under epoxies, etc. The completed ring is etched in CP4 and boiled in 1% sodium-dichromate solution to produce a "p" surface [15] [16]. This type of surface was found to go through intrinsic quite easily by cycling the ambient between wet N₂ and a vacuum. Thus, having determined its minimum conductivity σ_m , the ring is cemented between two mica sheets (Fig. 9) with the epoxy selected for testing. Measurement of the final conductivity σ_f now gives $\sigma_s = \sigma_f - \sigma_m$. Application of high voltage to the electrodes on the mica produces a DC field-effect which serves to determine whether the surface is of a "p" or "n" type.

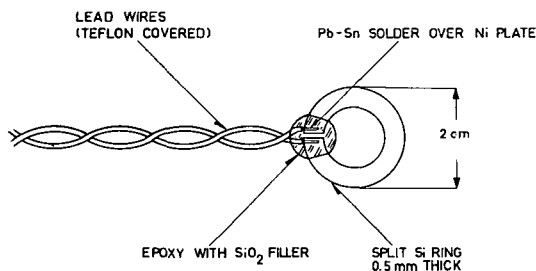


Fig. 8
Silicon ring assembly used for surface-conductivity measurements

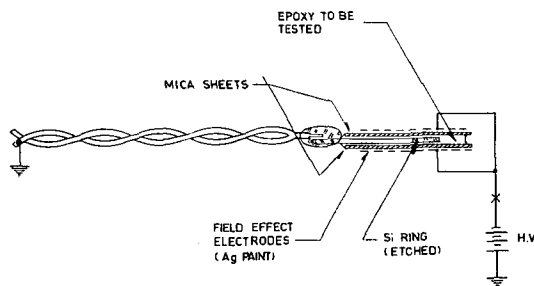


Fig. 9

Silicon ring assembly cemented between mica sheets

V. dE/dx silicon-surface barriers

The rate at which a non-relativistic ionizing particle of mass M loses energy E in its passage through matter is given by $dE/dx = k \frac{MZ^2}{E}$ where the constant k is only a function of the absorber. Thus if both dE/dx and E can be determined, the mass and the atomic number Z of the particle may be inferred.

Gas proportional counters have been used to measure dE/dx , but the use of thin silicon semiconductor detectors for this purpose [17] has several demonstrated advantages. Experience with both types at the ORNL 86-in Cyclotron [18] indicates that the semiconductor device is definitely superior in long-term gain stability. The maximum counting rate is also improved by approximately a factor of 10. Furthermore, the silicon detector is so much thinner than its corresponding gas-filled counterpart that a loss of particles by scattering is much reduced.

VI. Performance

An alpha spectrum taken with an 0.2 mm thick dE/dx surface-barrier detector of $\frac{1}{2}$ cm² area is seen in Fig. 10. The 22.50-keV energy-resolution is typical of this area. In these thin detectors the sensitive depth may be extended to within approximately 10 μ of the rear surface. However, as punch-through voltage is reached, typically between 3 and 100 V, the barrier region extends into the lap damage on the reverse side of the silicon producing an abrupt increase in leakage current. Because of the coplanar geometry of the device, increased sensitive depth can easily be obtained by stacking these units. In this manner particle telescopes of various types can be assembled.

VII. Construction of features

Details of fabrication of these surface-barrier detectors [19] are relatively simple. A lapped silicon "n"-type, plane-parallel wafer is etched on one surface only and cemented into a mounting ring with an epoxy resin. A thin deposit of gold provides electrical contact to the silicon surfaces. A ceramic ring is used to roughly match the thermal expansion rate of the silicon. Full ingot sections mounted in this manner have survived operation at 77° K.

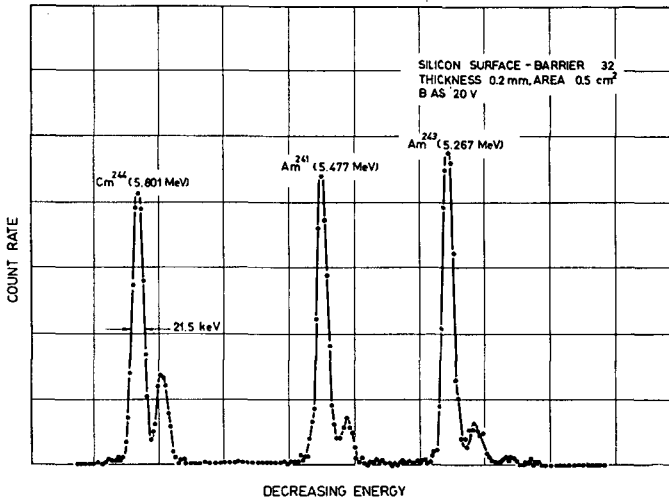


Fig. 10

Pulse-height spectra of Am^{243} , Am^{241} , and Cm^{244} taken with a 0.2-mm thick silicon surface-barrier detector of 0.5 cm^2 sensitive area. Bias is 20 V

VIII. Amplifier requirements

Since the fundamental quantity to be measured is electrical charge, a charge-sensitive first stage in the amplifier is desirable [20—22]. The output from a charge-sensitive amplifier is relatively independent of changes in diode bias and capacitance.

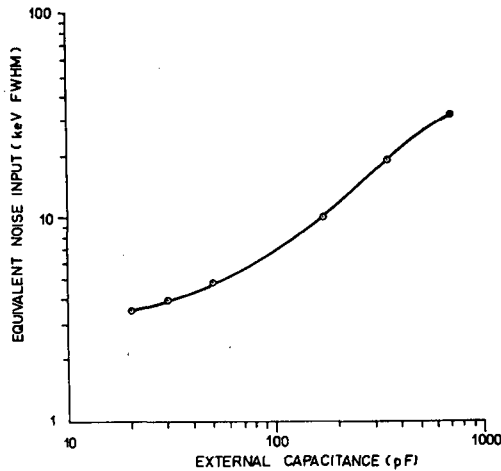


Fig. 11

Equivalent noise input as a function of external capacitance on the input for the “Q-2069C — Linear Amplifier for Alpha Analysis”

The noise performance of a charge-sensitive amplifier (Q-2069C) as a function of input capacitance is shown in Fig. 11. The circuit diagrams for the pre-amplifier and main amplifier are shown in Figs. 12* and 13*. The electronic noise with a 20 and 180-pF capacitive load on the input is $\sim 3\frac{1}{2}$ and 10 keV (FWHM), respectively. The design includes a window amplifier which allows a small part of the pulse-height spectrum to be amplified and spread out over the entire memory of a multi-channel pulse-height analyser. The entire system including window amplifier has a drift rate of < 300 eV/h and a line-voltage sensitivity of < 250 eV/line volt, when analysing a charge pulse on the input equivalent to 5.5 MeV.

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BEHAVIOUR OF SEMICONDUCTOR NUCLEAR-PARTICLE DETECTORS

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Abstract — Résumé — Аннотация — Resumen

Behaviour of semiconductor nuclear-particle detectors. Experimental and theoretical studies of the behaviour of semiconductor nuclear-particle detectors have been carried out over the temperature range of 0.2°K to 300°K. A simple theoretical model for the detector behaviour, which is found to describe the observed behaviour over a wide range of parameters, is presented. The importance of semiconductor purity and bias voltage in connection with pulse height, pulse rise-time and detector area is discussed.

Empirical studies of noise and energy resolution indicate that for alpha particles the smallest observed peak-widths are substantially larger than those expected on the basis of electrical noise from the detector and amplifier. Equivalent noise values of ≤ 3 keV full-width at half maximum (FWHM) have been found for a 40-mm² silicon surface-barrier detector at 77°K.

Semiconductor detectors exhibit a "pulse-height defect" for fission fragments. There is evidence that this defect is not caused by a "dead layer". If electric fields which are insufficient to insure complete "collection" are responsible for the defect, the necessary minimum field (at the surface) is $> 3 \times 10^4$ V/cm for fission fragments, as compared to the value of 2×10^3 V/cm which is found necessary in the case of alpha particles in Ge and Si.

Detailed considerations regarding pulse rise-time at the amplifier have shown that in high-resistivity material both the "dielectric" relaxation time and the resistance associated with the undepleted base material can play an important role. A quantitative description of the effect of detector and amplifier parameters on the shapes and rise-times associated with the pulse are presented.

The advantages and problems associated with the use of surface-barrier detectors in several unique low-temperature nuclear-alignment experiments are discussed. These experiments involved fission-fragment angular distributions and resolution of alpha-fine structure with long-term stability. Matched expansion-coefficient fabrication techniques which have been successfully used to make detectors up to 8 cm² in active area are also described.

Comportement des semi-conducteurs comme détecteurs de particules nucléaires. Les auteurs ont fait des études théoriques et expérimentales sur le comportement des semi-conducteurs comme détecteurs de particules nucléaires à des températures allant de 0,2°K à 300°K. Ils présentent un modèle théorique simple du comportement du détecteur qui correspond au comportement observé pour toute une gamme de valeurs des paramètres. Ils examinent quelle est l'importance de la pureté du semi-conducteur et de la tension de polarisation en ce qui concerne l'amplitude de l'impulsion, le temps de montée de l'impulsion et la surface du détecteur.

Des études empiriques sur le bruit et la résolution en énergie montrent que, pour des particules alpha, les plus petites largeurs de crête observées sont très nettement plus importantes que les largeurs que l'on avait prévues en tenant compte du bruit d'origine électrique provenant du détecteur et de l'amplificateur. A 77°K, on a relevé pour un détecteur à barrière de surface au silicium, d'une surface de 40 mm², des intensités de bruit équivalant à ≤ 3 keV (largeur totale à mi-hauteur du maximum).

Les semi-conducteurs présentent un «défaut d'amplitude» à l'égard des fragments de fission. On a tout lieu de penser que ce défaut n'est pas dû à une «couche morte». Si des champs électriques insuffisants pour assurer une «collection» complète sont la cause de ce défaut, le gradient de

champ nécessaire (à la surface) est supérieur à $3 \cdot 10^4$ V/cm dans le cas de fragments de fission contre $2 \cdot 10^3$ V/cm dans le cas de particules alpha de Ge et de Si.

Des études détaillées sur le temps de montée des impulsions au niveau de l'amplificateur ont montré que pour des substances de grande résistivité le temps de relaxation diélectrique et la résistance propres aux substances de base non appauvries peuvent jouer un rôle important. Les auteurs présentent une description quantitative de l'effet des paramètres des détecteurs et des amplificateurs sur les formes et les temps de montée des impulsions.

Ils étudient les avantages et les défauts des détecteurs à barrière de surface utilisés dans des expériences d'alignement nucléaire à basse température invariable. Ces expériences comprennent l'étude des distributions angulaires des fragments de fission et de la résolution — stable à long terme — des structures fines des particules alpha. On décrit également les techniques de fabrication, selon des coefficients de développement adaptés, qui ont été utilisées avec succès pour réaliser des détecteurs de surface active pouvant aller jusqu'à 8 cm².

Поведение детекторов ядерных частиц на полупроводниках. Были проведены экспериментальные и теоретические исследования поведения детекторов ядерных частиц на полупроводниках при температурах от 0,2°K до 300°K. В докладе приводится простая теоретическая модель поведения детектора, которая, как было установлено, отражает наблюдаемое поведение при большой амплитуде параметров. В докладе обсуждается важность чистоты полупроводников и смещения напряжения в связи с амплитудой импульса, временем нарастания импульса и зоной детекции.

Эмпирические исследования шума и энергетического разрешения свидетельствуют о том, что для альфа-частиц наблюдаемая наименьшая ширина пиков значительно больше, чем та, которая ожидается на основе электрического шума от детектора и усилителя. Для барьерного детектора с кремниевой поверхностью в 40 мм² при 77°K были установлены показатели шума, эквивалентные с ≤ 3 кэв (полная ширина при полумаксимуме).

Полупроводниковым детекторам свойственен „дефект амплитуды импульса“ для осколков деления. Имеются данные, свидетельствующие о том, что этот дефект не вызывается „нерадиоактивным слоем“. Если электрические поля, которые являются недостаточными для обеспечения полного „сбора“, вызывают этот дефект, необходимым минимальным полем (на поверхности) является поле выше 3×10^4 вольт/см для осколков деления по сравнению с 2×10^3 вольт/см, необходимость чего была установлена для альфа-частиц в германии и кремнии.

Подробные исследования времени нарастания импульса в усилителе показали, что в материалах с высокой сопротивляемостью как время „диэлектрической“ релаксации, так и сопротивление, связанное с неистощенным основным материалом, могут играть важную роль. В докладе дается количественное описание действия параметров детектора и усилителя на формы и время нарастания, связанные с импульсом.

В докладе обсуждаются преимущества и проблемы, связанные с использованием поверхностных барьерных детекторов в некоторых опытах по ядерному выравниванию при уникально низких температурах. В ходе этих опытов происходили угловые распределения осколков распада и разрешение альфа-микроструктуры с долгосрочной стабильностью. В докладе также дается описание техники изготовления с коэффициентом согласованного расширения, которая успешно использовалась для изготовления детекторов до 8 см² в активной зоне.

Propiedades de los detectores de partículas nucleares a base de semiconductores. Los autores han realizado estudios experimentales y teóricos del comportamiento de los detectores de partículas nucleares a base de semiconductores, en el intervalo de temperaturas de 0,2°K a 300°K. Presentan un modelo teórico muy sencillo para las características del detector, que describe las propiedades observadas experimentalmente para un amplio margen de parámetros. Discuten la importancia de la pureza del semiconductor y de la tensión de polarización en relación con la amplitud del impulso, con su tiempo de elevación y con el área del detector.

Los estudios empíricos del ruido y de la resolución energética indican que, en el caso de partículas alfa, las menores anchuras observadas en los máximos son sensiblemente mayores

de lo que cabe esperar del ruido del detector y del amplificador. Para un detector de silicio de barrera superficial, de 40 mm², han encontrado para el ruido a 77°K valores ≤ 3 keV (anchura total al semimáximo).

Los detectores basados en semiconductores dan un «defecto de amplitud de impulsos» para los fragmentos de fisión. Existen pruebas de que dicho defecto no se debe a una «capa muerta». Si los responsables del defecto fueran campos eléctricos incapaces de asegurar una colección completa, el campo mínimo necesario (en la superficie) para los fragmentos de fisión sería de más de $3 \cdot 10^4$ V/cm, frente a $2 \cdot 10^3$ V/cm para las partículas alfa en el Ge y el Si.

Un estudio detallado del tiempo de elevación del impulso en el amplificador ha puesto en claro que tanto el tiempo de relajación «dieléctrica» como la resistencia correspondiente al material de base no purificado pueden desempeñar un papel muy importante en los materiales de elevada resistividad. La memoria presenta una descripción cuantitativa del efecto de los parámetros del detector y del amplificador sobre la forma y el tiempo de elevación de los impulsos.

Se discuten las ventajas y los problemas que presenta la utilización de detectores de barrera superficial en varios experimentos muy especiales de alineación nuclear realizados a baja temperatura, entre otros, referentes a las distribuciones angulares de fragmentos de fisión y a la resolución de la estructura alfa fina con estabilidad a largo plazo. También se describen técnicas de fabricación basadas en coeficientes de dilatación equiparados, que han permitido obtener detectores con áreas activas de hasta 8 cm².

I. Introduction

Experimental and theoretical studies of the behaviour of semiconductor nuclear-particle detectors have been carried out over the temperature range 0.2° K—300° K in connection with a number of nuclear alignment and fission dynamics studies at Oak Ridge National Laboratory. A simple theoretical model based on the characteristics of the SCHOTTKY barrier [1] has been found to apply to Ge detectors at temperatures below the sublimation temperature of CO₂ and above liquid He temperatures [2]. More recently this work has been extended to the use of Si detectors in the temperature range 77° K—300° K and further verification of the utility of this model has been obtained. In this work, a comparison between the observed and expected behaviour showed agreement in the areas of device capacitance, pulse heights from α -particles and sensitive depths over a wide range of parameters. Other investigators have also found agreement with this simple model [3].

In the Schottky barrier model, the sensitive depth (depletion depth) is given by

$$\lambda = (2K\epsilon_0 V_t / qN)^{1/2} \quad (1)$$

where K is the dielectric constant, ϵ_0 is the permittivity of free space, V_t is the total potential across the barrier (including the naturally occurring barrier height), q is the magnitude of the electronic charge, and N is the net uncompensated impurity density within the material. The dynamic capacitance per unit area of the barrier is given by

$$C = (qNK\epsilon_0 / 2V_t)^{1/2} \quad (2)$$

and the pulse height predicted by the model for the case where a particle loses an amount of energy W by production of charge carriers (electron-hole pairs) within the barrier is

$$\Delta V = (2qV_t / K\epsilon_0 N)^{1/2} \times (W\eta / A\epsilon) \quad (3)$$

where A is the detector area, η is the "charge collection efficiency" and ϵ is the average energy required to produce an electron-hole pair in the detector material.

From equation (3) we note that if one wishes to have a large output pulse, the material should have a small uncompensated impurity density N . In order to preserve high carrier mobility and long carrier lifetime, it is desirable to obtain this condition by using high-purity material. To the extent that η/ϵ is independent of the nature of the ionizing particle and its energy, the pulse height ΔV will be proportional to the energy W . This proportionality seems to hold quite well for most particles, but an exception seems to occur in the case of fission fragments; see section III.

II. Resolution, noise and stability

An examination has been made of the feasibility of using Si detectors, operated in the temperature range 77° K—300° K, in connection with nuclear-orientation experiments which require the separation of α -particle fine structure and various α -particle groups.

As expected, leakage currents were reduced by large factors in cooling to 77° K. Factors of 100 were found on cooling to —20° C. The peak-width resulting from bombardment with alpha particles as well as the peak-width resulting from electrical noise from the detector and amplifier were measured as a function of detector temperature. These tests were made using the low-noise Q2069B-3RO amplifier system [4]. The noise width of this "charge-sensitive" amplifier system, as a function of input capacitance, is shown in Fig. 1. (The stepwise behaviour of the pulse-generator measurements at small peak-widths is a result of rounding off to the next larger integral number of channels.) As can be seen from Fig. 2, the smallest observed peak-widths for α -particles are substantially larger than the widths associated with the electrical noise from the detector and amplifier. The electrical noise from the detector was reduced to ≤ 3 keV (FWHM) by cooling to 77° K. This fact may be used to advantage in cases where this noise is the controlling factor in peak-widths. For alpha particles with detectors of relatively large area the electrical noise is important in this sense. For lightly ionizing

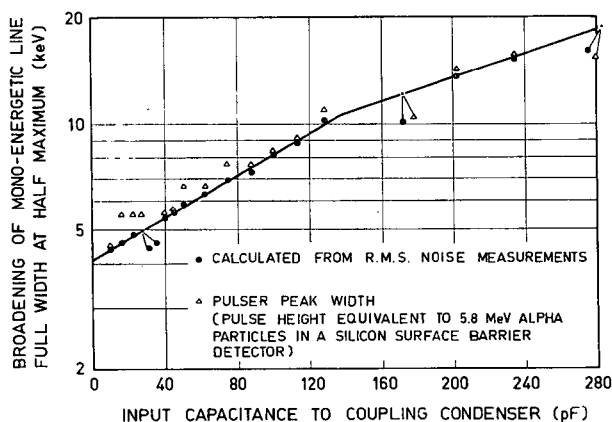


Fig. 1

Electronic noise as a function of input capacitance for ORNL preamp. Q-2069B-3 with selected input tube and 20-M Ω load resistor

particles (e.g., electrons or minimum ionizing particles) further improvements in amplifier noise levels may permit (5) an approach to the situation indicated by the bottom curve in Fig. 2.

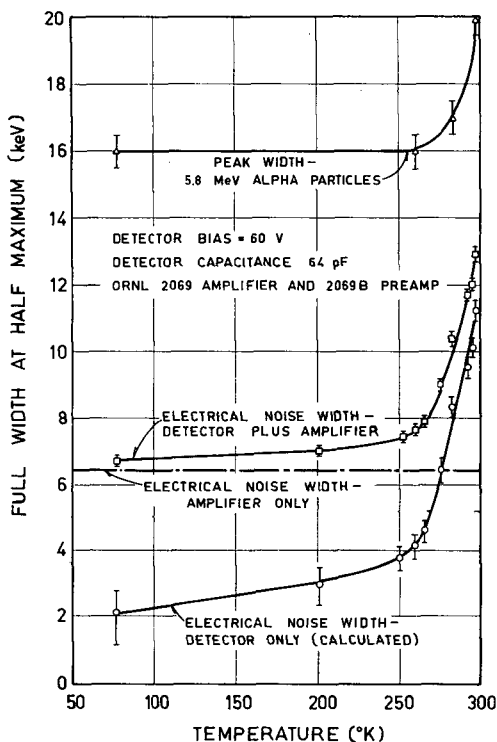


Fig. 2

Energy resolution and noise for 40-mm² silicon surface-barrier detector as a function of detector temperature

For certain experiments the problems of long-time stability and peak shape are important. A study of these aspects, with particular attention to the variation in measured peak areas, was made. Fig. 3 shows a typical multichannel pulse-height spectrum, representing 4 hours of counting near the middle of a 20-h stability test made with the detector at room temperature. The peak locations remained constant within 10 channels, or 16 keV, during the entire period. During the 20-h counting period the electrical noise contribution increased from 13 keV (FWHM) to 16.5 keV (FWHM) and the alpha peak-widths increased from 17.5 keV (FWHM) to 23 keV (FWHM). (The latter change may have been caused by the gradual accumulation of contaminants from the untrapped vacuum system.) A separate test of the amplifier system and analyser showed only a few kilo-electron-volts peak-location drift during a comparable interval.

A study of the peak shapes was made by fitting the sum of two gaussian functions to the alpha peaks associated with the ground and first excited states of Pu²⁴⁰. In the

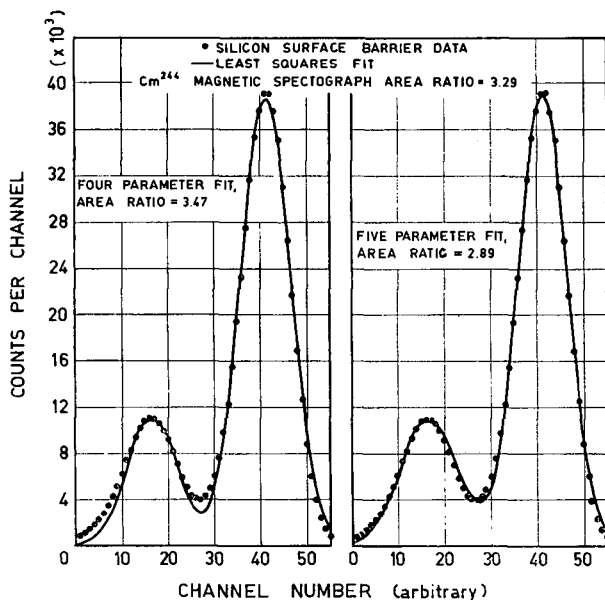


Fig. 3

Cm²⁴⁴ alpha fine structure

four-parameter fit the width of both peaks was required to be the same. The five-parameter fit allowed individual variation of the widths, and subjectively appears to be a better fit. However, a comparison of the gaussian areas under the two fine structure peaks revealed that the four-parameter fit not only gave an area ratio in closer agreement with magnetic spectrograph data, but also showed much less variation in the ratio during the 20-h period. Using the four-parameter fit, the variation in the calculated area ratio was less than 0.7%, while the five-parameter fit gave a variation of 9%. It is clear that the peaks of Fig. 3 are not gaussian; the disagreement with the gaussian sum-curve in the valley cannot be caused by conversion electrons because of the small solid angle.

III. Response of detectors to fission fragments

In connection with fission-fragment energy and mass correlation studies at Oak Ridge National Laboratory, H. W. Schmitt, J. H. Neiler, F. J. Walter and R. J. Silva have carried out an investigation of the linearity of the response of silicon surface-barrier detectors (n-type) to fission fragment energy. Their preliminary findings indicate that the measured pulse height is not strictly proportional to fragment energy, but that an empirical relation of the form $E = (a \times PH) + \delta$ is followed, where E = fragment energy, a = constant, PH = pulse height, and δ has been termed "pulse-height defect".

Fission fragments from the spontaneous fission of Cf²⁵² were used. The source was approximately 1 cm in diam. and was usually positioned about 1 cm from the detector. For any given set of operating conditions, the shape of the fission spectrum did not change with source-to-detector distance above ~ 6 mm. The detectors were in general 5 mm $\times$ 5 mm in size; in most cases the effective detection area was somewhat smaller.

The low-noise, charge-sensitive preamplifier, main amplifier and biased amplifier were of the modified ORNL Q-2069 type [4]. Calibration in every case was made relative to an ORNL Q-1212 mercury relay-pulsar which was experimentally known to be linear with zero intercept.

On the basis that the normalized pulse-height spectra obtained in these measurements agreed in shape with the energy spectrum deduced from double time-of-flight measurements [6] [7] seven points over the spectrum were selected for the pulse-height vs. energy correlation for each set of operating conditions. These were the heavy and light-fragment peaks, the valley, the points at half-maximum on the low and high-energy edges of the spectrum and extrapolated minimum and maximum energies obtained from these edges.

In all the cases studied, the slope a at sufficiently high applied bias was approximately constant and was not inconsistent with the slope expected on the basis of $\epsilon = 3.5$ eV/electron-hole pair. As the bias was reduced, the value of a was found to increase substantially. An indication of the manner in which this increase occurred is given in Fig. 6 for two of the detectors used. The barrier depth in the 120 Ω cm detector was less than the fragment ranges at bias values below about 7 V. In the 2600 Ω cm detector the value of E_0 at 10 V bias is about 2600 V/cm, which compares well with the value found necessary for complete "charge collection" in the case of α particles in Ge [2] and Si [5].

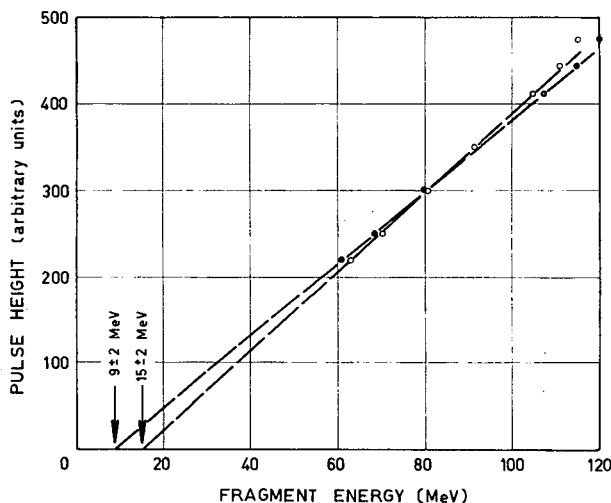


Fig. 4
Typical pulse-height vs. energy relation

A typical pulse height vs. energy plot is shown in Fig. 4. Note that the empirical equation

$$E = (a \times PH) + \delta \quad (4)$$

describes the data, although the values of a and δ depend on whether one uses the energy spectrum of MILTON and FRASER [6] or that of STEIN and WHETSTONE [7]. A

basic constant difference was found in the value of δ for all runs, the energies of Stein and Whetstone yielding the smaller values of δ . The latter energies have been arbitrarily chosen for purposes of plotting the pulse-height defect δ vs. maximum electric field E_0 in the barrier region. The maximum field E_0 for silicon detectors is given by

$$E_0 = 4.2 \times 10^4 \times \sqrt{V/\rho} \text{ V/cm} \quad (5)$$

where V = detector bias in volts = applied bias plus ~ 0.6 volt, and ρ = resistivity in Ω cm.

The experimental values of δ as a function of E_0 are shown in Fig. 5. With the exception of the 3600 Ω cm case, the value of δ appears to be approximately constant. As can be seen in Fig. 5, the data obtained in the 3600 Ω cm case showed an ageing effect. The application of a surface treatment designed to improve the surface potential characteristics of this detector resulted in an additional decrease in δ at a given field (these data are not shown). It should be pointed out that the estimated energy losses in the Cf^{252} source and the front gold electrode did not exceed 2.5 MeV. In view of the discrepancy between the two sets of time-of-flight data, the possibility that the observed values of δ arise from an incorrect energy scale should not be overlooked. No theoretical studies of possible carrier-loss mechanisms have been undertaken in connection with this work. However, if the energy scale is approximately correct, the form of the empirical relation suggests the possibility that more than one loss mechanism may be involved.

IV. Pulse rise-times

Under certain circumstances, the charge-carrier transit times in semiconductor particle detectors can be quite short [2]. This presents the possibility of using such detectors

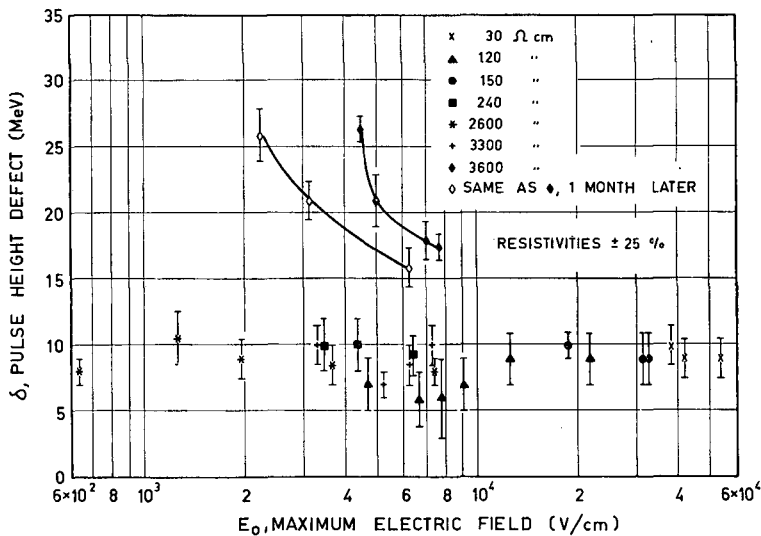


Fig. 5

Pulse-height defect δ vs. maximum electric field E_0 in barrier region

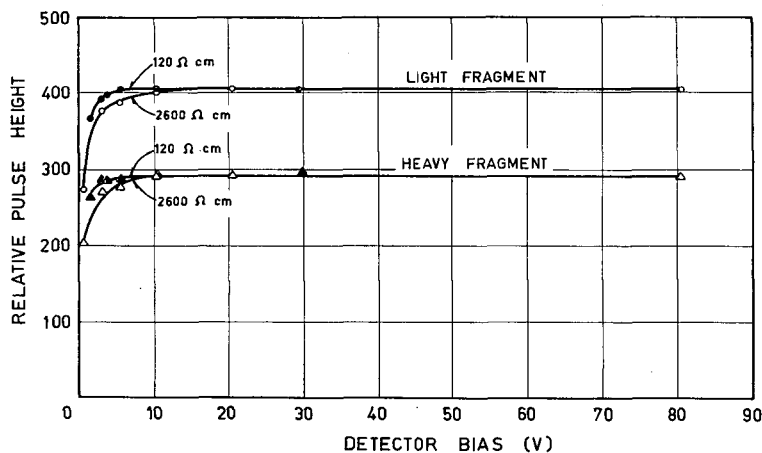


Fig. 6

Relative pulse-height vs. detector bias for fission fragments (surface-barrier detectors)

in nanosecond-timing applications. Even though the transit times of the charge carriers across the depletion region may be short, the rise-time at the amplifier input may be relatively long. An estimate of the observable rise time requires that one consider not only the charge transit times, but the time required to transmit the information to the amplifier through the undepleted base material and through any contact or sheet resistances which may exist.

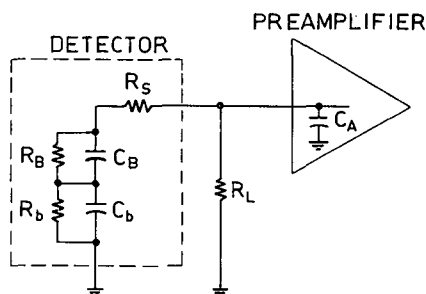


Fig. 7

Equivalent circuit of semiconductor detector

Fig. 7 shows an equivalent circuit for a junction detector [2]. C_B and R_B are the effective capacitance and resistance of the depletion region, while C_b and R_b represent these quantities for the undepleted bulk region. C_A is the input capacitance of the amplifier including any stray capacitances, R_L is the load resistor and R_S is any additional series resistance. In Fig. 7 let $V_A(t)$ be the voltage across C_A resulting from a current $I(t)$ which corresponds to the transit of charge carriers across C_B . $V_A(t)$ is given by

$$V_A(t) = L^{-1} \left\{ [LI(t)] \cdot \frac{1}{R_S C_A C_B} \cdot \left[\frac{s + (\tau_D)^{-1}}{s^3 + 2as^2 + \gamma^2 s} \right] \right\} \quad (4)$$

where $\tau_D = R_b C_b = \rho K \epsilon_0$ (the "dielectric" relaxation time),

$$\alpha = \frac{1}{2} [(R_S C_S)^{-1} + (R_S C_b)^{-1} + (\tau_D)^{-1}],$$

$$\gamma^2 = (\tau_D)^{-1} (R_S C_S)^{-1},$$

$$C_S = (C_A C_B) / (C_A + C_B),$$

ρ = resistivity of bulk semiconductor,

K = dielectric constant,

ϵ_0 = permittivity of free space, and

L = Laplace transform operator ($s = \sigma + j\omega$).

In Eq. (4), R_B and R_L are neglected, since they normally contribute only to the pulse decay. It is also assumed that stray inductances are negligibly small.

Consider the case where the charge carrier transit time is sufficiently short that $I(t)$ may be represented by a delta function, i.e., $I(t) = \delta(t - t_0)$. Q or $I(s) = L\{I(t)\} = Q$. Then the voltage at the amplifier is given by

$$V_A(t) = \frac{Q}{C_A + C_B} \left\{ 1 - \left[\cosh \beta t - \frac{1}{\beta} \left(\frac{1}{R_S C_S} - \alpha \right) \sinh \beta t \right] \cdot \exp(-\alpha t) \right\} \quad (5)$$

where

$$\beta = (\alpha^2 - \gamma^2)^{\frac{1}{2}}.$$

For the case where R_S is negligibly small (e.g., with an evaporated metal front electrode), the voltage at the amplifier becomes

$$V_A(t) = \frac{Q}{C_A + C_B} \left\{ 1 - \left[1 - \left(\frac{C_b}{C_b + C_S} \right) \right] \exp \frac{-t}{\tau_D + R_b C_S} \right\}. \quad (6)$$

It is apparent from the above that the rise time can only approach the transit times if C_A , R_S , τ_D , and R_b are sufficiently small. Eq. (6) gives an initial pulse height equal to $V_A(0) = Q C_b / (C_A C_B + C_b C_A + C_b C_B)$; this corresponds to the capacitive coupling associated with the bulk region. This value can be made to approach the asymptotic value $Q / (C_A + C_B)$ by making the bulk region sufficiently thin.

In the limit of extremely large bulk resistivity ($\tau_D \rightarrow \infty$), the expected pulse height is the initial pulse height $V_A(0)$ mentioned above. This value has been experimentally observed in Ge detectors cooled to very low temperatures [2].

In the above, the carrier current has been represented by a delta function in order to delineate the effects of various circuit parameters. In practice, transit times are by no means always as short as a few nanoseconds and detailed consideration of the mobilities, electric fields and transit distances is required. It should also be noted that in the case of densely ionizing particles, the internal electric fields will be strongly perturbed by the charge carriers. Another difficulty in realizing this potential application to fast-timing problems is connected with the unresolved question of obtaining satisfactory signal-to-noise ratios when semiconductor detectors are used with very fast amplifiers.

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SURFACE-BARRIER COUNTERS FOR NUCLEAR REACTION STUDIES

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Abstract — Résumé — Аннотация — Resumen

Surface-barrier counters for nuclear reaction studies. Silicon surface-barrier counters have been in routine use at Oak Ridge National Laboratory since October 1959 for spectroscopy of alpha particles and heavier ions emitted from nuclear reactions. Applications in recent experiments, including two ($dE/dx, E$) particle identification systems, are described. The counters were made at this Laboratory from n-type silicon with a thin layer of gold deposited by vacuum evaporation. The pulse-height response to N^{14} ions up to 26 MeV was shown to be linear within 1/2%; also, the responses were identical for all particles tested, including protons, deuterons, alphas, boron, carbon, nitrogen, oxygen, and magnesium ions. No pulse-height defect was observed. Counters with shallow barriers were used successfully for study of scattering and transfer reactions of heavy ions. To stop high-energy alpha particles, several counters with the highest available resistivity (1500 to 2300 Ω -cm) were biased at 500 V; the barrier thicknesses were as large as 0.6 mm. The barrier depth in several counters was measured by two methods and found to be proportional to the square root of the bias from 0.005 to 0.6 mm. Evaporation spectra of 5 to 35-MeV alpha particles were studied. The proton contamination, which was present up to 9 MeV at full bias, was eliminated by reducing the bias, thereby decreasing the maximum energy a proton could lose in the sensitive region. In a 1500 Ω -cm counter exposed to 4-MeV N^{14} ions, slight increases in reverse current and noise level were noted after an accumulated dose of $\sim 10^9$ ions/cm². After 10^9 or 10^{10} ions/cm² the increased noise level rendered the counter useless. Several thin (0.08 to 0.2 mm) silicon wafers were successfully operated as dE/dx counters in conjunction with a thick scintillation counter. This new system provides a cleaner separation of protons, deuterons, and tritons than was obtained in the previous system with a gas proportional counter. It is also more stable, more convenient, and more tolerant of high counting rates. A ($dE/dx, E$) telescope was constructed for short-range heavy ions; here the dE/dx detector was a thin gas counter. To minimize energy losses, the silicon E counter was placed, in effect, inside the gas volume. In preliminary tests, C^{12} was bombarded with 28-MeV N^{14} , and C, N, Na, Mg, and Al ions emitted from the target were successfully separated.

Compteurs à barrière de surface pour l'étude des réactions nucléaires. Le laboratoire d'Oak Ridge utilise couramment des compteurs à barrière de surface depuis octobre 1959 pour la spectroscopie des particules alpha et des ions lourds émis lors des réactions nucléaires. L'auteur décrit des expériences effectuées à l'aide de ces compteurs et notamment deux systèmes d'identification de particules ($dE/dx, E$). Les compteurs ont été construits au Laboratoire d'Oak Ridge à partir de silicium de type n et d'une fine couche d'or déposée par évaporation sous vide. La réponse en amplitude d'impulsion pour les ions ^{14}N , jusqu'à 26 MeV, est linéaire à 0,5% près; de plus, les réponses sont identiques pour toutes les particules essayées, notamment des protons, des deutérons, des particules, alpha et les ions bore, carbone, azote, oxygène et magnésium. On n'a pas observé de défaut d'amplitude d'impulsions. Des compteurs à barrière de surface ont été utilisés avec succès pour l'étude de la diffusion et des réactions de transfert des ions lourds. Pour arrêter les particules alpha de grande énergie, on a polarisé à 500 V plusieurs compteurs à l'aide de la plus forte résistivité possible (1500 à 2300 Ω /cm), ce qui a permis d'obtenir jusqu'à 0,6 mm d'épaisseur pour la barrière. L'auteur étudie des spectres d'évaporation de particules alpha de 5 à 35 MeV. La contamination des protons, qui existe jusqu'à 9 MeV en polarisation totale, est éliminée lorsqu'on diminue la polarisation, ce qui réduit l'énergie maximum qu'un proton peut perdre dans la région sensible. Dans un compteur de

1500 Ω/cm bombardé par des ions ^{14}N de 4 MeV, l'auteur a noté que le courant inverse et le niveau du bruit avaient légèrement augmenté après une dose accumulée d'environ 10^9 ions/ cm^2 . Lorsque la dose accumulée dépasse 10^9 ou 10^{10} ions/ cm^2 , le niveau du bruit rend le compteur inutilisable. On a employé avec succès, comme compteurs dE/dx , plusieurs pastilles minces (0,08 à 0,2 mm) de silicium en combinaison avec un compteur à scintillation de grande dimension. On a pu ainsi séparer les protons, deutérons et tritons plus nettement qu'avec le système précédent comportant l'usage d'un compteur proportionnel à gaz. Le nouveau système est en outre plus stable, plus pratique et se prête mieux à des taux de comptage élevés. On a construit un télescope ($dE/dx, E$) pour l'étude des ions lourds de faible parcours; le détecteur dE/dx est ici un compteur à gaz de petite dimension. Pour réduire les pertes d'énergie, on place le compteur au silicium E à l'intérieur même du gaz. Au cours d'essais préliminaires, ^{12}C a été bombardé avec des ions de ^{14}N d'une énergie de 28 MeV, et l'on a réussi à séparer les ions carbone, azote, sodium, magnésium et aluminium émis par la cible.

Поверхностно-барьерные счетчики для исследований ядерных реакций. С октября 1959 года в Окриджской национальной лаборатории в повседневной работе использовали кремниевые поверхностно-барьерные счетчики для спектроскопии альфа-частиц и более тяжелых ионов, испускаемых в результате ядерных реакций.

В докладе описывается их применение в недавних опытах, включая опыты с двумя системами для опознавания частиц ($dE/dx, E$). Счетчики изготовлялись в этой лаборатории из кремния типа n с тонким слоем золота, нанесенным путем вакуумного испарения. Зависимость амплитуды импульса для ионов азота-14 от энергии в интервале между 2 и 26 мэв была линейной в пределах $\frac{1}{2}\%$; аналогичной была также зависимость для всех других использованных частиц, включая протоны, дейтроны, альфа-частицы и ионы бора, углерода, азота, кислорода и магния. Никаких искажений амплитуды импульсов не наблюдалось. Счетчики с тонкими барьерами успешно использовались для изучения реакции рассеяния и переноса тяжелых ионов. Для остановки альфа-частиц высокой энергии несколько счетчиков с самым высоким сопротивлением (от 1500 до 2300 ом/ см) были использованы при смещении в 500 вольт, что дало толщину барьеров до 0,6 мм. Были изучены спектры испарения альфа-частиц от 5 до 35 мэв. Загрязнение протонами, которое существовало до 9 мэв при полном смещении, было ликвидировано путем сокращения с уменьшением тем самым максимальной энергии, которую может потерять протон в зоне чувствительности. В счетчике на 1500 ом/ см , подверженном действию ионов азота-14 в 4 мэв, были отмечены небольшие увеличения обратного тока и уровня шумов после аккумулязированной дозы приблизительно в 10^9 ионов/ см^2 . После 10^9 или 10^{10} ионов/ см^2 возросший уровень шума делал счетчики бесполезными. Несколько тонких (0,08—0,2 мм) кремниевых облаток успешно использовались в качестве счетчиков dE/dx с толстым сцинтилляционным счетчиком. Эта новая система обеспечивает более чистое разделение протонов, дейтронов и ядер трития, чем предыдущие системы, в которых использовались газовые пропорциональные счетчики. Она также более устойчива, более удобна и более вынослива по отношению к высоким скоростям счета. Был сооружен телескоп ($dE/dx, E$) для тяжелых ионов с коротким пробегом; в нем детектором dE/dx был тонкий газовый счетчик. Для сокращения потерь энергии кремниевый счетчик E был помещен фактически в газовый объем. Во время предварительных опытов углерод-12 бомбардировался азотом-14 с энергией 28 мэв и ионы углерода, азота, натрия, магния и алюминия, испускаемые из мишени, успешно разделялись.

Contadores de barrera superficial para el estudio de reacciones nucleares. En el Laboratorio Nacional de Oak Ridge se utilizan corrientemente, desde octubre de 1959, contadores de silicio del tipo de barrera superficial, para la espectroscopia de partículas alfa y de iones pesados emitidos en las reacciones nucleares. El autor describe algunos experimentos recientes realizados con ayuda de esos contadores y, en particular, dos sistemas de identificación de partículas ($dE/dx, E$). Los contadores han sido construidos en el Laboratorio de Oak Ridge empleando silicio de tipo n , con una delgada capa de oro depositado por evaporación al vacío. La respuesta en amplitud de impulso para los iones ^{14}N de 26 MeV, como máximo, es lineal con un margen

de error del 0,5 por ciento; además, las respuestas son idénticas para todas las partículas ensayadas, que comprenden protones, deuteronos, partículas alfa, iones de boro, carbono, nitrógeno, oxígeno y magnesio. No se han observado defectos en la amplitud de los impulsos. Se han utilizado con éxito contadores con barrera de escaso espesor para estudiar reacciones de dispersión y transporte de iones pesados. Para detener las partículas alfa de elevada energía, se han polarizado a 500 V varios contadores con ayuda de la máxima resistividad posible (1500 a 2300 Ω/cm) logrando de esa forma espesores de barrera de hasta 0,6 mm. Se han estudiado espectros de evaporación de partículas alfa de 5 a 35 MeV. La contaminación protónica, observada hasta los 9 MeV en polarización total, es eliminada reduciendo dicha polarización, con lo que disminuye la energía máxima que puede perder un protón en la zona sensible. En un contador de 1500 Ω/cm bombardeado por iones ^{14}N de 4 MeV, el autor ha observado que la corriente inversa y el nivel de ruido aumentan ligeramente después de una dosis acumulada de unos 10^9 iones/ cm^2 . Cuando la dosis supera los 10^9 ó 10^{10} iones/ cm^2 el aumento del nivel de ruido inutiliza el contador. Se han empleado con éxito, como contadores dE/dx , varias hojas delgadas de silicio (0,08 a 0,2 mm) en combinación con un contador de centelleo de gran dimensión. La separación de protones, deuteronos y tritones efectuada con este nuevo sistema es más neta que la obtenida con el sistema anterior, en que se utilizaba un contador proporcional de atmósfera gaseosa. El nuevo sistema es, además, más estable, más práctico y se presta mejor a velocidades de recuento elevadas. Se ha construido un telescopio (dE/dx , E) para iones pesados de corto alcance; en este caso, el detector dE/dx es un contador con atmósfera gaseosa, de dimensión reducida. Para reducir al mínimo las pérdidas de energía, el contador E de silicio se coloca en el interior de la masa gaseosa. En ensayos preliminares se ha bombardeado ^{12}C con iones de ^{14}N de 28 MeV, y se han separado con éxito los iones de C, N, Na, Mg y Al emitidos por el blanco.

I. Introduction

Surface-barrier counters, even with shallow barriers, are very well suited for spectroscopy of heavy ions at moderate energies. Almost immediately after the development of practical silicon devices in late 1959 they replaced scintillators for heavy-ion detection in experiments with the Oak Ridge 63-Inch Cyclotron. More recently, counters with relatively deep barriers have been successfully used for studies of alpha-particle spectra and angular distributions from N^{14} bombardment of low- Z targets. Information on radiation damage and on the use of surface-barrier counters as elements in (dE/dx , E) particle identification schemes are also presented.

II. The counters

The silicon detectors used in this work were manufactured at Oak Ridge National Laboratory by the Instrumentation and Controls Division. Most of them consisted of n-type silicon wafers about 1 mm thick, cast in epoxy resin. In some counters contact to the surface states of the silicon was made by the evaporation of a continuous film of gold on to the entire front face of the mounted wafer, after the silicon was edged with polystyrene as described in references [1] and [2]. In later models, including most of the counters operated at high voltage, a mask was used during evaporation to keep both the epoxy resin and a 1-mm border around the wafer free of gold. The gap between the gold film on the silicon and a brass ring cemented to the epoxy resin was then bridged with a fine gold wire. The wire contacted the gold film at one corner through a small ($\sim 1 \text{ mm}^2$) spot of dried Aquadag (colloidal graphite suspension). Silver paste was used to connect the other end to the brass ring; the ring served both for electrical connections and the protection of the delicate gold-wire assembly. The counters used

as the dE/dx elements were 0.08 to 0.2 mm thick, mounted in ceramic rings and vacuum-coated on both sides with gold.

III. Pulse-height response

The results of a test [1] of the response of a 50 Ω -cm counter to scattered N^{14} ions from the ORNL 63-Inch Cyclotron are shown in Fig. 1. The energy scale for the solid dots is quite accurate since the energy variation was accomplished by changing the scattering angle; the kinematic energy variation can of course be calculated exactly. Corrections were made for the small (~ 0.1 MeV) energy loss in the gold film. The rms deviation of these data from perfect linearity is $\frac{1}{2}\%$, about the same as the accuracy with which the pulse heights could be determined. The open circles were obtained by degrading the beam energy with absorbers and scattering at a fixed angle; the large errors indicated are due to imperfect knowledge of the energy loss in the absorbers.

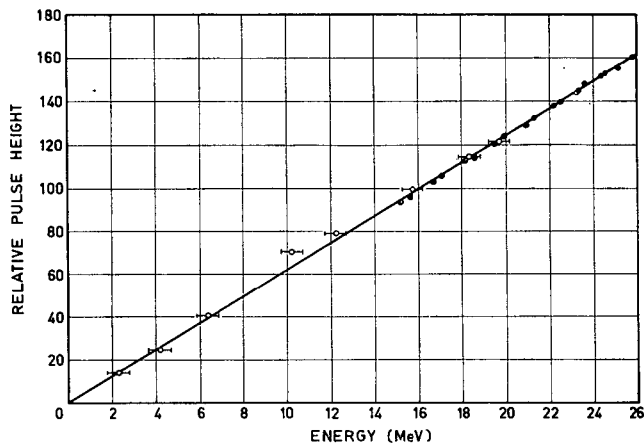


Fig. 1

Pulse-height response of a silicon surface-barrier counter to N^{14} ions. For the solid dots the N^{14} was scattered by a thin aluminium foil; the energy was varied by changing the angle of scattering. For the open circles the N^{14} was scattered through 90 deg by a thin gold foil; the energy was varied by degrading the incident beam with nickel absorbers. The error bars are estimates of the uncertainty in the range-energy relation used to convert absorber thickness to energy loss

The data from the linearity measurement indicate that no pulse-height defect exists for the heavily ionizing N^{14} particle ($dE/dx \sim 5$ MeV/mg-cm $^{-2}$). Such a defect would have been detected had it been appreciably larger than 0.3 MeV. The data do not, however, exclude the possibility of a defect $\lesssim 0.3$ MeV.

The relative response for natural alphas and for N^{14} ions was carefully checked [1] and found to be identical within $\frac{1}{2}\%$. This has since become the basis for the determinations of the beam energy of the 63-Inch Cyclotron; the pulse height from an alpha source of known energy is compared with that due to N^{14} from the cyclotron beam.

The response to high-energy alpha particles (20 to 35 MeV) was measured by reactions of 26-MeV N^{14} with deuterium, leading to well-known states of C^{12} . The alpha pulse

heights were proportional to energy within 1%. Experiments on elastic recoil ions from various targets showed identical pulse height response for protons, deuterons, boron, carbon, oxygen, and magnesium.

IV. Barrier depth

Measurements of capacity vs. bias by a method described elsewhere [1] gave a linear relation between the barrier capacity and the inverse square root of the bias for counters covering a wide range of resistivities (50 to 2300 Ω -cm). The Schottky theory of barrier depth, which assumes an abrupt end to the depletion layer, was verified in this way for barriers from 0.005 to 0.1 mm thick. For barriers deeper than about 0.1 mm, the capacity was generally much smaller than the stray capacities, and accurate measurements were difficult.

Fortunately another type of measurement is applicable. If a continuous spectrum of charged particles impinges on a counter it gives rise to a continuum of pulse heights, but with a maximum pulse height due to particles of range equal to the sensitive depth. Higher energy particles have lower specific energy loss and therefore give a smaller pulse height; the pulse height due to lower energy particles must of course be smaller than the maximum. By observing the position of the cutoff as a function of bias it is possible, from the appropriate range-energy curve, to determine the sensitive depth as a function of bias.

A series of spectra of alpha particles and protons from the N^{14} bombardment of oxygen are shown in Fig. 2. At 500 V the alpha spectrum is complete out to the maximum alpha energy possible in this reaction, about 33 MeV. The sharp rise at about 9 MeV is due to the proton cutoff. As the bias (and thus the sensitive depth) is reduced, the proton cutoff moves to lower energy, revealing the low-energy portion of the alpha continuum. An alpha cutoff appears at 200 V; it, too, moves down with decreasing bias.

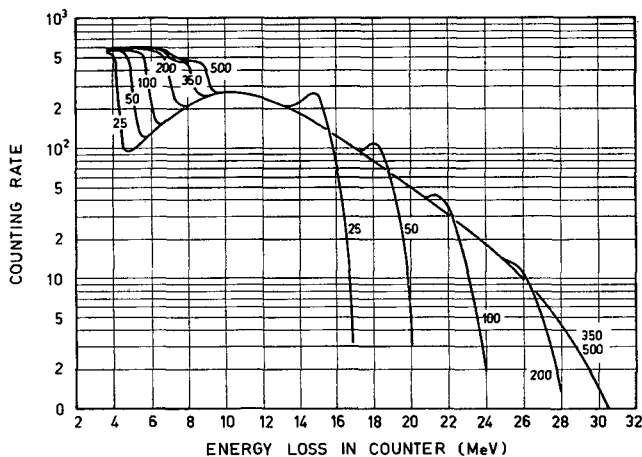


Fig. 2

Spectra of alpha particles and protons from N^{14} bombardments of oxygen at 28 MeV. The bias voltage at which each curve was obtained is given by the numbers on the graph. The original data showed some structure which was suppressed for clarity in this Figure

Fig. 3 was constructed from the data of Fig. 2 by using range-energy data [3] for protons and alphas in aluminium and multiplying the aluminium ranges by 1.03 to convert to silicon. The good fit with the line of slope $\frac{1}{2}$ shows that the sensitive depth of the counter does follow the Schottky theory. A correction for diffusion into the barrier of carriers produced below the barrier ought to be made; from earlier data [1] this diffusion length should be approximately 0.02 mm, which mainly affects the somewhat inaccurate low-bias data, but does not change the overall agreement with the Schottky theory. The resistivity calculated from these data ($\sim 2600 \Omega\text{-cm}$) agrees satisfactorily with that from capacity measurements on the same counter ($\sim 2300 \Omega\text{-cm}$).

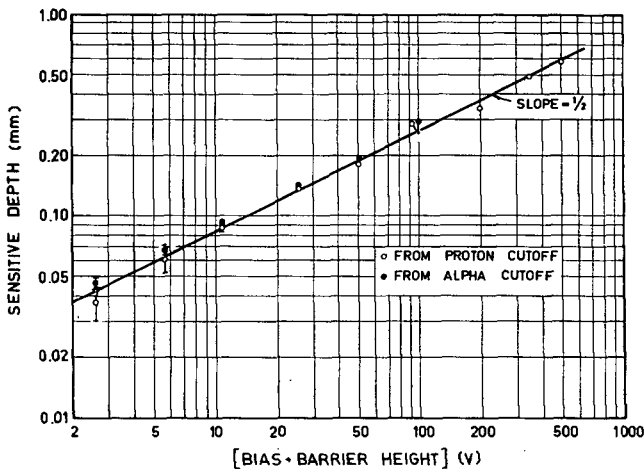


Fig. 3

Sensitive depth from the data of Fig. 2 as a function of bias; the barrier height was assumed to be 0.6 V

V. Deep barriers

The achievement of surface barriers extending deep into the body of the silicon (at least 0.5 mm) was the goal of much development work at Oak Ridge. Even with material of the highest available resistivity, a bias of several hundred volts is required; it is unusual for a diode to operate at such high bias without generating excessive noise. Nevertheless, some selected counters have performed very well at 500 V; these have been used in several recent experiments to measure energy spectra and angular distributions of alphas from N^{14} -induced reactions.

An example of a spectrum obtained recently with one of these counters is shown in Fig. 4. The width of the peaks was determined primarily by the groupings of close-lying states in the residual nucleus, by the target thickness, and by the spread of energy in the incident beam. The resolution of this counter at 500 V for natural alpha particles was excellent (~ 20 keV full width at half maximum). With thinner targets and sharper definition of the beam energy, isolation of individual nuclear states would be possible and the properties of the states could be studied without the usual slow and expensive magnetic analysis.

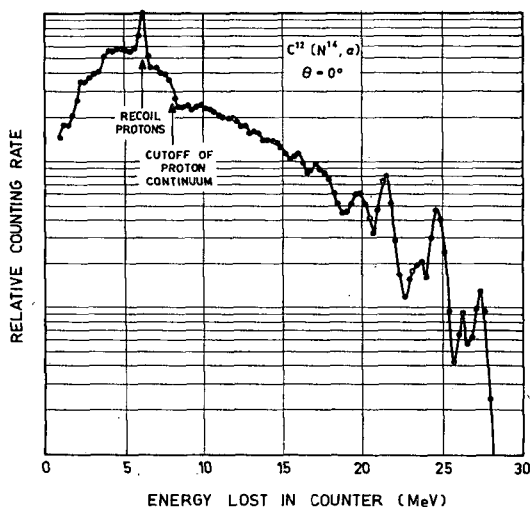


Fig. 4

Spectra of alpha particles and protons at zero degrees, from N^{14} bombardment of carbon at 28 MeV. A thin nickel absorber on the target stopped the N^{14} beam. The proton recoil peak arises from collisions of the N^{14} with hydrogen atoms present as an impurity in the target

Although it now appears that the future for very deep barriers lies with the Li-drifted diodes [4], some comments should be made on the behaviour of surface-barrier diodes in vacuum at high bias. Of twelve high-resistivity ($\sim 1500 \Omega\text{-cm}$) diodes tested, only two (each of 16-mm^2 area) accepted 500-V bias without perceptible generation of noise. One of these was taken up to 700 V with no ill effects. Both probably could have gone higher, but since these diodes were valuable for experiments in nuclear physics they were not tested at voltages beyond those needed in such experiments for fear of ruining them. The reverse current at 500 V was about $0.5 \mu\text{A}$ for one and $0.1 \mu\text{A}$ for the other. It varied somewhat from day to day; for a time it was less than $0.05 \mu\text{A}$ in one diode. This corresponds to a back resistance greater than $10^{10} \Omega$.

Most of the other counters functioned in vacuum according to the following pattern. The noise and reverse current would increase as the bias was raised until at some point between 50 and 300 V the noise was about 5 or 10 times greater than the preamplifier noise level. With the bias held at this level, a marked decrease in both noise level and reverse current would usually be noted within the first few minutes, after which the decrease became progressively slower. Raising the bias would then repeat the cycle. Leaving such a counter several hours (or even days) in vacuum without bias did not reduce the noise level. With some diodes this step-wise increase of bias could be continued until eventually operation at 500-V bias was possible with imperceptible generation of noise. One such counter was taken to 1000 V with no difficulty; however, others remained noisy above about 200 V no matter how cautiously the bias was increased. After each exposure to air a similar gradual increase of bias was required, although usually less time was required.

VI. Radiation damage

A 1500- Ω -cm counter 0.2 cm² in area was inadvertently exposed to N¹⁴ ions at about 4 MeV; the dose rate was $\sim 10^4$ /s. Increases of both the noise level and the reverse current occurred over a period of several hours, as shown in Table I. The dose estimates are believed accurate within a factor of three.

TABLE I

HISTORY OF A 1500 Ω -cm SURFACE-BARRIER DIODE EXPOSED TO AN INTENSE FLUX OF N¹⁴ ions. THE REVERSE CURRENTS QUOTED ARE THOSE AT 500-V BIAS

The letters A through D refer to entries in Table II

Energy Deposited ($\times 10^9$ MeV/cm ²)	Equivalent number of 4-MeV particles ($\times 10^9$ /cm ²)	Reverse Current (μ A)	Over-all Relative Noise Level (Amplifier noise = 1.0)
0.0	0.0	0.9	1.0 A
0.7	0.2	2.0	1.2
4.0	1.0	5.0	1.4
8.0	2.0	6.8	2.1
11.0	2.8	8.2	2.4
(Here the counter was left in vacuum 10 h with zero bias)			
11.0	2.8	6.6	2.0 B
(Here the counter was left in air 10 h with zero bias)			
11.0	2.8	5.5	2.0 C
13.0	3.3	8.5	—
15.0	3.8	8.7	2.2
16.0	4.0	9.7	—
17.0	4.3	10.0	40.0
18.0	4.5	17.0	—
19.0	4.8	19.5	100.0
(Here the counter was left in vacuum 12 h with zero bias)			
19.0	4.8	14.5	30.0 D

The deterioration in counter performance may have been due to radiation damage by the N¹⁴ ions. Their depth of penetration into the silicon was about 0.004 mm. In a layer of this thickness the surface density of impurities in the original silicon was about 1.4×10^9 /cm². If it is assumed that radiation damage began to show itself when the density of radiation-induced defects became comparable with the original impurity concentration, each N¹⁴ ion would be responsible for about one such defect.

The current-voltage relation for this counter at the four periods indicated in Table I as A, B, C, and D are presented in Table II. No correction was made for the iR drop in a 2-M Ω series resistor.

TABLE II

CURRENT-VOLTAGE RELATIONS FOR THE DIODE OF TABLE I AT FOUR DIFFERENT PERIODS DURING ITS EXPOSURE TO AN INTENSE FLUX OF N^{14} ions

The letters A through D identify these periods according to the radiation history outlined in Table I

Reverse bias (V)	Reverse Current (μA)			
	A	B	C	D
0.1	0.0	0.8	—	—
5.0	—	—	—	1.5
10.0	—	4.5	—	4.0
20.0	—	—	3.9	7.5
50.0	—	5.2	4.2	8.1
60.0	0.2	—	—	8.2
100.0	—	5.5	4.4	8.7
120.0	0.3	—	—	—
150.0	—	5.7	4.6	9.5
200.0	0.4	5.9	4.7	10.0
250.0	—	—	4.9	10.7
300.0	0.5	6.1	5.0	11.7
350.0	—	6.3	—	13.0
400.0	0.6	6.3	5.2	14.1
500.0	0.8	6.6	5.5	14.5

VII. Particle-identifying counter systems

Two different systems using the surface-barrier counter as one element in a dE/dx , E telescope were developed for identifying nuclear particles. In one, a wafer of high-resistivity silicon, either 0.08 or 0.2 mm thick, replaces the gas proportional counter formerly employed as the dE/dx element for distinguishing protons, deuterons, and tritons. The wafer is supported at its periphery with a ceramic ring, as mentioned in Section II. It is operated with a barrier depth slightly less than the wafer thickness because the reverse current and noise level increase sharply when the bias is raised high enough to extend the depletion layer through to the back surface. A conventional NaI(Tl) scintillation counter is retained as the E element. This new system provides a cleaner separation of the particles and is more stable, more convenient, and more tolerant of high counting rates. The replacement of the scintillation counter by a solid-state device will undoubtedly be undertaken when such devices are available to stop medium-energy protons within their sensitive volume.

For distinguishing various types of heavy ions at about 2 MeV/nucleon, counter systems like that diagrammed in Fig. 5 have been quite satisfactory. The dE/dx element, in which the heavy ions give up about 2 MeV, is a gas proportional counter with a 0.6 mg/cm² Ni entrance window. A solid-state device would, of course, be preferable but the practical difficulties of making a counter sufficiently thin (~ 0.002 mm) are formidable. The wire is 0.001-in diameter stainless steel. Argon with 3% CO₂ flows through the counter at about 1 cm³/min. Normally the gas pressure is 6 cm Hg and

the wire potential is 420 V. The E element is a surface-barrier counter of 250 Ω -cm material operated with the front grounded and a bias of 3 V applied to the back. Although the silicon counter is effectively inside the gas counter, both counters work well and no interaction between them has been noted.

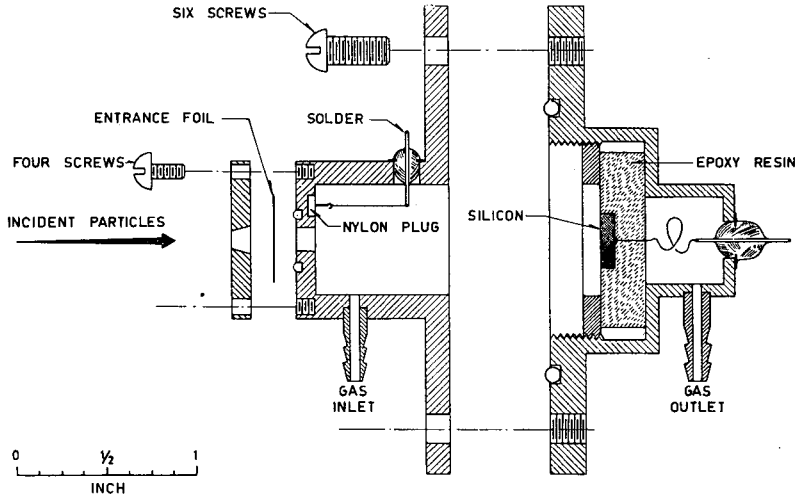


Fig. 5

Particle-identifying counter for heavy ions. The original design is diagrammed; an improved model is now in use with a longer wire and with other changes which minimize the dead spaces in the gas

An example of the separation of heavy ions achieved with such a system is given in Fig. 6. For this test a target containing boron, carbon, and oxygen was bombarded with 28-MeV N^{14} ions. Fig. 6 is a time-exposure photograph of an oscilloscope face registering many individual traces. The proportional-counter pulses were applied to the vertical amplifier and the silicon-counter pulses to the horizontal amplifier. The trace was brightened for a short time when each pulse was at its maximum; thus each dot represents one particle.

Each line in Fig. 6 represents ions of one particular Z . The prominent cluster of dots (much over-exposed on this photograph) is due to N^{14} elastically scattered by the different elements in the target. The line directly below is due to carbon ions; two boron dots may be seen below it. Groups due to oxygen, fluorine, neon, and sodium are above the nitrogen. In tests with a carbon target, carbon, nitrogen, sodium, magnesium, and aluminium ions were successfully distinguished.

Distinguishing isotopes of a given element at these energies is unfortunately impossible with any method based on dE/dx because the range-energy relation for slow-moving heavy ions of a given nuclear charge is practically independent of particle mass.

ACKNOWLEDGEMENTS

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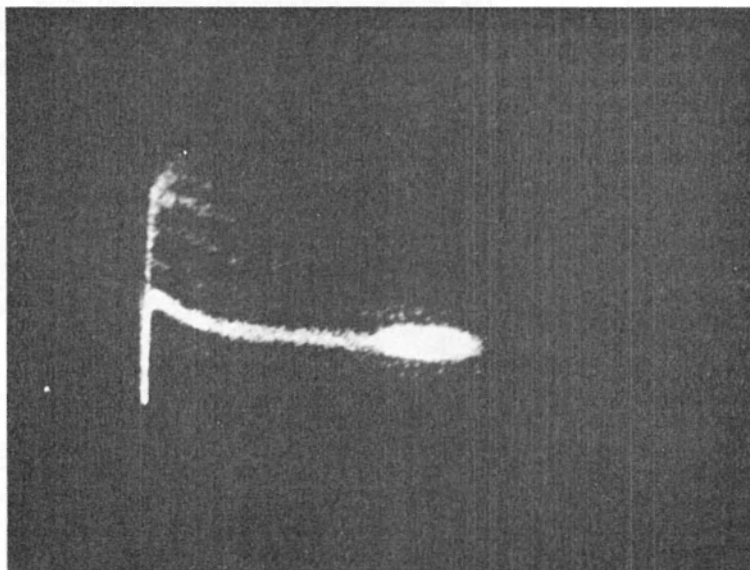


Fig. 6

Example of separation of heavy ions achieved with the system of Fig. 5 (improved model)

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A SILICON SURFACE-BARRIER FAST-NEUTRON SPECTROMETER

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Abstract — Résumé — Аннотация — Resumen

A silicon surface-barrier, fast-neutron spectrometer. A new type neutron spectrometer has been constructed by depositing a thin layer of Li^6F between two silicon surface-barrier counters. The small size and low mass (approximately 10 g total), the relative insensitivity to gamma rays, and the simplicity of construction and operation are the principle advantages of the device. Neutrons are detected by simultaneously observing the alpha particle and triton from the $\text{Li}^6(n, \alpha)\text{T}$ reaction. The sum of the energies of these two particles is proportional to the energy of the incoming neutron plus the 4.78 MeV Q of the reaction. Pulses from the two counters are added and the sum pulse which should be proportional to the total energy absorbed by both counters is amplified and stored. The experiments described below demonstrate that the pulse height is indeed a linear function of the neutron energy. Pulse-height spectra from slow neutrons and from mono-energetic neutrons in the energy region, 0.6 to 15 MeV, have been recorded from several counters of this type using sensitive areas of 0.7 cm^2 with a Li^6F layer about $150\text{ }\mu\text{g/cm}^2$ thick. In further performance tests the groups of mono-energetic neutrons from the $\text{Be}^9(\alpha, n)\text{C}^{12}$, $\text{Be}^9(d, n)\text{B}^{10}$ and $\text{C}^{12}(d, n)\text{N}^{13}$ reactions were largely resolved. The resolution is limited by charged-particle energy losses in the LiF layer, giving a full width at half maximum of about 300 keV for the fast neutron peaks, approximately independent of neutron energy. Coincidence circuitry was used to eliminate the background from gamma rays and to considerably reduce the serious background for the silicon (n , charged particle) reactions. However, even with the coincidence circuitry this background reduces the fraction of the pulse-height spectrum which appears in the peak from 90% for 5-MeV neutrons to 1% for 8 MeV and to 0.1% for 15 MeV. The present counters have an efficiency (limited by the thickness of the $150\text{ }\mu\text{g/cm}^2$ Li^6F layer) of 3×10^{-3} for thermal neutrons and $\sim 10^{-6}$ for 2-MeV neutrons.

Spectromètre à barrière de surface au silicium pour neutrons rapides. Les auteurs ont construit ce nouveau type de spectromètre pour neutrons en faisant déposer une couche mince de ^6LiF entre deux compteurs à barrière de surface au silicium. Les principaux avantages de ce système sont les suivants: dimensions réduites, faible masse (environ 10 g au total), insensibilité aux rayons gamma relative et simplicité de construction et de fonctionnement. On détecte les neutrons en observant simultanément des particules alpha et des tritons provenant de la réaction $^6\text{Li}(n, \alpha)\text{T}$. La somme des énergies de ces deux particules est proportionnelle à la somme de l'énergie du neutron incident et de l'énergie de la réaction $Q = 4,78\text{ MeV}$. On additionne les impulsions des deux compteurs et la somme obtenue, qui doit être proportionnelle à l'énergie totale absorbée par les deux compteurs, est amplifiée et emmagasinée. Les expériences décrites montrent que l'amplitude d'impulsion est en réalité une fonction linéaire de l'énergie du neutron incident. Les auteurs ont enregistré dans plusieurs compteurs de ce type les spectres d'amplitude d'impulsion de neutrons lents et des neutrons monoénergétiques, dans une gamme d'énergie allant de 0,6 à 15 MeV, dans des zones sensibles de $0,7\text{ cm}^2$, à l'aide d'une couche de ^6LiF de $150\text{ }\mu\text{g/cm}^2$ d'épaisseur. Au cours d'autres essais pour l'étude du comportement de l'appareil, les groupes de neutrons monoénergétiques provenant des réactions $^9\text{Be}(\alpha, n)^{12}\text{C}$, $^9\text{Be}(d, n)^{10}\text{B}$ et $^{12}\text{C}(d, n)^{13}\text{N}$ ont pu être séparés. Cette séparation est limitée par les pertes d'énergie des particules chargées dans la couche LiF et donne une largeur totale d'environ 300 keV à 50% du maximum pour les pics d'impulsion de neutrons rapides, et ceci presque indépendamment de l'énergie des neutrons. Des circuits de coïncidence ont été utilisés pour éliminer le bruit de fond des rayons gamma et diminuer dans une large mesure celui qui se produit pour les réactions du silicium

(n , particule chargée). Cependant, même avec le circuit de coïncidence, ce bruit parasite réduit le pic du spectre d'amplitude d'impulsion de 90% pour les neutrons de 5 MeV à 1% pour ceux de 8 MeV et 0,5% pour ceux de 15 MeV. Les compteurs actuels ont une efficacité (limitée par les $150 \mu\text{g}/\text{cm}^2$ d'épaisseur de la couche ^6LiF) de $3 \cdot 10^{-3}$ pour les neutrons thermiques et d'environ 10^{-6} pour les neutrons d'une énergie de 2 MeV.

Кремниевый поверхностно-барьерный спектрометр для быстрых нейтронов. Новый тип нейтронного спектрометра был сооружен путем помещения тонкого слоя Li^6F между двумя кремниевыми поверхностно-барьерными счетчиками. Главными преимуществами этого прибора являются небольшой размер и малая масса (всего около 10 грамм), относительная нечувствительность к гамма-лучам и простота сооружения и эксплуатации. Нейтроны обнаруживаются путем одновременного наблюдения альфа-частицы и тритона от реакции $\text{Li}^6(n, \alpha)\text{T}$. Сумма энергий этих двух частиц пропорциональна энергии входящего нейтрона плюс 4,78 мэв Q реакции. Добавляются импульсы от двух счетчиков и суммарный импульс, который должен быть пропорционален всей энергии, поглощенной обоими счетчиками, усиливается и сохраняется. Нижеописанные опыты показывают, что амплитуда импульса является действительно линейной функцией нейтронной энергии. Спектры амплитуды импульса от медленных нейтронов и от моноэнергетических нейтронов в области энергий от 0,6 до 15 мэв были записаны с нескольких счетчиков этого типа с использованием зон чувствительности в $0,7 \text{ cm}^2$ со слоем Li^6F около $150 \text{ мкг}/\text{cm}^2$ толщиной. В дальнейших опытах были в значительной степени разрешены группы моноэнергетических нейтронов от реакций $\text{Be}^9(\alpha, n)\text{C}^{12}$, $\text{Be}^9(d, n)\text{B}^{10}$ и $\text{C}^{12}(d, n)\text{N}^{13}$. Разрешение ограничивается потерей энергии заряженными частицами в слое LiF , давая полную ширину при полумаксимуме около 300 кэв для пиков быстрых нейтронов приблизительно независимо от нейтронной энергии. Была использована схема совпадений для уничтожения фона от гамма-лучей и для значительного уменьшения фона для кремниевых (n , заряженная частица) реакций. Однако, даже со схемой совпадений этот фон сокращает часть спектра амплитуды импульса, которая появляется при пике от 90% для нейтронов 5 мэв, до 1% для 8 мэв и до 0,1% для 15 мэв. Существующие счетчики обладают эффективностью (ограниченной толщиной в $150 \text{ мкг}/\text{cm}^2$ слоя Li^6F) в $3 \cdot 10^{-3}$ для термических нейтронов и приблизительно 10^{-6} для нейтронов в 2 мэв.

Espectrómetro de silicio de barrera superficial para neutrones rápidos. Depositando una delgada capa de ^6LiF entre dos contadores de silicio de barrera superficial, los autores han construido un nuevo tipo de espectrómetro para neutrones. Las principales ventajas de este aparato son sus reducidas dimensiones, su pequeño peso (aproximadamente 10 gramos en total), su relativa insensibilidad al efecto de los rayos γ y la sencillez de su construcción y manejo. Los neutrones se detectan por la observación simultánea de la partícula α y del tritón provenientes de una reacción $^6\text{Li}(n, \alpha)\text{T}$. La suma de las energías de estas dos partículas es proporcional a la energía del neutrón incidente, más los 4,78 MeV que corresponden a la Q de reacción. Se suman los impulsos de los dos contadores y se amplifica y almacena el impulso resultante, que deberá ser proporcional a la energía total absorbida por ambos contadores. Los experimentos que se describen más adelante demuestran que la amplitud del impulso es efectivamente función lineal de la energía neutrónica. Con varios contadores de este tipo, usando superficies sensibles de $0,7 \text{ cm}^2$ con una capa de ^6LiF de un espesor de $150 \mu\text{g}/\text{cm}^2$ aproximadamente, se han registrado espectros de amplitud de impulso de neutrones lentos y de neutrones monoenergéticos dentro de la zona de energía de 0,6 a 15 MeV. En otros ensayos fue posible separar satisfactoriamente los neutrones monoenergéticos provenientes de las reacciones $^9\text{Be}(\alpha, n)^{12}\text{C}$, $^9\text{Be}(d, n)^{10}\text{B}$, y $^{12}\text{C}(d, n)^{13}\text{N}$. El poder de resolución queda limitado por las pérdidas de energía de la partícula cargada en la capa de LiF , resultando una anchura a la mitad del máximo, de alrededor de 300 keV para los picos de neutrones rápidos, siendo dicho valor casi independiente de la energía del neutrón. Se utilizaron circuitos de coincidencia para eliminar el fondo debido a los rayos γ y para reducir considerablemente el intenso fondo correspondiente a las reacciones del silicio (n , partícula cargada). Sin embargo, aun con circuitos de coincidencia, el fondo citado reduce la fracción del espectro de amplitud que aparece en el pico, desde el 90%, para los neutrones

de 5 MeV, hasta el 1% para los neutrones de 8 MeV y el 0,1% para los de 15 MeV. El rendimiento de los contadores que se construyen actualmente (que queda limitado por el espesor de $150 \mu\text{g}/\text{cm}^2$ de la capa de ^6LiF) es de $3 \cdot 10^{-3}$ para los neutrones térmicos y aproximadamente 10^{-6} para los neutrones de 2 MeV.

I. Introduction

This paper describes recent experiments for the development of a semiconductor counter which may be suitable for certain types of fast neutron spectral measurements where time-of-flight techniques are not feasible. A neutron-sensitive semiconductor detector has been constructed by vacuum evaporating a thin layer of Li^6F between two silicon-gold surface-barrier counters. Neutrons are detected by observing the $\alpha + \text{T}$ pair resulting from the $\text{Li}^6(\text{n}, \alpha)\text{T}$ reaction; pulses from the two counters are added and the sum pulse is amplified and recorded on a multichannel analyser. Since the sandwich arrangement permits the simultaneous detection of both reaction products, the magnitude of the resulting sum pulse should be proportional to the energy of the incident neutron plus the reaction Q value (4.78 MeV).

Silicon-gold surface-barrier counters have been used as alpha-particle spectrometers with extremely good energy resolution; for example, within 0.25% for collimated alpha particles with energy of about 5 MeV [1]. The pulse-height distribution to be expected from mono-energetic neutrons on a sandwich detector of the type described here will exhibit a much broader peak, since the $\alpha + \text{T}$ reaction products are subject to energy loss in the Li^6F and gold layers before reaching the sensitive volume of silicon. The energy loss in a particular event depends on the angle at which the reaction products are emitted; since the α and T may be emitted at any angle, the energy loss is a variable from some minimum value up to the total energy available [2]. In a practical counter, with a Li^6F layer of given thickness, this variable energy loss will govern the width of a mono-energetic neutron peak, with a much smaller contribution from the inherent line width of the silicon counter. The average energy loss in the Li^6F and gold described here is approximately 180 keV and therefore pulse height vs. energy curves will show the neutron energy plus 4.6 MeV rather than neutron energy plus the 4.78-MeV reaction Q value.

The results presented here summarize principally the construction of these devices, the development of the electronic system and the results of some experiments with mono-energetic neutrons.

II. Counter construction

The general method of construction of silicon-gold surface-barrier counters has been described elsewhere [1]. The counters used in this work differ principally in that the silicon was mounted in fluorothene sheets. A schematic diagram of the sandwich counter is shown in Fig. 1. The device consists essentially of two silicon counters seated in thin fluorothene sheets and spaced by a 0.002-in ring of fluorothene. A layer of Li^6F of nominal thickness $150 \mu\text{g}/\text{cm}^2$ is vacuum-evaporated on to one of the counters before assembly. A small wire is used to make an electrical contact to the gold surface. The wire is cemented to the gold with a tiny drop of aquadag and is then grounded. A reverse bias of 100 V is applied through a resistor of $\sim 500000 \Omega$ and the signal is fed through a coupling capacitor to a low-noise, high-gain preamplifier.

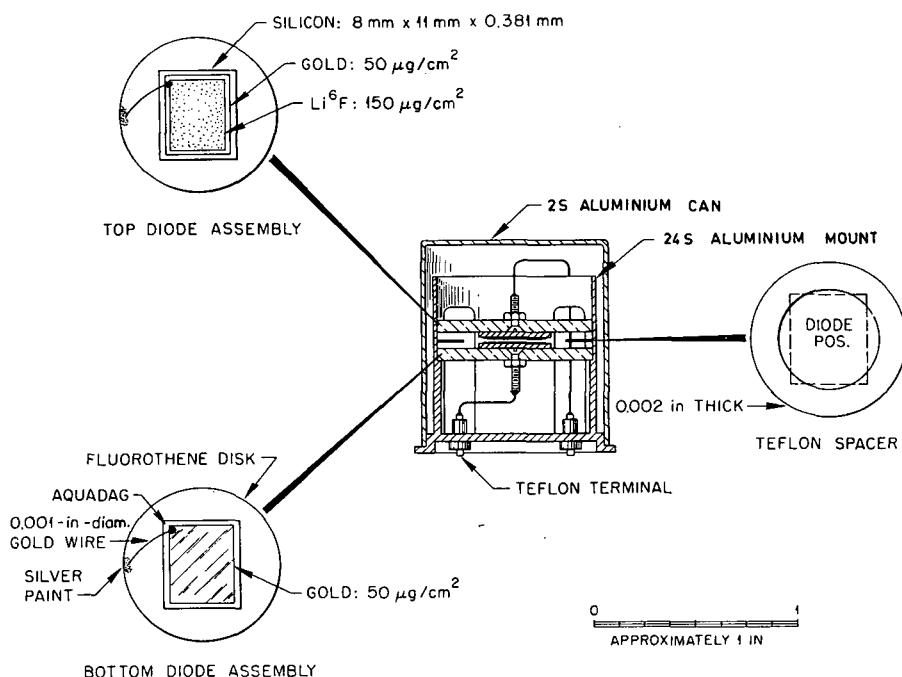


Fig. 1
Schematic diagram of sandwich counter

III. Counting system

A block diagram of the electronics is shown in Fig. 2. The signal from each detector is fed into a pre-amplifier which in turn feeds a DD-2 double delay-line amplifier with a 0.7- μs clipping time. The output of the amplifier is fed into a discriminator circuit biased to reject all pulses which represent less than 1.5 MeV energy deposited in the diode. The response from a single detector (with no discrimination) exposed to thermal neutrons is shown in Fig. 3. The triton and alpha peak are clearly defined. Counts at lower energies arise from those reaction products which have lost several hundred kilo-electron-volt energy and from gamma rays. Only about 5% of the pulses from the reaction products fall below the 1.5-MeV point on this curve. Also, if all pulses below 1.5 MeV are thrown out essentially all gamma-ray background is rejected. A gamma-ray background with the discriminator set at 1.5 MeV has the same effect as noise; i.e., the peak from mono-energetic neutrons will be broadened. Referring to the block diagram, the coincidence circuit requires that the pulses occur within 10^{-7} s of each other. The output of this circuit is used to gate the multi-channel analyser. With this circuit, $\text{Li}^6(\text{n}, \alpha)\text{T}$ events in which the alpha particle and triton deposit at least 1.5 MeV in separate counters are recorded but those events (largely due to background) that deposit less than this amount in either counter are eliminated. As shown in Fig. 3, only about 5% of the $\text{Li}^6(\text{n}, \alpha)\text{T}$ events are eliminated for incident thermal neutrons. The number of events eliminated will be much higher, perhaps as much as

30% for 10 to 15-MeV incident neutrons due to forward-peaking of the reaction products.

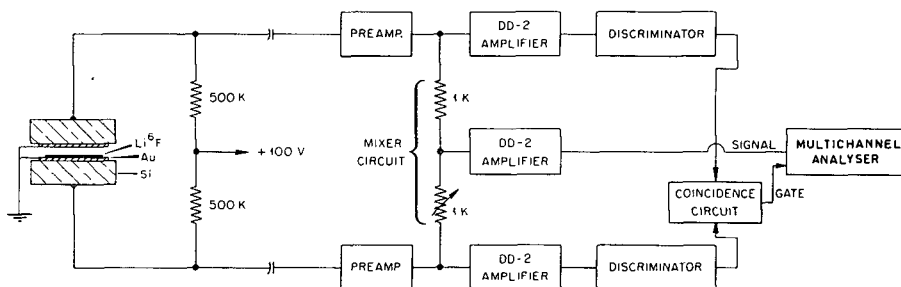


Fig. 2
Block diagram of the electronics

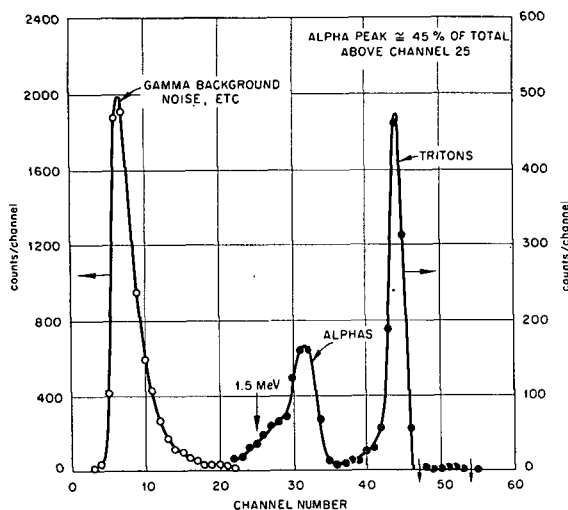


Fig. 3
Response of single detector exposed to thermal neutrons (with no discrimination)

Figs. 4a and 4b show the pulse-height response to the 2.95-MeV neutrons from the $D(d, n)He^3$ reaction with and without the coincidence circuit. The background in Fig. 4a is attributed to events resulting from 14.7-MeV neutrons that arise from the $T(d, n)He^4$ reaction, which is due to a small amount of tritium present in the beam tube and on the target of the Cockcroft-Walton.

The output of the pre-amplifiers is also fed into a mixer circuit. The output of the mixer circuit is amplified by a third DD-2 amplifier whose output is recorded in the multi-channel analyser. The input of each pre-amplifier also has a provision for accepting

a pulse from a multi-channel pulse generator. This arrangement allows each amplifier to be checked separately for linearity and the analyser to be checked for both linearity and zero position. The pulse generator also allows a secondary check for stability.

IV. Experimental pulse-height spectrum and discussion

Pulse-height spectra have been recorded for neutrons of known energy produced by the $T(p, n)He^3$ reaction, the $D(d, n)He^3$ reaction, the $T(d, n)He^4$ reaction and the $Be^9(d, n)B^{10}$ reaction. Slow neutrons were obtained by moderating fast neutrons by blocks of paraffin. The response of the counter to slow neutrons is shown in Fig. 5. This data was recorded without the coincidence circuit. The full width at half maximum is about 300 keV. The average energy loss of the charged particles in the Li^6F and the gold indicates that the slow-neutron peak should occur at a pulse height corresponding to 4.6 MeV (rather than the Q value of 4.78 MeV).

Background effects from $(n, \text{charged})$ particle reactions appeared at all neutron energies above the threshold energy for such reactions in silicon. Pulses from these charged particles were recorded only in the neutron pulse-height spectrum for incident neutrons above about 5 MeV since the reactions are endothermic. In order to determine the background, a pair of silicon diodes without Li^6F was constructed. Pulse-height spectra were taken for diodes with and without Li^6F for mono-energetic neutrons

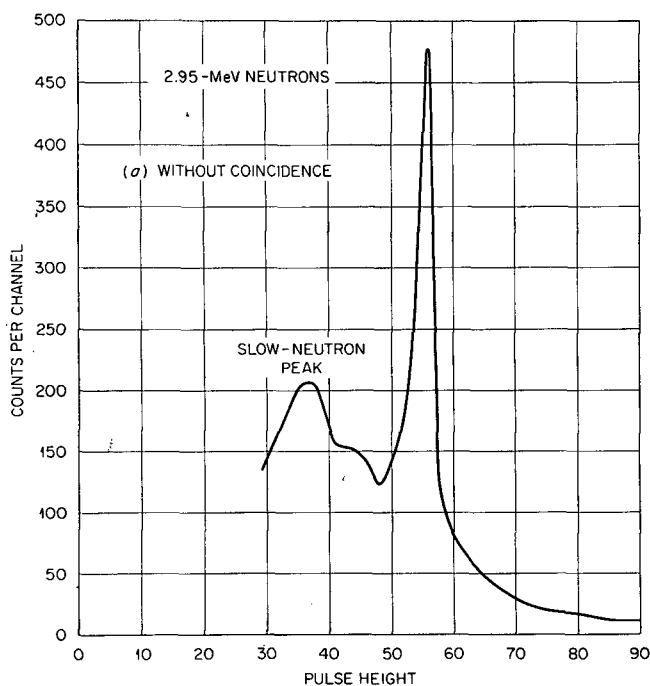


Fig. 4a
Response to neutrons from $D(d, n)He^3$

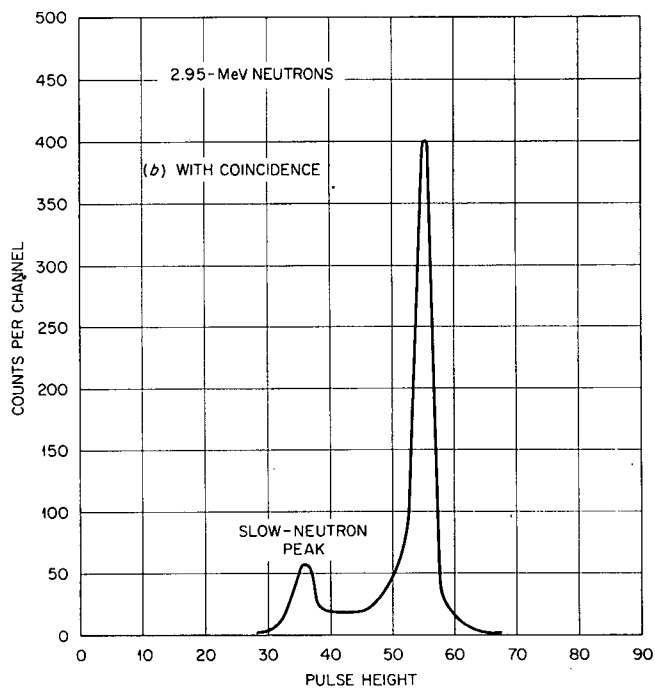


Fig. 4b
Response to neutrons from $D(d, n) He^3$

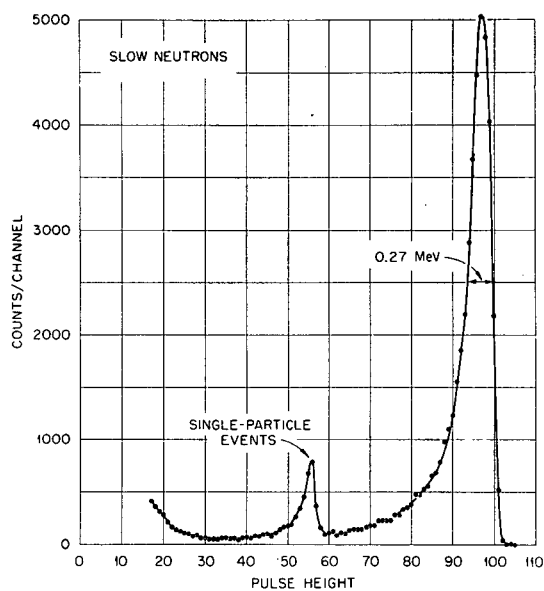


Fig. 5
Pulse-height spectrum from slow neutrons

at several energies. Later modifications now allow gains to be adjusted more accurately, for matching both sets of diodes by use of a pulse generator.

In Fig. 6 two curves are shown for neutrons of energy 5.73 MeV from the $D(d, n)He^3$ reaction incident on a counter with Li^6F and a counter with no Li^6F . The peak at the pulse height representing 2.19-MeV neutrons appears because of carbon contamination of the target and come from the $C^{12}(d, n)N^{13}$ reaction. Fig. 7 shows the response of the counters with and without the Li^6F for neutrons of 8.13 MeV energy and Fig. 8 is the response to 14.7 MeV-neutrons.

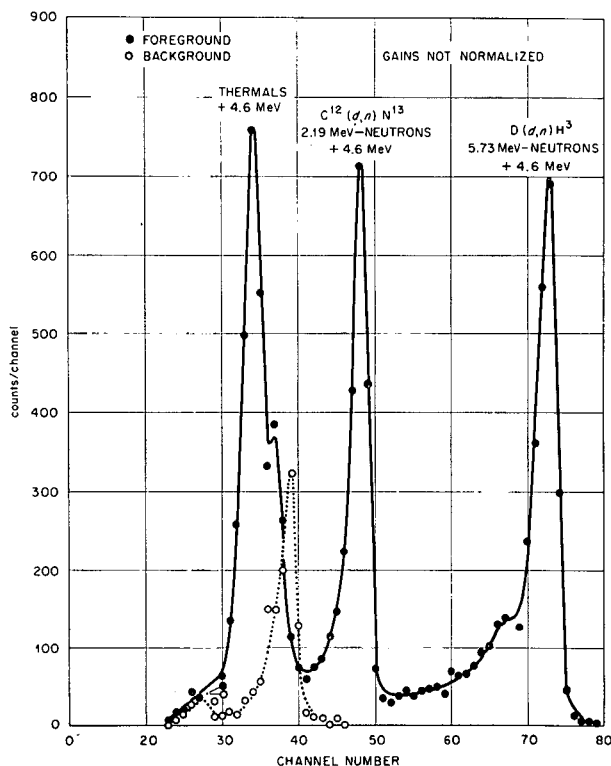


Fig. 6
Pulse-height response for 5.73-MeV neutrons

The response to groups of neutrons from the $Be^9(d, n)B^{10}$ reaction for a deuteron energy of 1.85 MeV is shown in Fig. 9. The numbers in parentheses are reported values for neutrons from this reaction. The observed pulse-height spectra have not been corrected for the efficiency.

The data in Fig. 10 demonstrates the linearity of the device over the range (0—14.7 MeV) examined. During the data accumulation represented in Figs. 3, 4a, 4b and 5, the counter was enclosed in thin aluminium. For the data shown in Figs. 6, 7, 8, and 9 the counter was enclosed in a 0.040-in Cd can.

The background data from mono-energetic neutrons of energies of 4.62 MeV, 5.73 MeV, 7.40 MeV, 8.13 MeV, 13.7 MeV and 14.7 MeV were recorded. Using this basic data, a rough calculation was made to estimate the background from fission neutrons. These calculations predict a foreground-to-background ratio of about 5 to 1 for the fission spectrum.

A preliminary experiment was performed to get an estimate of the foreground and background, as measured by these counters, from the neutrons escaping from a light-water-moderated, unshielded reactor. The background was found to be $\sim 20\%$ of the foreground in agreement with the above calculations.

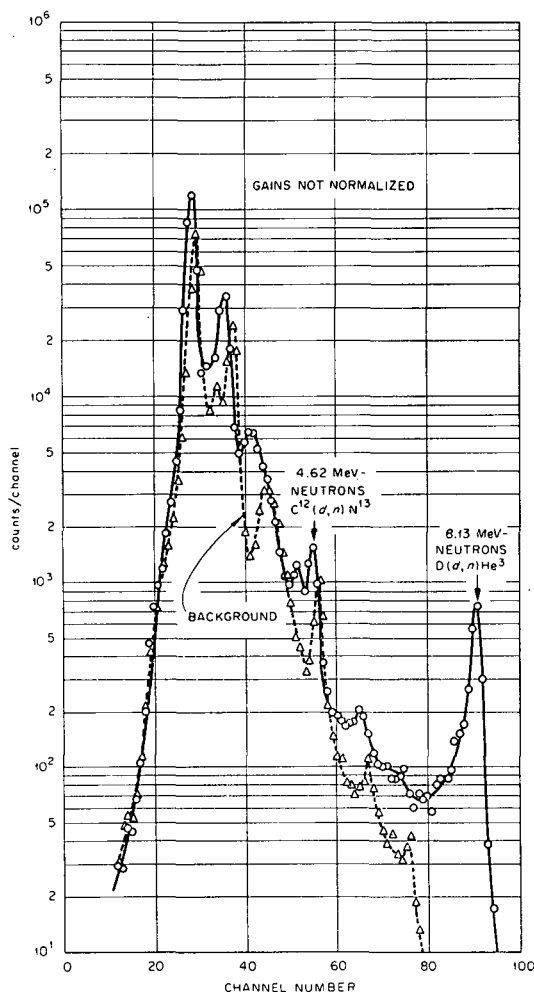


Fig. 7
Pulse-height response for 8.13-MeV neutrons

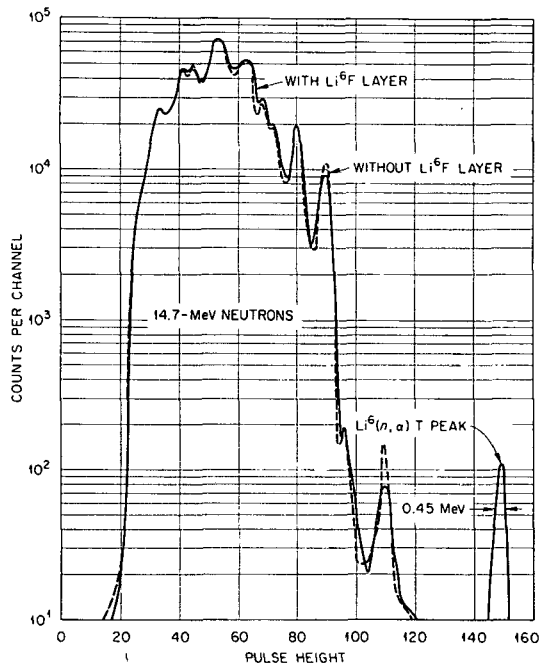


Fig. 8
Response to neutrons from $\text{T}(d, n) \text{He}^4$

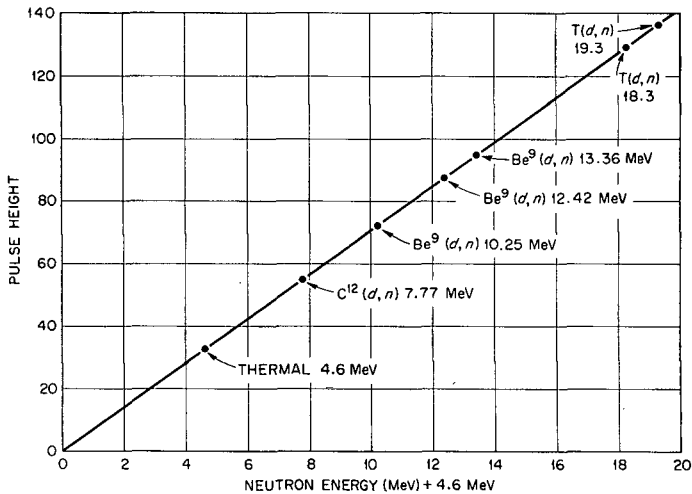


Fig. 10
Pulse-height as a function of neutron energy plus 4.6 MeV

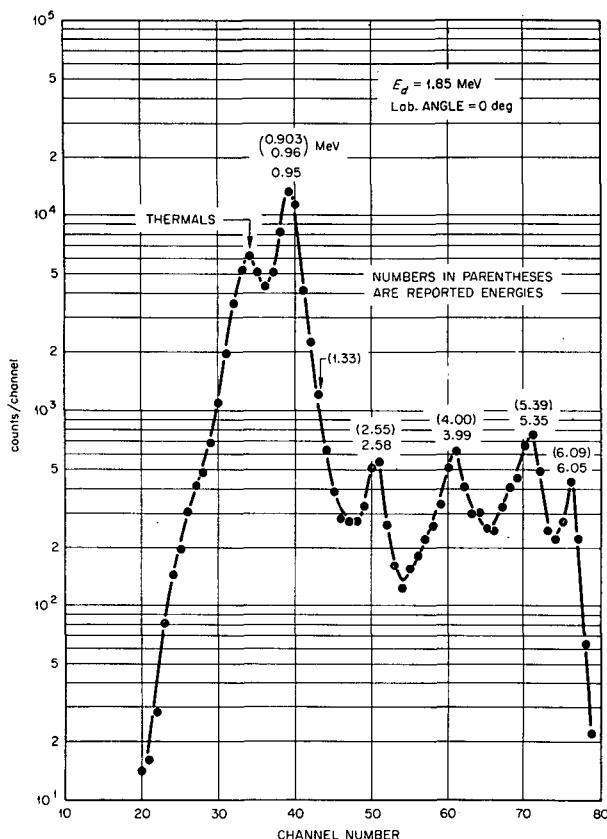


Fig. 9

Pulse-height response to neutrons from $\text{Be}^9(d, n)\text{B}^{10}$

V. Conclusion

The experiments described here indicate the possible application of neutron detectors of this type for certain problems involving the detection or spectroscopy of fast neutrons. The principle advantages appear to be its simplicity of construction and operation, its small size (the entire assembly weighs ~ 10 g), its relative insensitivity to gamma rays and a reasonably good resolution for neutrons of energy above 1 MeV. A further advantage is the ability of the counter to accept neutrons from any direction, thereby eliminating the need for neutron collimation.

The detection efficiency is limited by the thickness of the Li^6F layer. A layer $150 \mu\text{g}/\text{cm}^2$, as used in these counters, offers an efficiency of the order of 3×10^{-3} for thermal neutrons and 1×10^{-6} for 2-MeV neutrons assuming incident neutrons normal to the Li^6F layer. These low efficiencies limit the use of such a device to problems which involve fairly high neutron intensities.

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SEMICONDUCTOR DETECTOR SYSTEMS (dE/dx AND E) FOR THE DETECTION AND MASS IDENTIFICATION OF PROTONS, DEUTERONS, TRITONS, He^3 AND ALPHA PARTICLES IN THE 10 TO 30-MeV ENERGY REGION

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Abstract — Résumé — Аннотация — Resumen

Semiconductor detector systems (dE/dx and E) for the detection and mass identification of protons, deuterons, tritons, He^3 and alpha particles in the 10 to 30-MeV energy region. In the 10 to 30-MeV region of energy many different reactions can occur in a charged-particle scattering experiment and, without proper mass identification, complex spectra from different reactions are superimposed and in many cases impossible to analyse. A semiconductor detector system for the detection and mass separation of He^3 and alpha particles was described recently by the author. Briefly, a dE/dx p-n junction detector was constructed of a thin wafer of 6000- Ωcm p-type silicon, 0.002 in thick, with a useful area of $\sim 70\text{ mm}^2$. The E detector employed in this study was a 1-cm² silicon p-n junction. This semiconductor detector system could separate alpha from He^3 particles with intensity ratios as high as 100:1 to 1000:1 over a 10 to 25-MeV range of energies. Comparisons between the semiconductor and gas ion chamber dE/dx detectors showed that the energy resolution of the semiconductor detector was improved over the gas ion chamber in accord with the ionization efficiency of the stopping media. This system has been redesigned into a compact package more practical for experimental applications. The advantages and details of this new design will be discussed. The general method has been extended to protons, deuterons and tritons with the use of semiconductor detectors for E and gas ion chambers for dE/dx . Protons, deuterons, and tritons from reactions induced in Be^9 by 28-MeV alpha particles have been analysed with these systems and mass-separated spectra of each of the above particles will be shown. Although many of the particles were energetic enough to penetrate completely through the E detector (i.e., $> 10\text{-MeV}$ protons) the system was still able to separate the three masses effectively. An experimental lithium-diffused p-n junction with a $\sim 2\text{-mm}$ thick space-charge region detected 15-MeV protons, 17-MeV deuterons, and 15-MeV tritons with $\sim 1\%$ energy resolution and excellent mass separation. The advantages of these systems when applied to low-energy nuclear physics, such as increased resolution, improved mass identification, fast rise-time, and small size, will be discussed and demonstrated by comparison with NaI scintillation systems.

Semi-conducteurs pour la mesure dE/dx et E et l'identification des protons, des deutérons, des tritons, des ions ^3He et des particules alpha dans l'intervalle d'énergie compris entre 10 et 30 MeV. Dans l'intervalle d'énergie compris entre 10 et 30 MeV, de nombreuses réactions différentes peuvent se produire lors d'une expérience de diffusion de particules chargées; en l'absence d'une identification convenable, des spectres complexes provenant de réactions diverses se superposent et, dans beaucoup de cas, il est impossible de les analyser. L'auteur a décrit un système détecteur à semi-conducteur pour la détection et la séparation de masse des ions ^3He et des particules alpha en d'autres occasions. En bref, il a construit un détecteur dE/dx à jonction p-n à partir d'une mince pastille de silicium type p de 6000 $\Omega\text{-cm}$, de 0,002 pouce d'épaisseur, d'une surface utile d'environ 70 mm². Pour cette étude, il a employé un détecteur E à jonction p-n en silicium de 1 cm². Le semi-conducteur a pu séparer des particules alpha et des ions ^3He dans

des rapports d'intensités pouvant aller de 100:1 à 1000:1 dans l'intervalle d'énergie compris entre 10 et 25 MeV. Des comparaisons entre les semi-conducteurs et les détecteurs dE/dx à chambre d'ionisation à gaz ont montré que plus le pouvoir d'ionisation du milieu d'arrêt est élevé, meilleur est le pouvoir de résolution en énergie du semi-conducteur par rapport à celui de la chambre d'ionisation. Ce système a été transformé et présenté sous une forme compacte s'adaptant mieux aux applications expérimentales. Le mémoire indique les avantages et les détails de cette nouvelle présentation. La méthode générale a été étendue aux protons, aux deutérons, aux tritons et l'auteur a utilisé des semi-conducteurs pour E et des chambres d'ionisation pour dE/dx . Il a analysé à l'aide de ces systèmes les protons, les deutérons et les tritons provenant de réactions provoquées dans le ^9Be par des particules alpha de 28 MeV et il montre le spectre des masses séparées de chacune des particules ci-dessus. Etant donné leur énergie, beaucoup de particules ont traversé complètement le détecteur E (par exemple, des protons de plus de 10 MeV), mais le système a tout de même pu séparer efficacement les trois masses. Une jonction p-n expérimentale au lithium diffusé, avec une région de charge d'espace de 2 mm d'épaisseur, a détecté des protons de 15 MeV, des deutérons de 17 MeV et des tritons de 15 MeV avec une résolution d'environ 1% et une excellente séparation de masse. L'auteur étudie et montre les avantages de ces systèmes par rapport aux systèmes de scintillation NaI, lorsqu'ils sont appliqués à la physique nucléaire de faible énergie, tels que: augmentation de la résolution, meilleure identification, rapidité du temps de montée, dimensions réduites.

Полупроводниковые детекторные системы (dE/dx и E) для обнаружения и определения массы протонов, дейтронов, тритонов, He^3 и альфа-частиц в области энергий от 10 до 30 мэв. В области энергий от 10 до 30 мэв при опытах рассеяния заряженных частиц могут происходить многочисленные и разнообразные реакции, так что без надлежащего определения масс комплексные спектры различных реакций представляются в наложенном друг на друга виде, из-за чего во многих случаях нельзя провести их анализ. Автор недавно описал полупроводниковую селекторную систему для детекции и отделения массы He^3 от массы альфа-частиц. Короче говоря, из тонкой пластины кремния типа „ p “ в 6000 ом-см, толщиной в 0,002 дюйма и с полезной площадью детекции в 70 кв. мм. был создан детектор dE/dx с переходом p - n . Используемый в этом исследовании детектор для определения E состоял из кремниевого детектора в 1 кв. см. с переходом p - n . Эта система полупроводникового детектора могла отделять альфа-частицы от He^3 при соотношениях интенсивностей, доходящих до 100:1 и 1000:1 в диапазоне энергий от 10 до 25 мэв. Сравнение между полупроводниковым детектором и детектором с газовой ионизационной камерой для определения dE/dx показало, что энергетическое разрешение полупроводникового детектора улучшалось по сравнению с газовой ионизационной камерой в зависимости от ионизационной эффективности задерживающей среды. Эта система была переконструирована в более компактную форму, лучше приспособленную для экспериментальной работы. Будут обсуждены преимущества и детали этой новой конструкции. Общий метод был распространен на изучение протонов, дейтронов и тритонов с помощью полупроводниковых детекторов для определения E и газовых ионизационных камер для определения dE/dx . При помощи этих систем были проанализированы протоны, дейтроны и тритоны, образованные альфа-частицами в 28 мэв в ходе реакций в бериллии-9, и будут показаны отделенные по массе спектры каждой из этих групп частиц. Хотя многие из частиц имели достаточную энергию для полного проникновения через детектор E (т.е. протоны более 10 мэв), система все еще была в состоянии отделять друг от друга эффективным образом эти три массы. Диффундированный литием экспериментальный переход p - n с зоной пространственной зарядки толщиной около 2 мм мог обнаруживать протоны в 15 мэв, дейтроны в 17 мэв и тритоны в 15 мэв с энергетическим разрешением примерно в 1% и с хорошим разделением масс. Будут обсуждены преимущества этих систем для применения их в ядерной физике малых энергий, как, например, усиление разрешающей способности, улучшение определения массы, быстрота времени нарастания и малые размеры; эти преимущества будут продемонстрированы путем сравнения с сцинтилляционными системами, работающими с NaI.

Sistemas semiconductores (dE/dx y E) para detección e identificación de masa de protones, deuteronos, tritones, ^3He y partículas alfa, en el intervalo de energía 10 MeV—30 MeV. En el intervalo de energía 10 MeV—30 MeV pueden ocurrir muchas reacciones diferentes en un experimento de dispersión de partículas cargadas y los complicados espectros de las distintas reacciones se superponen, siendo en muchos casos imposible analizarlos si no se identifica adecuadamente la masa de las partículas. El autor ha descrito recientemente un sistema semiconductor para detección e identificación de la masa del ^3He y de las partículas alfa. En resumen, se ha construido un detector dE/dx de unión p-n utilizando una lámina soporte (0,002 pulgadas de espesor) de silicio tipo p, de $6000\ \Omega/\text{cm}$, con una superficie útil de $\sim 70\ \text{mm}^2$. El detector E empleado en dichos estudios fue un detector de unión p-n de silicio, de $1\ \text{cm}^2$. Este sistema fue capaz de distinguir entre partículas alfa y ^3He , con relaciones de intensidades de 100:1 a 1000:1 para un intervalo de energías de 10 MeV—25 MeV. La comparación entre el detector dE/dx semiconductor y el detector dE/dx de cámara de ionización gaseosa, demuestra que el poder de resolución del primero, en cuanto a la energía, es superior al del segundo, de conformidad con la eficiencia de ionización del material de frenado. Dicho sistema semiconductor se ha diseñado de nuevo, de manera que permita su construcción en unidades compactas, más adecuadas para aplicaciones experimentales. El autor examina las ventajas y particularidades del nuevo diseño. Este método general se ha aplicado también a los protones, deuteronos y tritones, empleando detectores semiconductores para E y cámaras de ionización gaseosa para dE/dx . Con este sistema se han analizado los protones, deuteronos y tritones resultantes de las reacciones inducidas en el ^9Be por partículas alfa de 28 MeV, mostrándose los espectros con identificación de masas de cada una de las mencionadas partículas. Aunque muchas de éstas poseían energía, suficiente para atravesar el detector E (por ejemplo, protones de más de 10 MeV), el sistema fue capaz de identificar eficazmente las tres masas. Con una unión experimental p-n difusa en litio y una zona de carga espacial de 2 mm de espesor, se han detectado protones de 15 MeV, deuteronos de 17 MeV y tritones de 15 MeV, con un poder de resolución de ~ 1 por ciento, en cuanto a la energía, y excelente identificación de masas. Estos sistemas presentan, para su aplicación en física de las partículas de baja energía, ventajas tales como un mayor poder de resolución, mejor identificación de masa, tiempo de elevación corto y escaso volumen. El autor expone esas ventajas y las estudia en comparación con los sistemas de centelleo de NaI.

Introduction

Present-day low-energy nuclear physics is being investigated in the 10 to 30-MeV region of energy with the use of two-stage tandem electrostatic generators and variable energy cyclotrons. Since this energy region is well over the Coulomb barrier for most nuclei, complex reactions can be employed to reach many unstable nuclei throughout the periodic table. These higher energies offer many advantages in nuclear physics investigations and a challenge in detector instrumentation.

Either magnetic spectrometers or electronic counter systems may be employed for these investigations. High-resolution magnetic spectrometers can be used for the study of the most complex reactions; however, they are expensive and their useful solid angle is somewhat limited in comparison to counter systems. Semiconductor detectors currently available [1] rival double-focusing spectrometers in both resolution and solid angle. In the energy region of 10 to 30 MeV, simple single-counter detecting systems cannot be employed except in special cases because of the many competing reactions which obscure the reaction of interest. For example, when 25-MeV He^3 ions interact with a Be^9 target, the reactions listed in Table I occur.

In each of these reactions the outgoing particles have energies corresponding to the input energy plus the Q value for each of the levels of the final nuclei. The highest energy group in each case corresponds to the ground state with succeeding lower energies corresponding to the various excited states. All of these reactions occur with approximately

TABLE I
He³ INDUCED REACTIONS IN Be⁹ AT 25 MeV

Reaction	Q Value (MeV)
Be ⁹ (He ³ , He ³) Be ⁹	0
Be ⁹ (He ³ , α) Be ⁸	+ 18.90
Be ⁹ (He ³ , t) B ⁹	— 1.09
Be ⁹ (He ³ , d) B ¹⁰	+ 1.09
Be ⁹ (He ³ , p) B ¹¹	+ 10.32

equal probability in the 10 to 30-MeV energy region. A detector set at some angle, θ , with respect to the direction of the incident beam of particles, will produce pulses corresponding to protons, deuterons, tritons, He³ and alpha particles from each of the above reactions. The observed energy spectrum (pulse-height distribution) will consist of many different peaks corresponding to various levels of all the above final-reaction nuclei. The experimental problem is to determine which peak belongs to which final nucleus. To further confuse the problem, as the detector is moved around from forward angles to back angles, the laboratory energies, corresponding to the various levels of final nuclei, change differently because of the reaction kinematics involved with a light target nucleus. This effect results in the superpositions of various peaks as the angle of observation is changed. When two peaks are superimposed it is extremely difficult to tell anything about the reaction.

One method of separating the various particle groups so that they may be observed independently is through the use of a dE/dx detector in conjunction with a total energy or E detector. The fractional energy, dE , lost in penetrating a fractional distance, dx , into matter, dE/dx , is approximately proportional to mZ^2/E , where m is the mass of the incident particle, Z its charge, and E its energy. Hence, the product $E \times dE/dx$ is nearly proportional to mZ^2 and is quite independent of energy over a rather large energy range. Therefore, the electronic multiplication of an E and dE/dx pulse results in a series of peaks which comprise a mass spectrum. According to the above relation, the relative pulse-height of each mass peak will be around 1, 2, 3, 12, and 16 for protons, deuterons, tritons, He³ and alpha particles, respectively. By arranging a dE/dx detector through which the particles can pass (an average dE/dx is measured) and an E detector in which they end their range, a separation of the various mass groups may be obtained. In practice, the simple product must be corrected to allow for the fact that the E pulse does not represent the energy of the incoming particle but that energy minus the energy lost in the dE/dx detector. There is also a correction for a logarithmic term not included in the above relation. These corrections can be made dynamically by an analogue multiplier. This general method is completely described by STOKES [2], BRISCOE [3], and STOKES *et al.* [4].

Fig. 1 illustrates a detector system using a gas ion chamber dE/dx counter and a semiconductor E counter. The ion chamber is of parallel plate design with guard-ring field correction on the centre electrode. A semiconductor detector is installed in the ground electrode (rear wall) of the parallel plate ion chamber. This electrode consists of a thin foil covering a large aperture. Particles passing through the dE/dx counter penetrate the thin foil and are detected by any convenient semiconductor detector. Li-diffused p-i-n junctions and p-n junctions have been used in this capacity. The same

design of ion chamber has been used with a NaI scintillation detector for E and is described elsewhere [5].

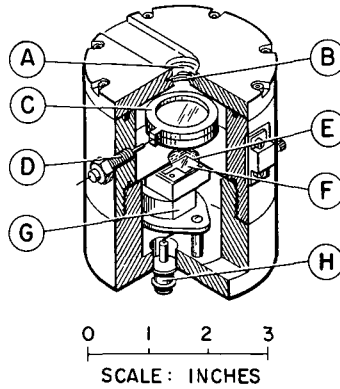


Fig. 1

dE/dx and E detector assembly. (A) Interchangeable gold aperture. (B) Thin foil front window of ion chamber. (C) Field correcting guard ring for collector plate. (D) Teflon insulator bushing. (E) Thin foil cover for exit aperture on ion chamber. (F) Semi-conductor E detector. (G) Transistor socket base for detector mount. (H) Kovar insulator bushing for signal lead

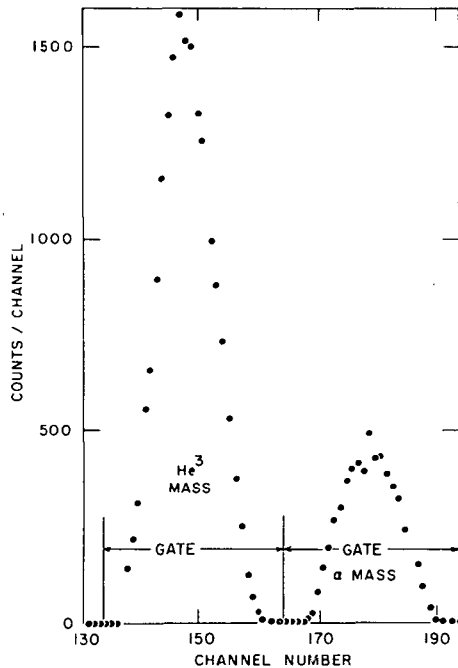


Fig. 2

Multiplier output at a 30° scattering angle for 25-MeV He^3 particles incident on C^{12} . Only the charge 2, mass 3 and 4, region of the mass spectrum is shown and the electronic gate settings for the two mass separations are indicated

Fig. 2 shows the mass identification ($E \times dE/dx$ spectrum) of a mixed beam of He^3 and He^4 particles under conditions in which all particles are being completely stopped in the E detector. The He^3 mass peak is greater than 100 times the intensity of the valley region between the peaks and indicates a high degree of mass separation. In the study of the $\text{Fe}^{56}(\text{He}^3, \alpha)\text{Fe}^{55}$ reaction, peak-to-valley ratios greater than 1000 were observed.

The energy spectra for each of the two mass groups of Fig. 2 are shown in Fig. 3. These spectra were obtained by gating a multichannel analyser with pulses obtained

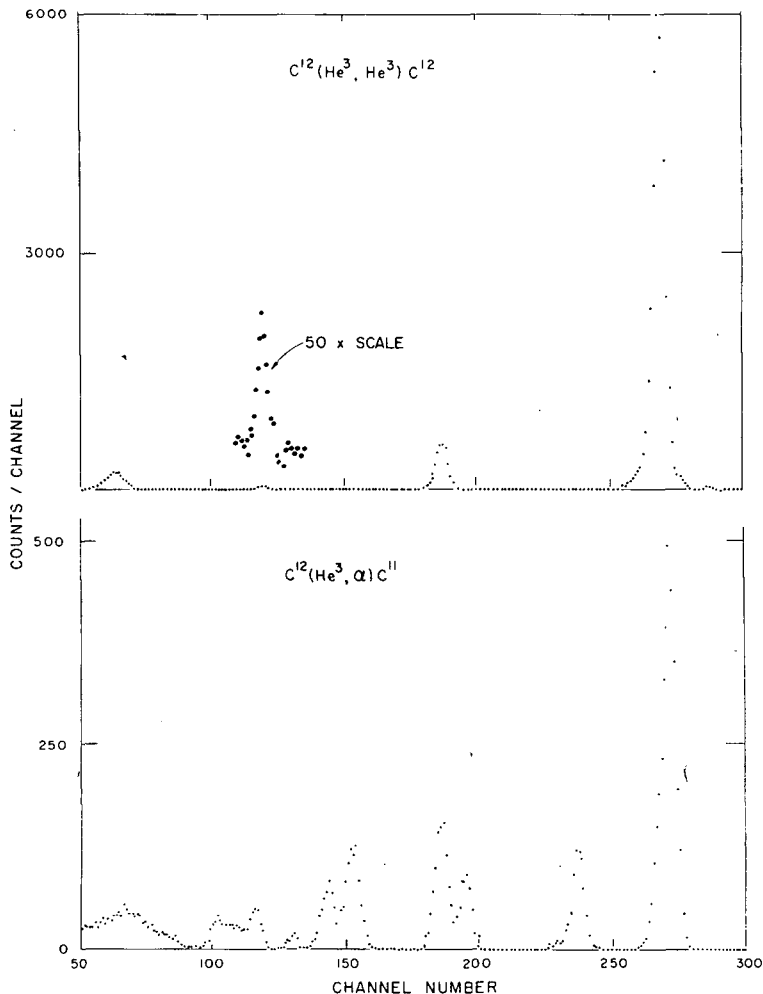


Fig. 3

Gated pulse-height energy spectra corresponding to the two mass settings of Fig. 2. In each spectrum the peak on the extreme right corresponds to the ground state of the final nucleus and each succeeding peak corresponds to excited states. The two spectra are completely free of background and the weak second excited state of C^{12} can easily be analysed

from an upper and lower-level discriminator set as shown in Fig. 2. The second excited state of C^{12} , which is very weak, can be easily measured with this system because of the high rejection for background and other particle events. A comparison of the C^{11} spectrum observed with a semiconductor system and a NaI system is shown in Fig. 4. In the NaI case, the limited resolution results in a complicated analysis for the two doublet-levels which are incompletely resolved. In the semiconductor case the levels are resolved in the low-energy region in distinct contrast to the NaI detector.

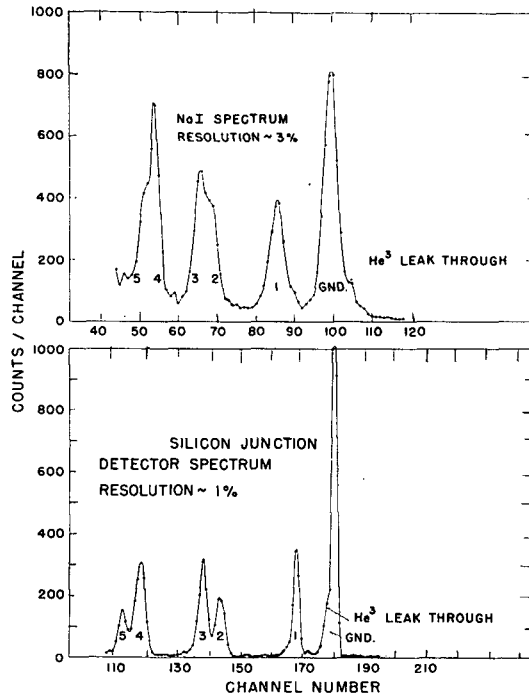


Fig. 4

A comparison of NaI and semi-conductor detector resolution for the gated alpha-particle spectrum from the $C^{12}(He^3, \alpha)C^{11}$ reaction at 25 MeV and 35° . The horizontal scales on these two spectra have been adjusted to help indicate the comparative resolutions. The two counter systems were not completely identical, which accounts for the different location of the He^3 leak-through in the two cases. The resolution comparison under the two conditions is valid

When semiconductor E detectors are used, the depletion region or active depth of the detector is limited by the characteristics of the particular detector employed [6]. Particles of sufficient energy to penetrate through the depletion region only deposit part of their energy in the E detector. Since the E pulses are lower than they should be the multiplied pulses are correspondingly lower. These low multiplied pulses lie in the valley region between the various mass groups and interfere with the mass separation efficiency of the system.

The (α, p) , (α, d) , and (α, t) reactions at 28 MeV with C^{12} and Be^9 result in proton, deuterons and triton energies sufficient to penetrate the depletion region of most semi-

conductor detectors (the range of a 10-MeV proton is the thickest currently available) [1]. A mass spectrum corresponding to protons, deuterons and tritons from the Be^9 -alpha particle reactions at 28 MeV is shown in Fig. 5. The valley regions between mass groups are partly filled with multiplied pulses corresponding to particles that penetrate the depletion region. There are so many protons penetrating the depletion region that they produce, as shown, an additional peak to the mass distribution. As long as the penetrating particles are not in the energy region of interest, they do not interfere with the mass separation of the system. Gated spectra corresponding to protons, deuterons, and tritons from these various reactions are shown in Fig. 6. The spectra are relatively free of background and can be easily analysed correctly in the region where the particles have been stopped by the E counter. The high-energy cutoff is readily observed in each case. With a simple single detector, these three spectra would be superimposed along with elastically scattered alpha particles and would be difficult, if not impossible to analyse.

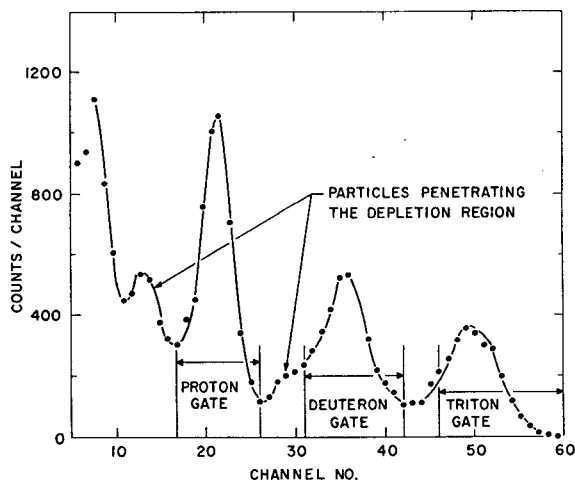


Fig. 5

Multiplier output at a 30° scattering angle for 28-MeV alpha-particles incident on Be^9 . The gate settings are indicated for the mass separation of charge 1, mass 1, 2, 3 particles. The effect caused by particles of sufficient energy to penetrate the depletion region of the semi-conductor E detector is shown

The recent development of lithium-diffused p-i-n junctions [7] allow much higher energy particles to be stopped since depletion regions can be made as thick as 1 cm. Preliminary measurements with a p-i-n junction of 2 mm-thick depletion region are shown in Figs. 7 and 8. The gated deuteron and proton spectra for the $\text{C}^{12}(\text{He}^3, \text{p})\text{N}^{14}$ and $\text{C}^{12}(\text{He}^3, \text{d})\text{N}^{13}$ reactions are shown in Fig. 7 and the gated spectra for the $\text{Be}^9(\text{He}^3, \text{t})\text{B}^9$, $\text{Be}^9(\text{He}^3, \text{d})\text{B}^{10}$ and $\text{Be}^9(\text{He}^3, \text{p})\text{B}^{11}$ reactions are shown in Fig. 8. In these cases the p-d-t mass separation is very good and deuterons with energies as high as 17 MeV were stopped in the depletion region of this type of detector. Fig. 9 shows an ungated spectrum for particles from the $\text{B}^9\text{-He}^3$ reaction at 25 MeV. The spectrum was measured with a single p-i-n junction detector without any coincidence or rejection

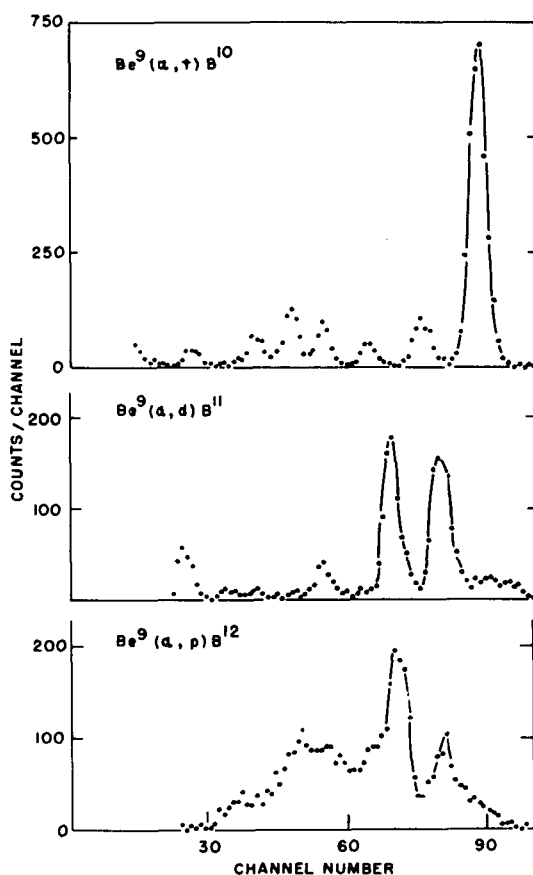


Fig. 6

Gated pulse-height spectra corresponding to each of the mass settings indicated in Fig. 5. The low-lying levels of B^{11} and B^{12} are not observed because the particles corresponding to them are of sufficient energy to penetrate the depletion region of the semiconductor E detector and are eliminated by the gate settings. Two of the peaks in the triton distribution are due to contaminations in the target

gates. The two highest peaks correspond to the ground and first excited states of B^{10} from the $\text{Be}^9(\text{He}^3, d)\text{B}^{10}$ reaction. The resolution for the ground-state 17-MeV deuterons with the simple detector is $\approx 1\%$ (full width at half maximum) and probably limited by the thick diffusion layer on the front of the lithium-diffused p-i-n junction.

Semiconductor dE/dx detector systems

The ideal system for mass separation is a complete semiconductor dE/dx and E detector. A thin semiconductor detector was constructed of 6000 Ωcm , p-type silicon. The active volume was $\approx \frac{1}{4}$ in in diam. and 0.002 in thick. With 5-V back bias the depletion region completely penetrated to the back surface of the detector. The details

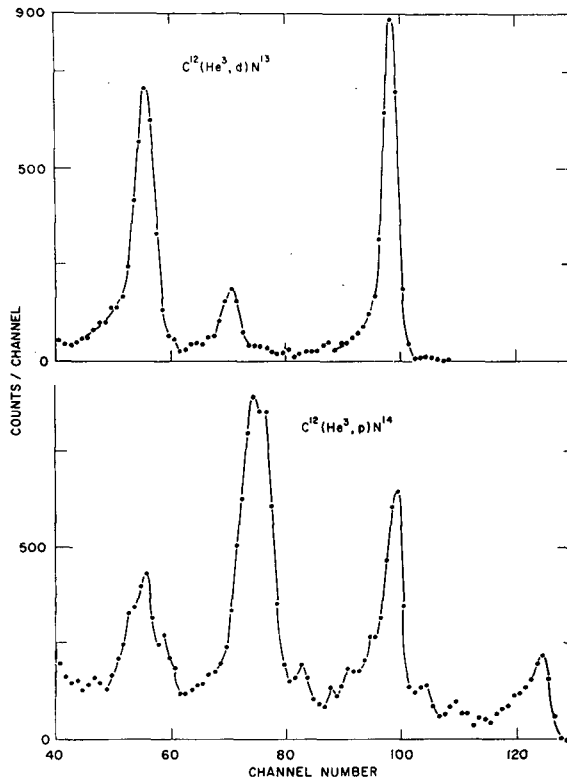


Fig. 7

Gated pulse-height spectra corresponding to protons and deuterons at 30° from 17-MeV He^3 particles incident on C^{12} . The E detector in this case was a Li diffused p-i-n junction. Deuterons corresponding to the ground, first, and second and third (doublet) states of N^{13} are observed. The high energy cut-off for protons (channel 125) is 15 MeV and only highly excited states of N^{14} are observed

of its construction and performance have been described recently by the author [8]. Fig. 10 shows the pulse-height distribution for 5-MeV particles (≈ 0.001 -in total range) into the front and into the back surface of the dE/dx detector. The slight difference in response corresponds to a range difference less than the grain size of the final grinding compound used in the fabrication. These data indicate that the depletion region actually penetrated into the hills between the valleys on the finished ground back surface.

The semiconductor dE/dx detector, when used with a semiconductor E detector, separated He^3 and He^4 particles in a manner similar to the gas ion chamber-semiconductor dE/dx and E system. The mass separation was improved because of the slightly superior resolution of the semiconductor dE/dx detector. The higher ionization efficiency of the semiconductor material (≈ 3 eV/electron-hole pair vs. ≈ 30 eV/electron-ion pair) [6] improves the signal-to-noise ratio which in turn improves the effective resolution. In general, the improved statistics have little to do with the resolution in a dE/dx detector [9]. The other desirable feature of the semiconductor dE/dx detector is its thin section and

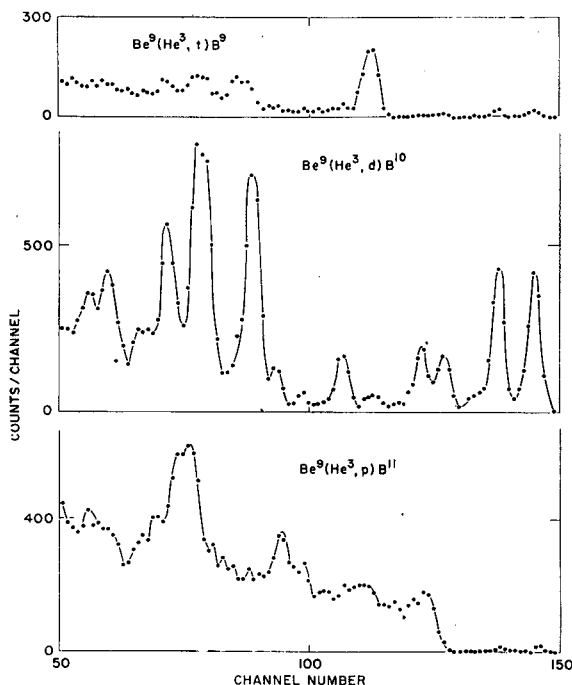


Fig. 8

Gated pulse-height spectra corresponding to protons, deuterons, and tritons at 30° from 17-MeV He^3 particles incident on Be^9 . The peak in the triton spectrum is the ground state of B^9 and corresponds to 15-MeV tritons. The peak on the extreme right in the deuteron spectra is the ground state of B^{10} and corresponds to 17-MeV deuterons. The proton peaks correspond to highly excited states of B^{11} .

elimination of entrance and exit windows. The ion chamber equivalent of this detector is 1000 times as thick because of the density ratio. Consequently, the E detector employed with the gas ion chamber must be of considerably larger area than the entrance aperture of the detector in order to allow for multiple Coulomb scattering through the gas. In most cases a factor of two to four in area-increase is required which results in a severe limitation on the entrance aperture when semiconductor E detectors are used.

Since the complete dE/dx and E semiconductor detector system can be decreased in size with improved performance over conventional systems, a new design has optimized these features. Fig. 11 shows the construction of a Kel-F plastic housing which mounts a semiconductor dE/dx and E detector in such a fashion that the detectors can be changed simply. This unit has been constructed; however, satisfactory dE/dx detectors have not yet been successfully manufactured in this particular form because of the severe mechanical problems involved in their fabrication [8].

Criteria for optimum energy resolution with dE/dx and E detector systems

It is well known that an absorber placed in front of a detector will increase the energy difference between two groups because of the energy dependence of dE/dx on E . At

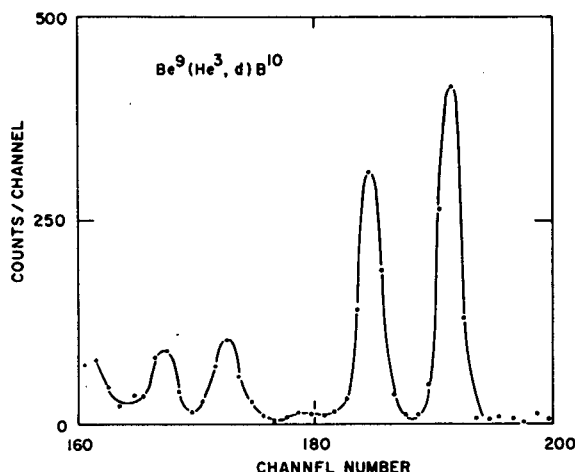


Fig. 9

Conditions are the same as in Fig. 8 except the dE/dx ion chamber has been removed and the Li diffused p-i-n junction detector is exposed directly to the scattered particles. The ground state deuteron peak on the extreme right shows a resolution of 1% (full width at half maximum) and is probably limited by a thick diffusion layer in the front of the detector

the same time the peaks are broadened by the statistical spread of the energy lost in the absorber. A detailed calculation of this effect was carried out by LANDAU [10] and is often referred to as the Landau effect or spread. Landau showed that the energy loss in the thin absorber has a gaussian distribution about some mean energy loss providing that some minimum amount of energy is removed from the particle ($\approx 10\%$ for 10 to 30-MeV protons). If less energy than this is removed, the distribution about the mean energy loss is skewed by a high energy "tail". For optimum mass-separation in dE/dx and E detector systems the highest practical resolution is used in the dE/dx detector, resulting in a working range of 10–50% energy removal in most cases. This amount of absorber in front of a detector amounts to a broadening of the groups of 0.7 to 2.5% depending on the conditions and particles.

The peak broadening is partially compensated by the increase in separation of two resolved groups. It is interesting to examine the conditions for an absorber to increase or decrease the ability of a detector to separate two energy groups. With semiconductor detectors capable of 0.25% to 0.5% energy resolution in the 20 to 30-MeV region it is unfortunate that the dE/dx detector required for the mass-separation of different particles may spoil the resolution to 1 or 2%. Since the energy lost in the dE/dx counter plus the energy lost in the E counter always adds up to the total energy (except for negligible window losses), the dE/dx pulse may be added back into the E pulse to eliminate the spread introduced in the E counter by the Landau spread in the dE/dx counter. In other words, when the energy loss in the dE/dx counter for a particular particle is unusually large, (i.e. corresponding to the high energy side of the dE/dx counter energy distribution), the energy loss in the E counter is correspondingly small and vice-versa. The Landau spread in the dE/dx counter is "coherent" with the resultant spread in the E counter. Hence, by the addition of the two pulses the resolution of the E detector

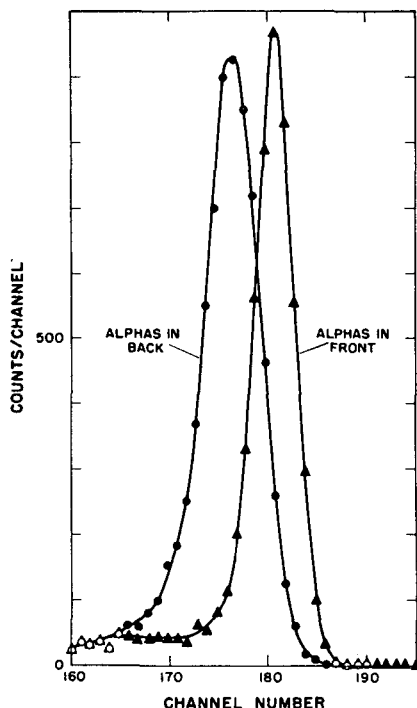


Fig. 10

Response of a 0.002-in thick, 6000 Ω cm, p-n junction, dE/dx detector to Po^{210} alpha particles into the front and back of the detector. The slight offset and increased broadening for alpha particles into the back of the detector (5 out of 180 channels) indicates a thin dead layer approximately 50 μ in

without any absorber in front of it may be regained electronically except for noise broadening from the various electronic components. If an absorber improves the ability of a detector system to separate two energy groups, coherent addition will not improve the separation ability since it merely returns the system electronically to the condition without an absorber. The exact conditions under which resolution is improved through the use of coherent addition are of interest in any nuclear physics investigation since the highest effective separation of partially resolved levels is always desirable.

Consider two groups of particles of nearly equal energies, E_1 and E_2 , but with $E_1 > E_2$. The response of a detector to these particles will appear on a multichannel analyser as two peaks proportional in pulse height to E_1 and E_2 and separated by $(E_1 - E_2)$. We define the separation S ,

$$S = 2(E_1 - E_2) / (E_1 + E_2) \quad (1)$$

which is a dimensionless number and may be expressed in percent. In this discussion we are concerned with S values of 1–2%, comparable with the energy resolution of the E detector. When an absorber is placed in front of the detector, the separation S_A is:

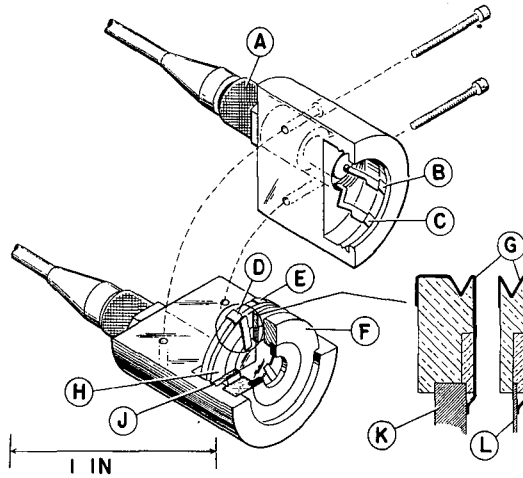


Fig. 11

Complete semiconductor dE/dx and E detector assembly. (A) Miniature coaxial signal connector. (B) Kel-F detector housing gold foil junction contact. (C) Kel-F detector housing gold foil back contact. (D) E detector gold foil junction contact. (E) E detector gold foil back contact. (F) Gold aperture assembly. (G) Detailed section of the circled region showing how the gold foil contacts follow the contour of the groove in the holder so as to make positive contact under compression. (H) E detector assembly. (J) dE/dx detector assembly. (K) (L) Detail showing the manner of support for the dE/dx and E detector Si disks in the Kel-F rings

$$S_A = 2 \left[\frac{(E_1 - \Delta E_1) - (E_2 - \Delta E_2)}{(E_1 - \Delta E_1) + (E_2 - \Delta E_2)} \right] \quad (2)$$

where ΔE_1 and ΔE_2 are the average energies lost in the absorber by the particles of energy E_1 and E_2 respectively. Since E_1 and E_2 are approximately equal (within 1–2% of each other), the logarithmic term in the derivation of dE/dx may be neglected so that:

$$\Delta E_1 = \frac{N}{E_1} \quad \text{and} \quad \Delta E_2 = \frac{N}{E_2} \quad (3)$$

$$N = E_1 \Delta E_1 = E_2 \Delta E_2 \text{ in this approximation,}$$

substituting (3) into (2) we have

$$S_A = 2 (E_1 - E_2) (1 + \Delta E_2/E_1) / (E_1 + E_2) (1 - \Delta E_1/E_2). \quad (4)$$

Since $E_1 \approx E_2$ let us define:

$$K = \Delta E_1/E_2 = \Delta E_2/E_1 = \Delta E/E \quad (5)$$

for this approximation where ΔE and E are averages of ΔE_1 , ΔE_2 and E_1 , E_2 respectively.

Substituting (5) and (1) into (4) results in

$$S_A = S (1 + K) / (1 - K). \quad (6)$$

This equation shows the increase in separation of two peaks caused by an absorber in front of the detector that removes a fraction, K , of the incoming energy. For the discussion of counter resolution capitalized subscripts will refer to the E counter and small letters will refer to the dE/dx counter. Then δ_I or δ_i is the contribution to the resolution width from "intrinsic" characteristics of the counter (crystal imperfections, noise, etc.), δ_L or δ_e the contribution from Landau spread, and δ_E or δ_e the contribution from electronic noise. The full width at half maximum of the pulse-height distribution for the response of a detector to mono-energetic particles is defined as the total width, Γ_{EI} . This width has a contribution from statistics, crystal imperfections, etc., Γ_I , along with the electronic noise of the system Γ_E . These contributions are incoherent and add as the square root of the sum of the squares. It is customary to express the width as fractional resolution δ .

$$\delta_{EI} = \Gamma_{EI}/E, \quad \delta_E = \Gamma_E/E, \quad \text{and} \quad \delta_I = \Gamma_I/E \quad (7)$$

hence

$$\delta_{EI} = (\delta_E^2 + \delta_I^2)^{1/2} \quad (8)$$

The Landau broadening Γ_L will add incoherently to the Γ_{EI} when an absorber is placed in front of the detector. The resulting full width at half maximum Γ_{EIL} expressed as resolution will be

$$\delta_{EIL} = (\delta_{EI}^2 + \delta_L^2)^{1/2} \\ \text{where } \delta_L = \Gamma_L/E \quad (9)$$

The ratio $S/\delta_{EI} = R$ represents the effective separation or the ability of a detector of a given resolution to separate two peaks (i.e. for $S/\delta_{EI} = 1$ the two pulse-height distributions overlap at their half height). Therefore, if

$$R < R_A \\ \text{where } R_A = S_A/\delta_{EIL} \quad (10)$$

then the effective separation with an absorber, R_A , is better than without. Substituting (9) and (6) into (10) we have:

$$\delta_{EI} > \delta_L (1 - K)/2 \sqrt{K} \quad (11)$$

Thus, if the energy resolution of the E detector is greater than the Landau spread times a constant, the effective separation will always be improved by adding an absorber.

For a typical case, $K = 0.2$ for 25-MeV alpha particles and $\delta_L \approx 2\%$.

Hence it is necessary that $\delta_{EI} > 2\% (0.9) = 1.8\%$ in order that an absorber improve the resolution.

Since NaI resolution for 25-MeV alpha particles is $\approx 3\%$ the effective separation is improved when used in a dE/dx and E detector system.

For most semiconductor detectors equation (11) is not true so the necessary addition of a dE/dx detector spoils the effective separation and coherent addition will improve it.

When a dE/dx detector is used as an absorber in front of an energy detector, Γ_e may be measured experimentally. The full width at half maximum of the pulse distribution from the dE/dx detector, Γ_{eie} , is comprised of the Landau broadening, Γ_e , electronic noise in the dE/dx system, Γ_e , and the intrinsic contribution, Γ_i . Hence

$$\begin{aligned}\delta_{ei} &= (\delta_e^2 + \delta_i^2 + \delta_e^2)^{\frac{1}{2}} = (\delta_{ei}^2 + \delta_e^2)^{\frac{1}{2}} \\ \text{where } \delta_{ei} &= (\delta^2 + \delta_i^2)^{\frac{1}{2}} \text{ and} \\ \text{where } \delta_e &= \Gamma_e/E, \delta_i = \Gamma_i/E, \text{ and } \delta_e = \Gamma_e/E.\end{aligned}\quad (12)$$

Since the dE/dx and E detector amplification systems are usually quite different the respective output pulse-heights are usually not in the correct proportion of ΔE and E . The adder circuit used for this work was adjustable so that $C\Delta E$ could be added to E .

The resolution for the E detector with coherent addition δ_{EIL} is:

$$\delta_{EIL}^2 = [\delta_{EI}^2 + C^2\delta_e^2 + \delta_e^2(1 - C)^2]^{\frac{1}{2}}. \quad (13)$$

The first term is the contribution from the E detector itself. The second term is the random electronic noise from the dE/dx amplification system and adds in as the square root of the sum of the squares. The third term is comprised of the algebraic sum of the δ_L in the E pulse, and the δ_e in the dE/dx pulse. For each particle passing through the counter, $\delta_L = -\delta_e$ because the energy loss or gain in one detector is coherent with the other. When E and dE/dx are added, the residual, $\delta_e(1 - C)$, adds as the square root of the sum of the squares.

The effective separation with coherent addition may be compared to that without coherent addition. In particular: what degree of simple detector energy resolution must be available in order that coherent addition will improve the effective separation? An analysis similar to that used for the derivation of (11) results in:

$$\delta_{EI}^2 \left[\left(\frac{1+K}{1-K} \right)^2 - \left(\frac{1+K^1}{1-K^1} \right)^2 \right] > [\delta_e^2(1-C)^2 + C^2\delta_e^2] \left[\left(\frac{1+K}{1-K} \right)^2 - \delta_e^2 \left(\frac{1+K^1}{1-K^1} \right)^2 \right] \quad (14)$$

where $K^1 = K(1 - C)$.

For $C = 0$ (no coherent addition) (14) reduces to the equality $\delta_e = \delta_e$. For $C = 1$ (ΔE added to E exactly as it was removed by the absorber) (14) reduces to

$$\delta_{EI}^2 < \delta_e^2(1 - K)^2/4K - \delta_e^2(1 + K)^2/4K. \quad (15)$$

Hence, if the simple detector resolution meets the above requirements, coherent addition will improve the effective separation. Comparing (15) and (11) we see that if $\delta_{EI}^2 < \delta_e^2(1 - K)^2/4K$ any absorber or dE/dx detector in front of the detector spoils the effective separation; however, coherent addition will not improve the effective separation if the noise in the dE/dx detector is sufficiently great. In the previous example it was shown that if $\delta_{EI} < 1.8\%$, the effective separation was spoiled by the addition of an absorber. However, with a noise contribution, δ_e , of 0.6% (typical for these conditions) coherent addition will not improve the effective separation unless $\delta_{EI} < 1.6\%$. In other words, the noisier the dE/dx detector system, the better the E detector must be in order to achieve any net improvement in effective separation. In summary, if the effective separation of a simple single detector is improved by the addition of an absorber (or dE/dx counter) then coherent addition will not improve the effective separation. If the effective separation is spoiled by the addition of an absorber then coherent addition will improve the effective separation providing dE/dx detector noise contribution is not too large.

Preliminary measurements with a gas ion chamber and semiconductor detector system illustrated in Fig. 1 demonstrate the improvements possible with coherent

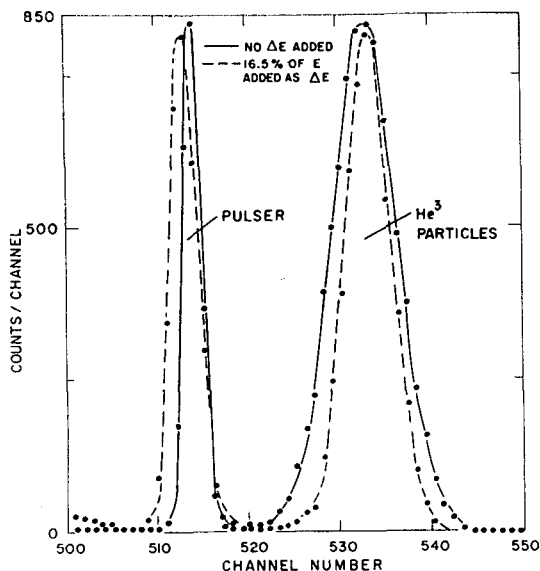


Fig. 12

Pulse-height distribution for 25-MeV He^3 particles elastically scattered from Ni at 30° (peak on the right) and standard pulser mono-energetic pulses (on the left). The width of the He^3 peak represents the inherent resolution at the detector including noise. The width of the pulser peak represents the noise contribution. When ΔE pulses are added as indicated the elastic peak decreases in width although the noise in the system is increased

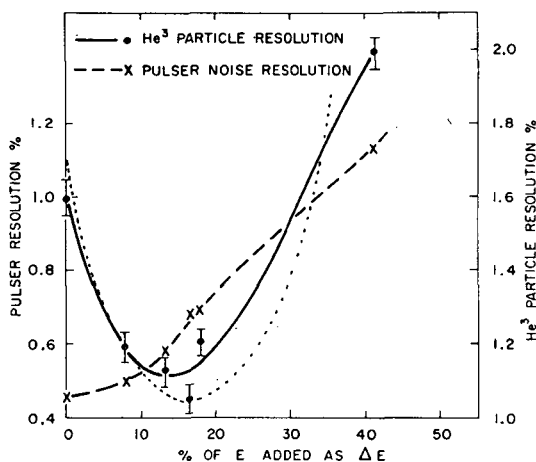


Fig. 13

Detector resolution (full width at half maximum) as a function of the percent of E added to E as ΔE . The dotted curve was calculated from the measured characteristics of the dE/dx and E detectors. The best resolution is obtained when ΔE is added back exactly as it was removed by the dE/dx counter

addition. Fig. 12 shows the elastic pulse-height distribution for 25-MeV He^3 particles elastically scattered from Ni at 30 degrees (on the right) and the distribution from a standard pulser (on the left) for the simple and coherent addition systems. Although the noise has increased with the coherent addition, the width of the elastic peak has decreased since δ_e has been subtracted out. Fig. 13 shows the noise and particle widths in percent as a function of the amount of dE/dx added back into the system. The dashed curve is calculated from equation (13) using measured values of δ_{EI} , δ_e , and δ_c . The agreement is as well as expected in terms of the difficulty of measuring resolutions of this degree with the energy stability of the cyclotron.

Fig. 14 shows an improvement in the effective separation (higher peak-to-valley ratio) for two partially resolved levels. The two peaks are the second and third excited states of C^{11} excited by the $\text{C}^{12}(\text{He}^3, \alpha)\text{C}^{11}$ reaction at 30 degrees. In this case the improvement in the effective separation is barely observable. However, the slight improvement is in qualitative agreement with equation (15).

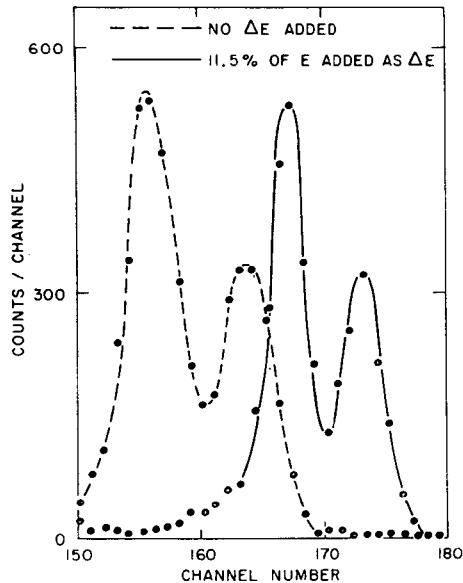


Fig. 14

Effective separation of the 2nd and 3rd excited states of C^{11} for conditions with and without ΔE addition. In each case the amplifier gain was adjusted so that the ground state was in the same channel. Although the spectrum is relatively compressed by the ΔE addition the peak-to-valley ratio and effective separation is improved.

The final limitation to dE/dx and E detector systems is the inability of the system to observe reaction events for negative Q value reactions in the forward angle region because of the excessive background of elastically scattered particles. The measurement of a reaction 1/1000 as strong as the elastic process is the practical limit for this detector system. However, the addition of a modestly sized magnet in the path of the scattered particles will eliminate a major part of the problem. For example, a small magnet of

high permeability steel operating in the 25 to 30-kg region is sufficient. Deuterons of 14 MeV will be deflected approximately 1 in in a 4-in path length. A 3/8-in magnet gap is adequate for a detector system with a 1/4-in diam. aperture. Such a magnet does not require the power nor control of a spectrometer magnet; however, it does eliminate the intensity problem of elastic scattering in the forward angle region. Particles with the same magnetic rigidity as the elastically scattered particles are still obscured, however with this geometry only a 3—6-MeV region of the spectrum of such particles is lost. In general the reaction Q values and charge to mass ratios for the various particles of interest move the spectrum of interest completely out of the elastic region. With such an arrangement the dE/dx and E detector system provides the mass identification and high resolution while the magnet is used only to eliminate the intense elastic contribution. In one position, with reasonable geometry, a 3—6-MeV region of spectra may be observed with each setting of the detector along the exit face of the magnet.

ACKNOWLEDGEMENTS

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SOLID-STATE DETECTORS FOR MEASUREMENT OF dE/dx AND TOTAL ENERGY IN NUCLEAR REACTIONS AT CYCLOTRON ENERGIES

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Abstract — Résumé — Аннотация — Resumen

Solid-state detectors for measurement of dE/dx and total energy in nuclear reactions at cyclotron energies. Surface-barrier p-n detectors with thick sensitive regions for measuring the total energy of the reactions initiated by the Argonne 60-in cyclotron, and physically thin detectors to identify the nature of particles by their rate of energy loss were developed by the authors.

The paper describes the main design elements of these detectors and the principal performance data of the solid-state counter systems used. Detectors of 1 cm² sensitive area (0.5 μ A leakage current at 400-V back bias in a typical case) are also described.

The very satisfactory resolution of the Argonne detectors allows accurate measurements to be made in nuclear reactions at cyclotron energy.

Détecteurs à semi-conducteurs pour la mesure dE/dx et E dans les réactions nucléaires produites dans un cyclotron. Les auteurs ont mis au point, d'une part, des détecteurs p-n à barrière de surface comportant des zones sensibles épaisses, pour mesurer l'énergie totale des réactions produites dans le cyclotron de 60 pouces de l'Argonne National Laboratory et, d'autre part, des détecteurs extra-plats, pour identifier les particules d'après la perte d'énergie par unité de distance.

Le mémoire décrit les principales caractéristiques de ces détecteurs et indique les données essentielles concernant la qualité de fonctionnement des compteurs à semi-conducteurs qui ont été utilisés. On y trouve également une description de détecteurs de 1 cm² de surface sensible (courant de fuite de 0,5 μ A sous une tension de polarisation de 400 V dans un cas type).

Le pouvoir de résolution très suffisant des détecteurs de l'Argonne National Laboratory permet d'effectuer des mesures précises sur les réactions nucléaires dans le domaine d'énergies propre au cyclotron.

Твердые детекторы для измерения dE/dx и общего количества энергии ядерных реакций на уровне энергий циклотрона. Авторами были усовершенствованы p-n детекторы с мощными поверхностными барьерами и с чувствительными зонами для измерений общего количества энергии реакций, возбужденных 60-ти дюймовым аргонским циклотроном, а также физически тонкие детекторы для определения характера частиц по скорости и потери ими энергии.

В докладе дается описание применявшихся главных конструкционных элементов этих детекторов и основных характеристик систем твердых счетчиков. Также дается описание детекторов с площадью чувствительности в 1 см² (0,5 микроампер утечки при напряжении заднего порога в 400 в в типичном случае).

Крайне удовлетворительная разрешающая способность аргонских детекторов позволяет проводить точные измерения в ядерных реакциях циклотронной энергии.

Detectors de estado sólido para la medida del cociente dE/dx y de la energía total de reacciones nucleares a energías de ciclotrón. Los autores han preparado detectores p-n de barrera superficial, con región sensitiva espesa, con el fin de medir la energía total de las reacciones iniciadas con ayuda del ciclotrón de 60 pulgadas de Argonne, y detectores delgados que utilizan para identificar las partículas por la pérdida específica de energía que experimentan.

La memoria describe las principales características constructivas de estos detectores y los datos esenciales de funcionamiento de los sistemas contadores sólidos que emplean. También

describe detectores de 1 cm^2 de área sensitiva (en un caso típico, una corriente de fuga de $0,5 \mu\text{A}$ para una polarización inversa de 400 V).

El elevado poder de resolución de los detectores de Argonne permite efectuar mediciones muy exactas en las reacciones nucleares que se verifican en el intervalo de energías ciclotrónicas.

We have made solid-state counter systems [1] suitable for studying nuclear reactions initiated by the 43-MeV α -particle and the 10.8-MeV proton beams of the 60-in cyclotron at Argonne National Laboratory. Since reactions at these energies may be complex, it is necessary to be able to distinguish one type of particle from another (e.g., α -particles from He^3) by using two counters—a thin one to measure dE/dx , the rate of energy loss and a thick one to measure E , the total energy lost. (Then $E dE \propto mZ^2$.) Our counters are surface-barrier diodes, made by evaporating a thin gold layer onto a carefully prepared surface of n-type silicon semiconductor. An electro-plated nickel layer is used as the “back” contact on the silicon. We have made counters of approximately 1 cm^2 area which are able to withstand a back bias of several hundred volts while passing back currents of a few tenths of a microampere per square centimetre (e.g., $0,5 \mu\text{A}/\text{cm}^2$ at 400 V in a typical case). When a charge-sensitive transistor preamplifier is used with a standard delay-line differentiated amplifier, such detectors have given resolution widths of 60 keV (uncorrected for preamplifier noise) when used to detect α particles from natural sources at such bias levels. Counters for dE/dx measurements have been made with 200- Ω -cm silicon reduced to a uniform thickness of 0.002 to 0.003 in or even thinner. (One detector has been made which is transparent to the 8.78-MeV alpha particles from ThC' .) These detectors are sensitive throughout their entire thickness at an applied bias of approximately 100 V. Measurements comparing the response to low-energy α particles incident on the front and back of these detectors have shown an insensitive layer about $1 \text{ mg}/\text{cm}^2$ at the back contact, because of the nickel layer itself. With 43-MeV α -particles incident on such a detector, we have obtained a line width of 11% for a total energy loss of 2.8 MeV. When the contribution from noise pickup in the cyclotron area is unfolded from this, the resulting half-width is 9.1%, to be compared with a calculated [2] width of 9.6%. There is no apparent contribution to the peak width from the non-uniform physical thickness of the detector over the illuminated region, $1/8$ in in diameter. This resolution enables α -particles and He^3 -particles to be distinguished from each other. A number of thick detectors have been made from 3000- Ω -cm silicon approximately 1 cm^2 in area and have been biased to voltages well over 500 V without impairing the 60-keV resolution-width obtained with α -particles from natural sources. One detector has been biased to 1100 V without breakdown and has been used in experiments at 800 V bias. At this voltage the thickness of the charge-depletion layer was measured, by use of the 21.6-MeV deuteron beam to be $230 \text{ mg}/\text{cm}^2$ Al equivalent (equal to the range of 48-MeV alpha particles). They are normally used at 540 V bias, which is adequate to give linear response for 43-MeV alpha particles and 10.8-MeV protons. The resolution under these conditions is limited principally by the spread in energy of the incident beams which is not less than 1%. We have observed 1.1% for the 48-MeV alpha particles and 1.4% for the 10.8-MeV protons (where a contribution of 0.2% is due, in the latter case, to the target and a thin absorber in front of the detector). A dE/dx , E pair have been used in a number of experiments over a period of 5 months with very stable characteristics. The high resolution in E and the ability to select the α and He^3 particles have made possible some measurements which could not be done as well or at all with scintillation counters. Examples of work which has been done by various experimenters include the (α , He^3)

reaction³ with 43-MeV α -particles, the (d, He³) reaction⁴ with 21.6-MeV deuterons and inelastic α -particle scattering on medium-weight nuclei [5].

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SPECTROMÈTRE A NEUTRONS RAPIDES A LITHIUM-6 ET DIODES AU SILICIUM

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Abstract — Résumé — Аннотация — Resumen

Lithium-6 and silicon-diode fast neutron spectrometer. The reaction $n + \text{Li}^6 = \text{He}^4 + \text{H}^3 + Q$ is utilized. The sum of the energies of the α and the triton is $E = E_\alpha + E_T = E_n + 4.78 \text{ MeV}$ (E_n = the energy of the incident neutron). E_α and E_T are measured by means of two silicon surface-barrier detectors, and the two pulses obtained are added.

The diodes used, with the corresponding electronic assembly, give a breadth of 30 KeV for the α . The thickness of the LiF layer has been calculated to give a 1 % enlargement of the alpha line.

The whole apparatus is undergoing tests.

Spectromètre à neutrons rapides à lithium-6 et diodes au silicium. On utilise la réaction $n + {}^6\text{Li} = {}^4\text{He} + {}^3\text{H} + Q$. La somme des énergies de l'alpha et du triton est $E = E_\alpha + E_T = E_n + 4,78 \text{ MeV}$ (E_n = énergie du neutron incident). On mesure E_α et E_T au moyen de deux détecteurs au silicium à barrière de surface et on effectue la somme des deux impulsions obtenues.

Les diodes utilisées donnent, avec l'électronique correspondante, une largeur de 30 keV pour les alphas. L'épaisseur de la couche de LiF a été calculée de manière à obtenir un élargissement de la raie α de 1 %.

Le montage, dans son ensemble, est en cours d'essais.

Спектрометр быстрых нейтронов с литием-6 и на кремниевых диодах. Применяется реакция $n + \text{Li}^6 = \text{He}^4 + \text{H}^3 + Q$. Сумма энергий альфа-частицы и трития- E равняется $E = E_\alpha + E_T = E_n + 4,78 \text{ MeV}$. E_n = энергия бомбардирующего нейтрона. E_α и E_T измеряются при помощи двух кремниевых детекторов с поверхностным барьером, и два полученных импульса суммируются.

Используемые диоды дают с соответствующей электроникой ширину в 30 кэВ для альфа-частиц. Толщина слоя LiF рассчитывалась таким образом, чтобы получить уширение линии на 1 %.

Схема в целом проходит испытания.

Espectrómetro para neutrones rápidos de litio-6 y diodos de silicio. Se utiliza la reacción $n + {}^6\text{Li} = {}^4\text{He} + {}^3\text{H} + Q$. La suma de las energías de la partícula alfa y del tritón es $E = E_\alpha + E_T = E_n + 4,78 \text{ MeV}$, siendo E_n la energía del neutrón incidente. Se mide E_α y E_T por medio de dos detectores de silicio de barrera superficial y se suman los dos impulsos obtenidos.

Los diodos utilizados dan con los circuitos electrónicos correspondientes una anchura de 30 keV para las partículas alfa. El espesor de la capa de LiF se ha calculado para poder obtener un ensanchamiento de la raya de α de 1 %.

En su conjunto, el montaje está siendo ensayado.

Principe

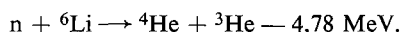
L'utilisation des semi-conducteurs permet aujourd'hui la mesure, avec une grande précision, de l'énergie des particules chargées.

On sait réaliser des chambres d'ionisation à l'état solide de 100μ d'épaisseur et de plusieurs dizaines de millimètres carrés de surface, la «fenêtre» d'entrée pouvant être largement inférieure au micron.

Lorsqu'une particule pénètre dans un tel détecteur, elle crée un nombre N de paires d'électrons et de trous égal à $N = \delta E / E_i$, où E_i est l'énergie nécessaire pour créer une paire électron trou, et δE la perte d'énergie par ionisation lors de la traversée de la zone isolante (barrière de Schottky).

Pour une particule α d'énergie E inférieure à 15 MeV, δE est pratiquement égal à E . Pour un neutron ou un photon γ , δE est beaucoup plus petit que E ; un tel détecteur n'est donc pas sensible à ces particules.

Pour mesurer l'énergie d'un neutron, il est nécessaire d'utiliser une réaction nucléaire ne produisant que des particules chargées. On peut par exemple utiliser la réaction



On déduit l'énergie du neutron de la mesure de la somme des énergies des particules α et t obtenue avec une grande précision; la distribution angulaire ne joue ainsi aucun rôle [4].

Le spectromètre à particules chargées se compose de deux diodes à barrière de surface [1], placées en face l'une de l'autre, qui délivrent des signaux proportionnels à l'énergie des particules incidentes, l'une d'elle est recouverte d'un dépôt d'environ 1μ de ${}^6\text{LiF}$.

Afin de supprimer les impulsions parasites, on élimine systématiquement tout événement qui ne correspond pas au cas où chacune des diodes a détecté une particule d'énergie supérieure à un certain seuil.

Sensibilité et résolution

Pour une énergie E_n de neutrons incidents, le produit sensibilité S résolution R ne dépend pas de l'épaisseur e de la couche de ${}^6\text{LiF}$.

$$S = \Sigma e A$$

où A est l'aire de la couche sensible, et Σ la section efficace macroscopique de la réaction (n, α) [2].

Pour déterminer R , nous avons calculé le spectre des particules sortant de la lame de LiF dans les hypothèses suivantes:

- a) Le flux de neutrons est isotrope;
- b) La section efficace différentielle de la réaction (n, α) est isotrope;
- c) On néglige la corrélation entre la particule α et le triton.

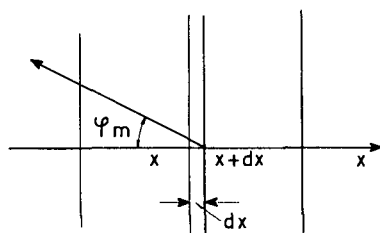


Figure 1
Angle limite d'émission.

On considère une source isotrope, de particules d'énergie E_0 , d'épaisseur dx et située à la distance x de la surface. Du fait de l'absorption, les particules ne peuvent sortir de la lame avec une énergie comprise entre E_0 et E' qu'à condition que leur angle d'émission φ soit inférieur à φ_m (fig. 1). Leur nombre est:

$$N(E', x) = \frac{1}{2} A \Sigma dx (1 - \cos \varphi_m).$$

On peut lier φ_m à E' en utilisant le parcours moyen R d'une particule d'énergie E : $R(E) = \alpha E^\beta$ [3], d'où:

$$\frac{x}{\cos \varphi_m} = \alpha (E_0^\beta - E'^\beta)$$

et si on pose $u = \cos \varphi_m$, le nombre total de particules sortant de la lame avec une énergie comprise entre E_0 et E' est:

$$N(E') = \frac{1}{2} A \Sigma \alpha (E_0^\beta - E'^\beta) \int_{u_1}^{u_2} (1-u) du.$$

Plaçons-nous dans le cas d'une faible épaisseur $e < R(E_0)$. Soit $\Delta E = E_0 - E_1$ la perte d'énergie d'une particule traversant normalement la lame; E_1 est défini par:

$$R(E_0) - R(E_1) = e.$$

1° Si $E' < E_1$, la sommation peut porter sur tous les points de la lame, d'où

$$\begin{cases} u_1 = 0 \\ u_2 = \frac{e}{R(E_0) - R(E')} \end{cases}$$

et
$$N(E') = \frac{1}{2} A \Sigma \left[e - \frac{e^2}{2\alpha(E_0^\beta - E'^\beta)^2} \right].$$

Le spectre d'énergie des particules est donc:

$$n(E) = \left(\frac{dn}{dE'} \right)_{E'=E} = \frac{1}{4} \frac{A \Sigma}{\alpha} \frac{e^2 \beta E^{\beta-1}}{(E_0^\beta - E^\beta)^2}.$$

2° Si $E_1 < E' < E_0$, φ_m peut varier de 0 à $\pi/2$, d'où:

$$u_1 = 0 \quad u_2 = 1$$

alors
$$N(E') = \frac{1}{4} A \Sigma \alpha (E_0^\beta - E'^\beta)$$

et
$$n(E) = \frac{1}{4} A \Sigma \alpha \beta E^{\beta-1}.$$

L'allure du spectre est représentée par la figure 2.

Il faut remarquer que:

$$\begin{aligned} N(E_1) &= \frac{1}{4} \Sigma e \\ N(0) &= \frac{1}{2} \Sigma e \left(1 - \frac{e}{2R_0} \right) \end{aligned}$$

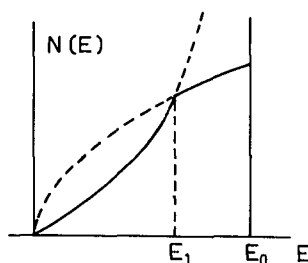


Figure 2
Spectre des particules.

et par conséquent, si $e < R_0$, le nombre de particules sortant de la lame avec une énergie comprise entre E_0 et E_1 est la moitié du nombre total de particules.

$\Delta E = E_0 - E_1$ représente donc la largeur du spectre sortant de la lame.

Si on remarque que $\Delta E/E_0 = e/\beta R_0$, la résolution R (pour la particule d'énergie E_0) $R_0 = E_0/\Delta E$ vaut donc $R = \beta R_0/e$ et est donc inversement proportionnelle à l'épaisseur.

Numériquement, nous prendrons comme énergie E_0 la moyenne des énergies de chaque particule émise:

$$\langle E_t \rangle = \frac{m_\alpha}{m_\alpha + m_t} \left[Q + \left(1 - \frac{m_n}{m_\alpha + m_t} \right) E_n \right]$$

($Q = 4,78$ MeV, et m_n est la masse du neutron)

et

$$\langle E_\alpha \rangle = \frac{m_t}{m_\alpha} \langle E_t \rangle.$$

D'où les résultats portés au tableau I.

TABLEAU I
VALEURS DU PRODUIT SENSIBILITÉ-RÉSOLUTION EN FONCTION DE
L'ÉNERGIE DU NEUTRON

E_n (MeV)	Σ (μ^{-1})	E_α (MeV)	E_T (MeV)	pour $e = 1 \mu$			$RS = \Sigma \frac{E_n}{\Delta E}$
				ΔE_α (MeV)	ΔE_T (MeV)	ΔE (MeV)	
0	$3,62 \cdot 10^{-4}$	2,05	2,73	0,25	0,059	0,31	0
0,1	$0,042 \cdot 10^{-4}$	2,09	2,78	0,25	0,059	0,31	$0,013 \cdot 10^{-4}$
0,25	$0,166 \cdot 10^{-4}$	2,14	2,86	0,25	0,058	0,30	$0,135 \cdot 10^{-4}$
0,5	$0,033 \cdot 10^{-4}$	2,23	2,97	0,25	0,058	0,30	$0,055 \cdot 10^{-4}$
1	$0,018 \cdot 10^{-4}$	2,42	3,22	0,24	0,056	0,30	$0,060 \cdot 10^{-4}$
2,5	$0,011 \cdot 10^{-4}$	2,97	3,95	0,23	0,056	0,28	$0,095 \cdot 10^{-4}$
3,6	$0,0072 \cdot 10^{-4}$	3,37	4,49	0,22	0,048	0,265	$0,097 \cdot 10^{-4}$
14	$0,0018 \cdot 10^{-4}$	7,20	9,58	0,15	0,027	0,175	$0,14 \cdot 10^{-4}$

On a porté sur la figure 3 l'efficacité $E = RS$ en fonction de l'énergie E_n .

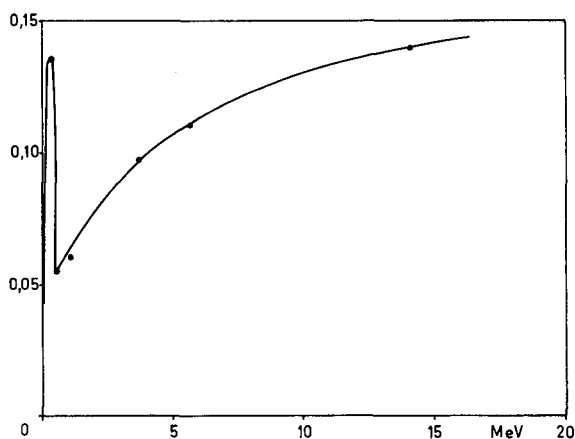


Figure 3

Efficacité du spectromètre en fonction de l'énergie des neutrons incidents.

Expérimentalement, on peut vérifier que la largeur du spectre de tritons émis par une lame de LiF irradiée en neutrons thermiques est bien plus faible que celle du spectre des particules α (fig. 4).

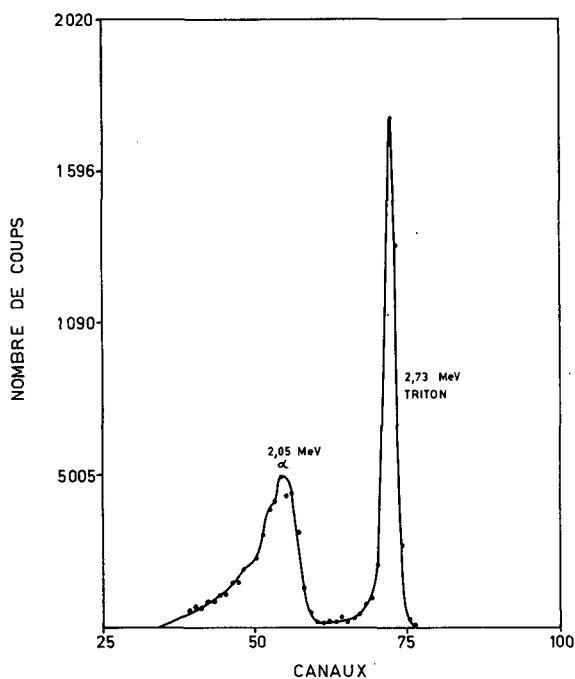


Figure 4

Spectre de particules. Réaction neutrons thermiques/ ^6Li .

Réalisation du spectromètre

Le spectromètre est formé par deux diodes à barrière de surface montées en regard; sur l'une d'elle on a déposé du ^6LiF par évaporation sous vide.

Pour éviter les protons de recul, la tenue mécanique est assurée par un montage où il n'y a pas de corps hydrogéné (fig. 5).

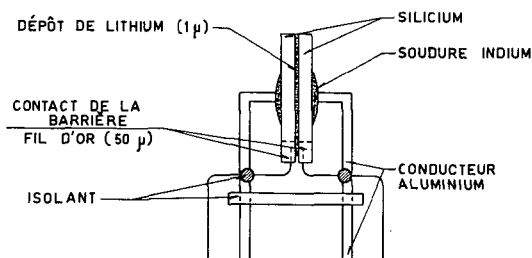


Figure 5

Schéma du spectromètre à neutrons rapides.

Les diodes utilisées sont fabriquées par oxydation de silicium type N. On obtient une couche d'inversion P; le dépôt métallique qui permet le contact électrique avec la couche d'inversion est très inférieur au micron.

Ces diodes répondent aux caractéristiques suivantes. Elles ont une grande surface, de l'ordre de 1 cm^2 . On peut leur appliquer des tensions inverses de polarisation supérieures à 300 V sans que le courant inverse dépasse $1,5\text{ }\mu\text{A}$. Cette propriété permet d'obtenir des épaisseurs de barrière ($300\text{ }\mu$) suffisantes pour utiliser le spectromètre avec des neutrons d'une énergie de 14 MeV tout en ayant un bruit dû aux diodes admissible. (Le silicium à utiliser doit être du $1500\text{ }\Omega$.)

Appareillage électronique utilisé

Chaque diode attaque un préamplificateur qui donne des impulsions proportionnelles aux charges créées. Ces deux préamplificateurs sont suivis par un sommateur et un amplificateur attaquant un analyseur d'amplitude à cent canaux (fig. 6).

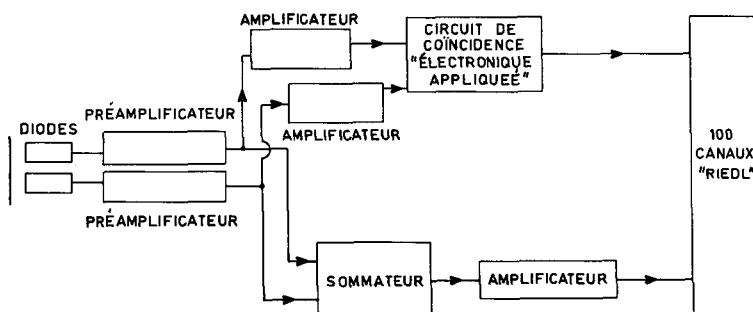


Figure 6

Bloc-diagramme de l'appareillage utilisé.

Un circuit de coïncidence a été ajouté, pour éliminer les impulsions parasites ne provenant que de l'une des diodes.

PRÉAMPLIFICATEUR (fig. 7)

Le montage étudié ne comporte qu'un seul tube (E 188 cc), ce qui permet de réduire son encombrement. Ce tube présente aussi l'avantage d'une faible résistance de bruit (250Ω). L'amplificateur est un montage Bootstrapp avec une intégration due à un effet Miller sur la capacité C ($C = 5 \text{ pF}$), le gain étant de 25 sans contre-réaction, la capacité ramenée à l'entrée est de 125 pF ; la capacité de la diode étant de l'ordre de 10 à 15 pF , la tension de sortie est donc proportionnelle à la charge sur la diode.

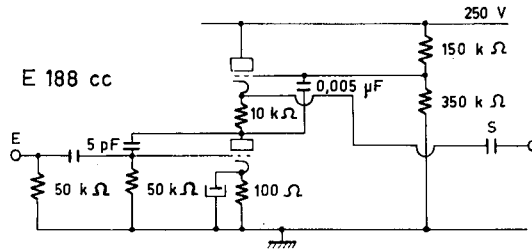


Figure 7
Préamplificateur.

La résistance d'entrée est de $50 \text{ k}\Omega$ pour avoir une constante de temps de $RC = 7 \mu\text{s}$, très supérieur au temps de collection des charges sur les diodes.

L'impédance de sortie du montage est de 75Ω .

SOMMATEUR (fig. 8)

Le montage utilisé est un sommateur classique. Le fort taux de contre-réaction égalise le gain sur les deux voies. Les amplificateurs sont très contre-réactionnés pour leur donner une grande stabilité de gain.

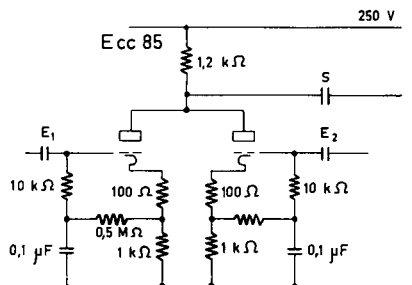


Figure 8
Sommateur.

Résultats expérimentaux

NEUTRONS THERMIQUES

L'utilisation des neutrons thermiques permet de tester le bon fonctionnement du spectromètre.

En effet, les particules chargées sont alors émises dans des directions opposées; leur énergie est bien déterminée (2,05 MeV pour la particule α , 2,73 MeV pour le triton).

Dans une expérience préliminaire, nous avons mesuré au moyen d'une seule diode le spectre des particules sortant de la couche de LiF (voir fig. 4). La largeur des raies est de 70 keV pour le triton et 280 keV pour la particule α , ce qui correspond au calcul dans le cas d'une couche de LiF d'une épaisseur de 1 μ . (Ceci prouve que la résolution de l'électronique est bien supérieure.)

Dans une expérience suivante, on trace le spectre en neutrons thermiques d'un spectromètre complet. Sans le dispositif de coïncidences, on voit apparaître (fig. 9) trois raies correspondant aux énergies de 2,05, 2,73 et 4,78 MeV, ce qui permet de tester la linéarité.

Enfin, on peut tracer le spectre avec coïncidence (fig. 10).

NEUTRONS RAPIDES

Nous avons mesuré les spectres de neutrons émis par la réaction (D, d) obtenue à l'aide d'un accélérateur SAMES 600 keV dans l'axe du faisceau, et dans une direction perpendiculaire.

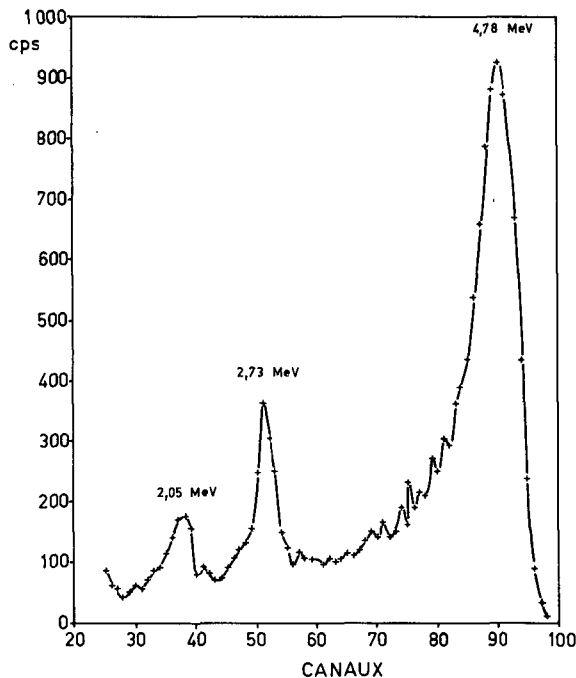


Figure 9
Spectre de neutrons thermiques avec diodes et ${}^6\text{Li}$.

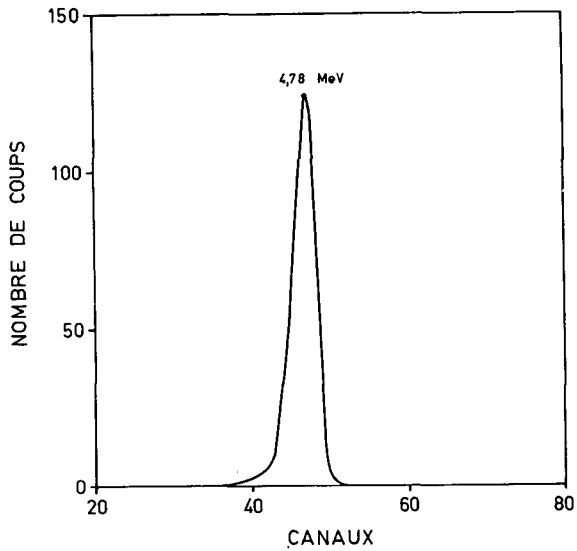


Figure 10
Pic thermique avec coïncidences.

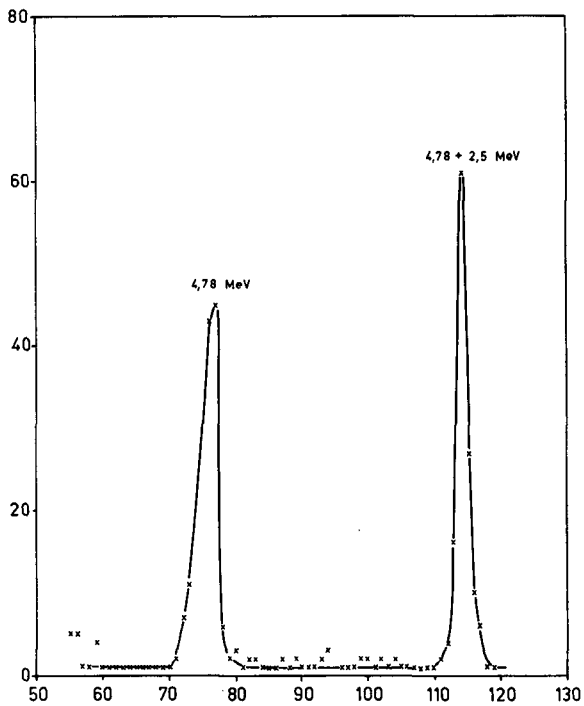


Figure 11
Spectre de neutrons de 2,5 MeV sans coïncidence.

L'énergie des neutrons émis dans l'axe du faisceau est de 3,6 MeV et, étant donné l'épaisseur du deutérium de la cible, l'énergie des neutrons est dispersée sur environ 300 keV. Dans la perpendiculaire au faisceau, étant donné la répartition énergétique des neutrons en fonction de l'angle dans la réaction (D, d), l'énergie des neutrons est de 2,5 MeV, et la définition en énergie est bien meilleure (30 keV). Le pic obtenu dans la deuxième mesure montre la résolution du spectromètre à cette énergie.

Les figures 11 et 12 représentent le spectre des neutrons de 2,5 MeV. Dans la figure 11, le spectromètre est placé contre la cible. Dans la figure 12, il occupe la même position, mais il est gainé de cadmium afin d'éliminer le pic produit par les neutrons thermiques.

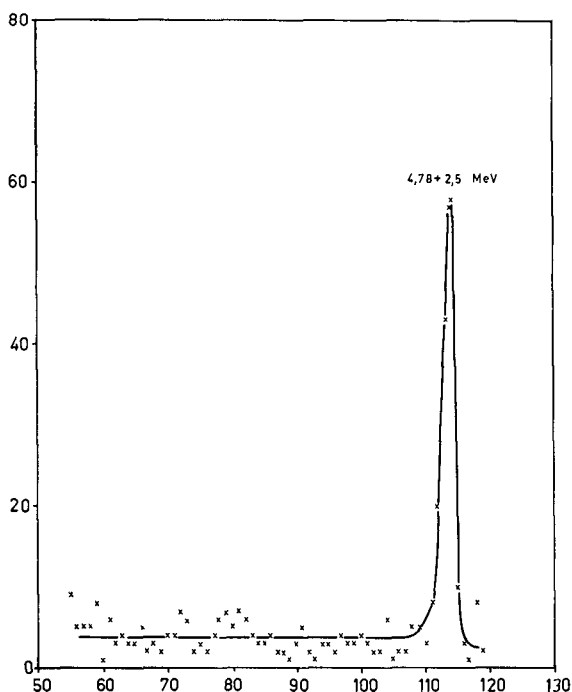


Figure 12

Spectre de neutrons de 2,5 MeV sans coïncidence. Spectromètre entouré de cadmium.

La courbe de linéarité du spectromètre est donnée sur la figure 13.

Nous avons fait varier l'épaisseur du LiF entre 0,5 et 1 μ . La résolution varie alors de 200 à 400 keV. La sensibilité est multipliée par 2.

Les ordres de grandeur de la résolution et de la sensibilité sont en accord avec les résultats obtenus par le calcul.

Nous avons enfin mesuré la répartition en énergie des neutrons issus d'une source de 3,5 MeV et diffusés par choc élastique et inélastique par l'aluminium (fig. 14). A cet effet, le spectromètre a été placé au centre d'une sphère d'aluminium de 10 cm de diamètre extérieur et de 3 cm d'épaisseur.

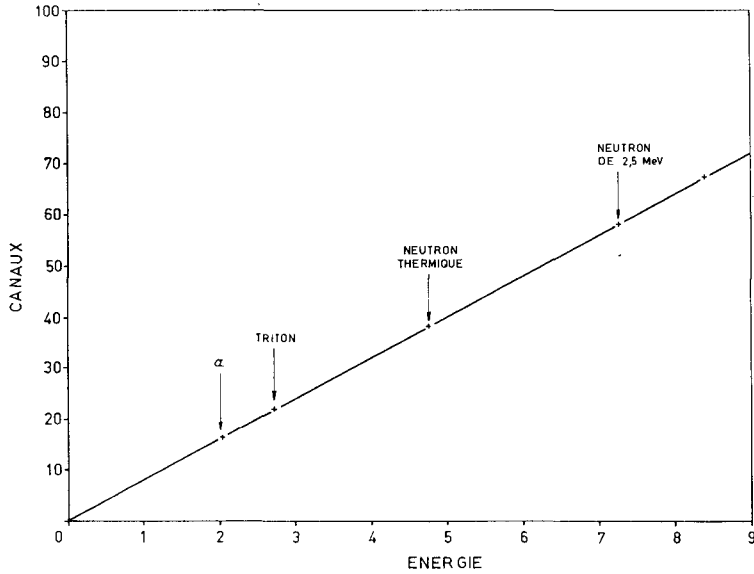


Figure 13
Courbe de linéarité du spectromètre.

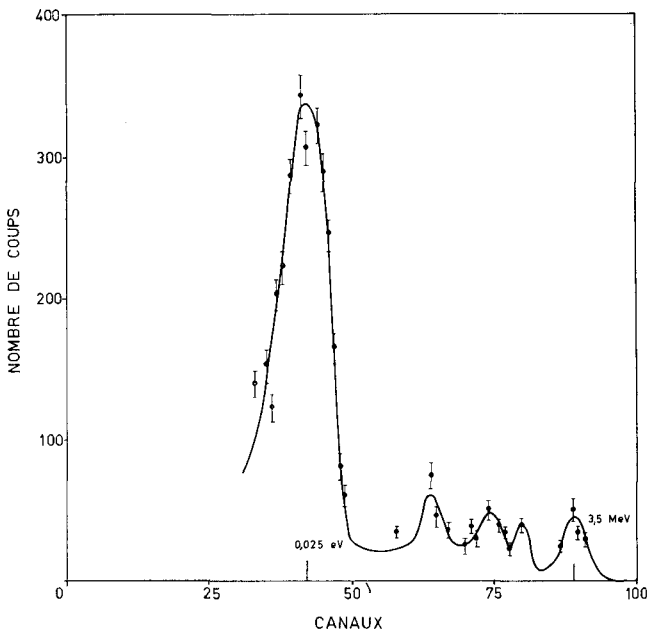


Figure 14
Spectre de neutrons de 3,5 MeV diffusé par l'aluminium.

On mesure alors un pic correspondant à des neutrons de 3,5 MeV et trois autres pics à 2,75, 2,6 et 1,35 MeV. Ces différents pics correspondent, à 200 keV, près à l'excitation des différents niveaux de l'aluminium de 0,85, 1,03 et 2,25 MeV.

Cette expérience n'est que qualitative étant donné la faible sensibilité du spectromètre: un spectromètre plus sensible fait à l'aide de diodes de surface utile plus grande est en cours de réalisation afin de mesurer le nombre de neutrons diffusés aux différentes énergies.

RÉFÉRENCES

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- [2] Neutron Cross Sections, BNL-325, 2^e éd. (1958).
- [3] EVANS, R. D., *The Atomic Nucleus*, Mc Graw Hill (1955).
- [4] LOVE, T. A. et MURRAY, R. B., Fast Neutron Spectroscopy, *I.R.E. Trans. NS8* 1 (1961) 91—97.

DISCUSSION

H. L. Anderson (United States of America): Could any of the speakers state what is the absolute efficiency for neutron detection in their solid-state neutron detectors?

C. J. Borkowski (United States of America): The efficiency for fast neutrons around 2 MeV is about 10^{-6} , and for thermals about 10^{-3} .

E. M. Gunnerson (United Kingdom): I would like to ask Mr. Borkowski two questions. Firstly, have surface barrier counters without gold layer been used at all for fission fragment work? And secondly, in his counting on alpha particles, where a resolution of 13.5 keV was observed, could he tell me what was the counting period involved?—in other words, what was the contribution from electronics drift and electronic noise?

C. J. Borkowski: The counting period for the alpha spectra where a figure of 13.5 keV was obtained was reasonably short—of the order of about one and a half or two hours. To the first question the answer is no, we have not as yet made any measurements using surface barrier detectors without gold layers deposited over them.

J. V. Kane (United States of America): I would like to make a comment. I am very impressed with the fact that Mr. Borkowski's counter gets a 3-kV bias, and I would like to ask him how the Bi^{207} spectrum appears at the higher values of bias; the curve shown is for only 500-V bias.

C. J. Borkowski: We have not obtained very many spectra at much higher voltages. We have run Bi^{207} at 1500 V for example, and the resolution is somewhat poor, but for 1-MeV beta particles the range is around a little over a millimeter, so that at 650 V the depletion region for Bi^{207} was not deep enough to take care of the highest energy conversion electron.

K. Behringer (Switzerland): Mr. Borkowski told us that he cooled down the crystals to the temperature of liquid nitrogen. How many times can this be done without damaging or changing the counter characteristics?

C. J. Borkowski: A fairly large number of times. The coefficient of expansion of the ceramic material which is placed around the silicon wafer has been matched to the thermal expansion coefficient of the silicon and since only a minimum of epoxy resin is used, the thermal expansions are reasonably well matched and they do survive repeated dunking in liquid nitrogen.

K. Kandiah (United Kingdom): I would like to ask Mr. Borkowski whether in his plot of resolution against capacitance, the time-constant of the amplifier was kept at a fixed value, and if so, what that value was.

C. J. Borkowski: The time-constant was kept at a constant value, and was about 1 μs .

B. de Cosnac (France): Has Mr. Borkowski studied fast neutron spectra from a reactor?

C. J. Borkowski: A preliminary observation was made on the fission-neutron spectrum emanating from a light-water reactor, and a five-to-one foreground-to-background measurement was obtained for the fission neutron spectrum.

B. de Cosnac: Have you managed to get rid of the noise due to n, p reaction with silicon?

C. J. Borkowski: No, certainly one still observes some of the n, p in silicon reactions. However, different spectra are still obtained of the order of 5 to 1, between the background with lithium fluoride on the surface barrier detector, and without it.

B. de Cosnac: How many pulses can the spectrometer count before being destroyed by neutrons?

C. J. Borkowski: We have very little information on the life of these detectors with respect to fast-neutron damage. They have been used for many days, for example, at counting rates, of the order of 10000 fast-neutron counts/s; this is the only information I can give you.

H. L. Anderson: I would like to ask Mr. Borkowski why, on one of his slides, the L X-ray energy was shown as greater than the K X-ray energy?

C. J. Borkowski: The K conversion is the 974 keV. The L conversion should be on the higher energy level. The binding energy of the L electron is obviously less than that of the K.

N. Vylkov (Romania): I have a question for Mr. Borkowski. In his installation for neutron detection with semi-conductors he introduced a discrimination threshold for the rejection of random coincidences. Was this discrimination threshold introduced in the H^3 channel, or the alpha channel, or the sum channel? Also, why was the threshold established at only 1.5 MeV, when the energy threshold of the reaction $Li^6(n, \alpha)H^3$ is about 5 MeV?

C. J. Borkowski: The second question, I believe, was why the discriminator bias was set at 1.5 MeV on the alpha and tritium channel. It was found empirically that no more than about 5% of the neutron pulses were lost by setting the discriminator at this bias for lower energy measurements, and the main concern was with the lower energy groups. The answer to the first question is that the discriminator bias was not introduced into the sum channel but into the two single channels. A coincidence of two pulses, each of which was above 1.5 MeV, opened the gate to the multi-channel analyser.

M. Paic (Yugoslavia): In connection with Mr. de Cosnac's paper I wish to ask what was the energy of the incident neutrons for inelastic scattering on Al. Secondly, what was the approximate total time required to obtain the spectrum of the neutrons scattered on aluminium?

B. de Cosnac (France): The energy of the incident neutrons, was 3.6 MeV. The flux on the diode was very low since the counting lasted three hours.

PROPRIÉTÉS DES JONCTIONS NIP DE SILICIUM—APPLICATION A LA DETECTION DES PARTICULES RELATIVISTES

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FRANCE

Abstract — Résumé — Аннотация — Resumen

Properties of silicon n-i-p junctions — application to the detection of relativist particles.
An account is given of experience gained at the CENS on the detection of nuclear particles by semiconductors.

One type of detector, of pin structure, has been specially studied. In comparison with the usual p-n or npp⁺ structures, and given an equal purity of the base material, it has the advantage of permitting a larger effective volume for the following reasons: (a) with an equal potential difference applied to the crystal, the total thickness of the barrier layers is greater; (b) with an equal reverse current, the maximum potential difference which they can withstand is greater; (c) other things being equal, their capacitance per unit of area is smaller and hence the permitted maximum surface is greater.

A detailed description is given of methods of obtaining pin structures in silicon, the intermediate zone reaching 1 mm.

Lastly, certain applications of these detectors are described: α and γ spectroscopy and the measurement of dE/dX for relativistic particles.

Propriété des jonctions nip de silicium — Application à la détection des particules relativistes.
Les auteurs exposent l'expérience acquise au CENS sur la détection des particules nucléaires par les semi-conducteurs.

Un type de détecteur, de structure pin, a été particulièrement étudié. Il présente par rapport aux structures classiques pn ou npp⁺, et à pureté égale du matériau de départ, l'avantage de permettre un volume sensible plus grand. En effet: a) à différence de potentiel égale appliquée au cristal, l'épaisseur totale des barrières est plus importante; b) à courant inverse égal, la d.d.p. maximum qu'ils supportent est plus grande; c) toutes choses égales d'ailleurs, leur capacité par unité d'aire est plus faible et la surface maximum permise est donc plus grande.

Les auteurs décrivent en détail quelques procédés permettant d'obtenir des structures pin dans le silicium, la zone intermédiaire atteignant 1 mm.

Enfin, ils décrivent quelques applications de ces détecteurs: spectroscopie α et γ , mesure de dE/dX pour les particules relativistes.

Свойства перехода р-і-п в кремнии — применение к обнаружению релятивистских частиц.
В данной работе говорится об опыте, проведенном в Центре ядерных исследований в Сакле, в области обнаружения ядерных частиц с помощью полупроводников.

В частности, изучался тип детектора с переходом р-і-п. По сравнению с обычными переходами р-п или npp⁺ и при условии равной чистоты исходного материала, этот переход имеет преимущество, заключающееся в более высокой чувствительности; действительно: 1) при равной разности потенциалов, приложенной к кристаллу, самым важным является общая толщина барьеров; 2) при равном обратном токе максимальная разность потенциалов, которую они выдерживают, более высока; 3) при других равных величинах их емкость на единицу поверхности ниже, а максимально допустимая поверхность выше.

В работе подробно описываются некоторые методы, позволяющие получить переход р-і-п в кремнии с промежуточной зоной в 1 мм.

Наконец, будут описаны некоторые виды применения этих детекторов: альфа- и гамма-спектроскопия, измерение dE/dX для релятивистских частиц.

Propiedades de estructuras nip de silicio — Aplicación a la detección de partículas relativistas. Los autores describen la experiencia adquirida en el CENS, en lo que se refiere a la detección de partículas nucleares por medio de semiconductores.

Han estudiado especialmente cierto tipo de detector, de estructura pin. Suponiendo que se trabaje con materiales de igual pureza inicial, este dispositivo presenta, con respecto a los aparatos de estructura corriente pn ó npp⁺, la ventaja de poseer un mayor volumen sensible. En efecto: a) a igual diferencia de potencial aplicada al cristal, el espesor total de las barreras es mayor; b) a igualdad de la corriente inversa, la máxima diferencia de potencial que admiten es mayor; c) siendo iguales todas las demás condiciones, su capacidad por unidad de superficie es menor y la máxima superficie admisible es, pues, más elevada.

Los autores describen detalladamente ciertos procedimientos que permiten obtener estructuras pin en el silicio, con un espesor de zona intermedia que alcanza a 1 mm.

Finalmente, describen algunas aplicaciones de estos detectores, tales como la espectroscopia α y γ , y la medida de dE/dX en el caso de las partículas relativistas.

Introduction

Le domaine d'application des détecteurs à semi-conducteurs était limité, il y a un an, à la détection de particules d'énergie comprise entre 100 keV et 30 MeV. Les limites d'utilisation étaient dues d'une part au bruit de fond du cristal et du dispositif amplificateur associé et d'autre part aux faibles dimensions du cristal, qui empêchaient de détecter les particules perdant trop peu d'énergie dans le cristal ou de mesurer l'énergie de celles dont le parcours n'était pas compris entièrement dans le cristal.

La réalisation de détecteurs de grandes dimensions, grâce notamment à l'utilisation de silicium de très haute résistivité (silicium compensé au lithium, à l'or), a permis des mesures précises avec des particules ayant un faible pouvoir d'ionisation: β , γ , particules au minimum d'ionisation [1]. Nous décrivons ici une expérience réalisée pour mesurer la perte d'énergie subie par des particules de grande énergie (protons et mésons π d'impulsion comprise entre 0,6 GeV/c et 1,5 GeV/c) en traversant une épaisseur connue de silicium. Ces expériences ont été réalisées avec des diodes de structure NIP utilisant du silicium de haute résistivité et du silicium compensé au lithium obtenus par la méthode de PELL [2].

Caractéristiques des structures nip réalisées par diffusion de bore et de phosphore dans du silicium

Les dimensions géométriques sont: $5 \times 3,2 \times 0,3$ mm. Les profondeurs de diffusion du phosphore et du bore sont respectivement de 30μ et 40μ . Le courant inverse est égal à $0,2 \pm 0,1 \mu A$ pour une différence de potentiel appliquée en inverse de 300 V. La dispersion indiquée correspond à vingt-cinq détecteurs*.

La figure 2 indique la valeur de la capacité en fonction de la différence de potentiel appliquée au cristal pour deux séries de diodes utilisant des silicium différents. On voit que la région de charge d'espace remplit toute la partie intermédiaire du cristal respectivement pour 325 V et 25 V, ce qui correspond à $e_1 = 1440 \Omega/cm$ et $e_2 = 24000 \Omega/cm$ pour les résistivités des silicium utilisés.

Le bruit de fond total dû au détecteur et au dispositif électronique d'amplification, pour des constantes de temps d'intégration et de différenciation égales à 10^{-6} s, est égal à 16 keV, le bruit de fond équivalent de l'amplificateur seul étant égal à 13 keV.

* Réalisés, sur notre demande, par la Compagnie française Thomson-Houston.

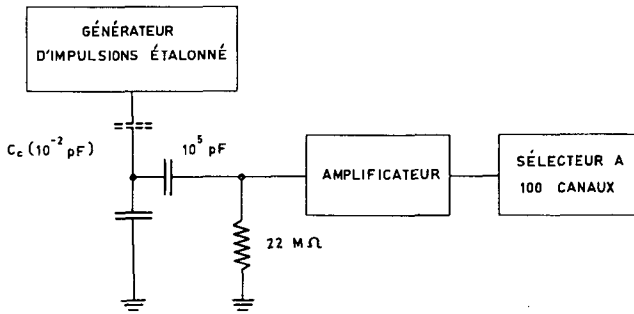


Figure 1

Dispositif expérimental pour l'étalonnage en énergie.

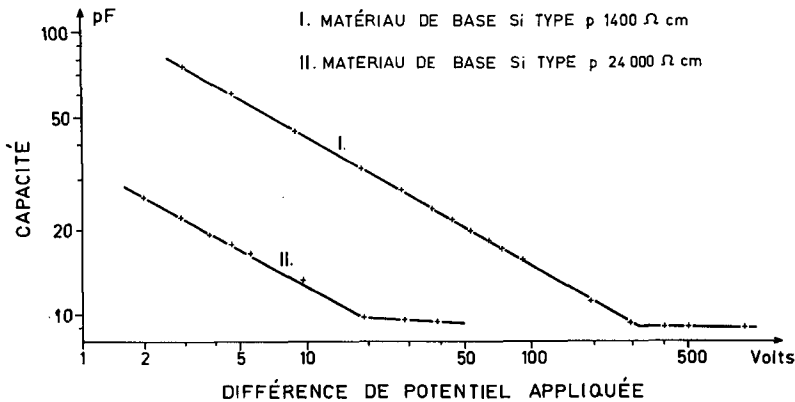


Figure 2

Diodes NIP. Variation de la capacité en fonction de la différence de potentiel appliquée.

- I. Matériau de base: Si type p, 1400/cm
 II. Matériau de base: Si type p, 24000/cm

COEFFICIENT DE COLLECTION

La diode est placée sous vide et des particules α issues d'une source de ^{239}Pu (5,15 MeV) placée à 10 cm du détecteur pénètrent dans ce dernier parallèlement au plan des jonctions NP et PP+.

Les impulsions, observées aux bornes du cristal sont amplifiées et analysées en amplitude avec un sélecteur à cent canaux (fig. 1). L'amplificateur est utilisé avec les mêmes constantes de temps que précédemment. Un générateur d'impulsions étalonnées en amplitude à 1 % près permet d'injecter dans le cristal, à travers une faible capacité C_c , une quantité de charges connue. On a étalonné le nombre de ces charges en les comparant au nombre de charges fournies par les rayons α dans la diode. En effet, on peut admettre que la diode nip collecte 100 % des charges créées, car on a pu mettre en évidence la

différence du nombre des charges collectées avec une diode à barrière de surface*, l'écart correspondant à l'absorption des rayons α dans la couche d'or couvrant la jonction (12 keV).

Caractéristiques des diodes nip au lithium

FABRICATION

Une plaquette de silicium de type P, de résistivité $1000 \Omega/\text{cm}$, est polie sur ses six faces. Un eutectique aluminium-silicium est formé sur une face. Le lithium est évaporé sous vide, puis diffusé sous vide pendant 90 s à 450°C pour former une jonction PN.

Pour accroître la région de charge d'espace, un champ électrique est appliqué dans le sens du champ naturel de la barrière, à une température telle que seuls les ions Li^+ migrent et viennent compenser les impuretés acceptrices. La vitesse de diffusion thermique est négligeable devant la vitesse de déplacement par le champ à la température considérée.

La migration est faite à 135°C pendant 10 heures, sous une différence de potentiel de 250 V. L'épaisseur intrinsèque ainsi obtenue est 800μ (fig. 3).

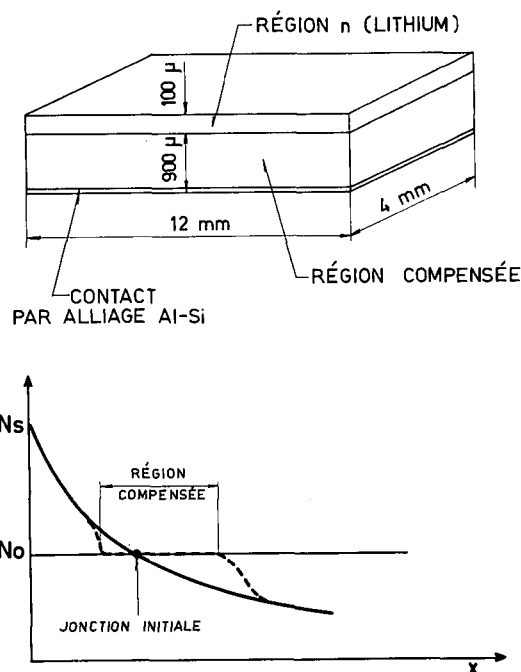


Figure 3
Diode au lithium.

* Réalisées par J. Bok, du Service d'étude de protections de piles du Commissariat à l'énergie atomique.

CARACTÉRISTIQUES

La figure 4 indique les variations de capacité en fonction des différences de potentiel appliquées avant et après compensation.

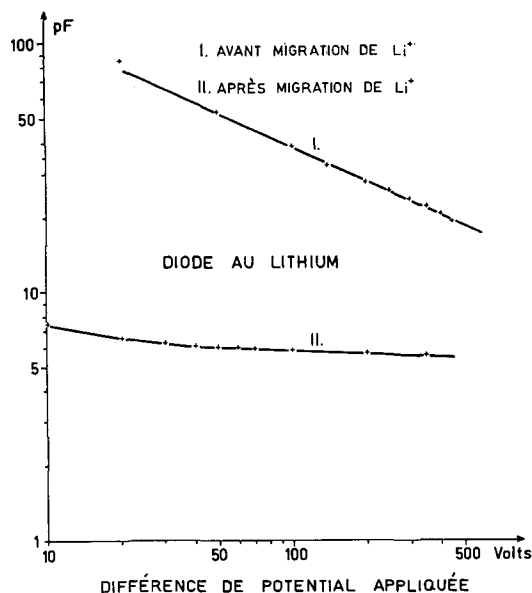


Figure 4

Diode au lithium. Variation de la capacité en fonction de la différence de potentiel appliquée.

I. Avant migration de Li^+
II. Après migration de Li^+

La capacité obtenue est faible, et varie très peu dès que la différence de potentiel atteint 20 V; elle vaut alors 0,14 pF/mm².

Le courant inverse mesuré sous vide est 0,35 μA à 100 V.

Laissées à l'air, le courant inverse et le bruit de ces diodes augmentent, mais elles récupèrent leurs caractéristiques quand on les remet sous vide.

Détection des particules relativistes et Mesure de la perte spécifique d'énergie

DISPOSITIF EXPÉRIMENTAL

L'expérience est réalisée avec des mésons π^+ et π^- , fournis par le synchrocyclotron SATURNE. Un aimant défecteur et trois lentilles quadrupolaires permettent de sélectionner les particules d'impulsion connue avec une précision égale à $\pm 3\%$ sur l'étendue de l'image (5,3 cm) [5].

Deux collimateurs en plomb et en acier de longueur 1 m et de diamètre 20 cm sont placés après l'aimant. Le détecteur est disposé au centre de l'image, à une distance du plan de sortie de l'aimant égale à 9 m.

L'analyse du faisceau par scintillations a montré que les mésons π^+ étaient accompagnés de protons et de deutons, les intensités respectives étant dans les rapports 22, 80, 3 [6].

Les détecteurs utilisés sont: a) les jonctions nip décrites précédemment, placées d'une part perpendiculairement au faisceau (surface de la diode: 16 mm^2 , épaisseur: $0,23 \text{ mm}$), d'autre part parallèlement au faisceau (surface utile: $1,15 \text{ mm}^2$, épaisseur: $4,93 \text{ mm}$); b) une jonction nip obtenue par compensation du silicium par le lithium. La diode, qui a une surface de 48 mm^2 et une épaisseur utile de 800μ , est placée perpendiculairement au faisceau.

Utilisés dans l'air en présence du faisceau, ces détecteurs ont un bruit de fond qui est beaucoup plus fort qu'en l'absence de faisceau; on les a donc toujours placés sous vide.

L'étalonnage en énergie a été réalisé comme on a vu précédemment.

RÉSULTATS EXPÉRIMENTAUX

Comme l'ont déjà montré d'autres auteurs [7] [8], il est possible de détecter des particules relativistes avec des diodes.

Nous avons d'abord tracé les courbes donnant les valeurs de la perte d'énergie totale dE/dx en fonction de l'impulsion pour les particules suivantes: mésons π^+ et π^- , et protons.

En fait, pour chaque valeur de l'impulsion, le dE/dx est affecté d'une répartition spectrale en fonction du numéro du canal du sélecteur d'amplitude, à cause de fluctuations d'origine physiques (effet Landau) dont nous discuterons plus loin.

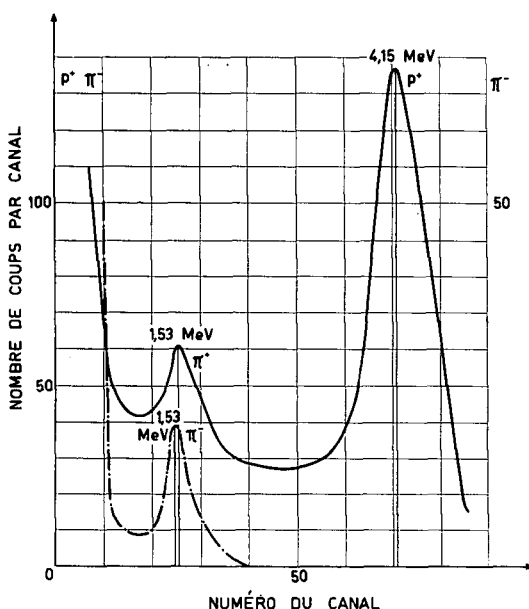


Figure 5

Diode au silicium NIP 14 ($24 \text{ k}\Omega/\text{cm}$). Impulsion: $615 \text{ MeV}/c$.

Lorsque l'on fait croître l'impulsion de 0,5 à 1,5 GeV/c, on constate que la perte spécifique d'énergie dE/dx diminue de 70 % pour les protons, alors qu'elle reste constante, à 1 % près, pour les mésons π^+ et π^- (ces derniers sont en effet au minimum d'ionisation, à peu de choses près, dans tout ce domaine d'impulsions).

La possibilité de discrimination de mésons d'impulsions différentes est donc impossible dans ce domaine, par cette méthode, alors que l'on peut distinguer facilement deux protons dont l'impulsion diffère de 150 MeV/c (au voisinage de 1 GeV/c); ceci correspond à une différence de 200 keV/g cm² dans les pertes d'énergie spécifique (la limitation est due uniquement à l'effet Landau).

A fortiori, on peut par cette méthode distinguer des mésons et des protons ayant la même impulsion (jusqu'à 2 GeV/c).

Les courbes des figures 5 et 6 sont obtenues avec une épaisseur traversée de silicium égale à 4,93 mm, celle de la figure 7 avec une épaisseur de 230 μ (cette dernière épaisseur a été obtenue par mesure de la capacité électrostatique de la jonction, alors que la première a été déterminée par mesure directe au palmer). Ces courbes correspondent respectivement à trois valeurs d'impulsions: 615, 787 et 1000 MeV/c.

La précision sur les valeurs de dE/dx à l'endroit des pics est 2 %.

Remarquons que la petite différence dans la position de l'abscisse des pics relatifs aux pions⁺ et ⁻ qui apparaît sur la figure 5 est un artefact dû à une légère variation accidentelle de capacité à l'entrée du préamplificateur.

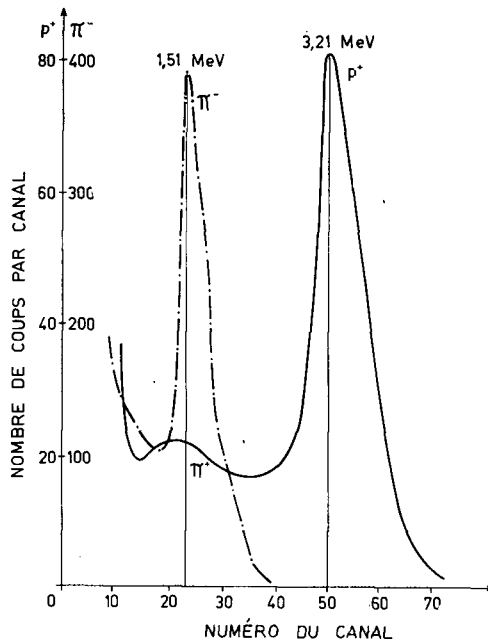


Figure 6
Diode au silicium NIP 14 (24 k Ω /cm). Impulsion: 787 MeV/c,

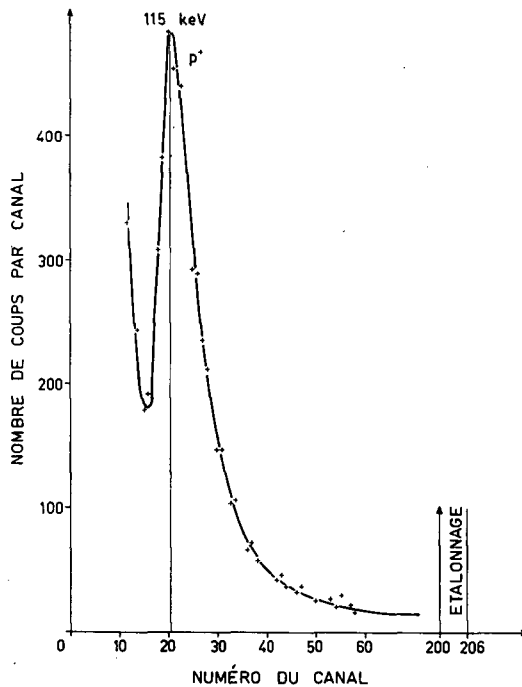


Figure 7

Spectre de protons. Diode au silicium NIP 7 (1450 Ω/cm) normale au faisceau $V = -330\text{V}$. Impulsion: 1 GeV/c

Dans le tableau I et sur la figure 8, on a porté, pour les protons et les pions ayant une impulsion donnée, les valeurs calculées et les valeurs mesurées de la perte la plus probable d'énergie. Ces valeurs sont relatives à des épaisseurs traversées de silicium égales à 4,93 et 0,23 mm.

Les valeurs calculées ont été obtenues, pour le silicium, à partir des formules données par Rossi [9], et en tenant compte de l'effet de densité, d'après les données de STERN-

TABLEAU I

PERTE D'ÉNERGIE LA PLUS PROBABLE*

Parcours utile (mm)	Impulsion (MeV/c)	Pions		Protons		Protons Rapport calcul mesure
		Calcul (MeV/g cm^2)	mesure (cm^2)	Calcul (MeV/g cm^2)	mesure (cm^2)	
4,93	615	1,337	1,30	3,64	3,51	1,037
4,93	787	1,339	1,27	2,80	2,62	1,069
4,93	984	1,340	1,28	2,23	2,09	1,067
0,23	1000	1,340		2,21	2,08	1,062
4,93	1478	1,34		1,67	1,54	1,032

* Calculée d'après B. Rossi. (Mesurée avec un détecteur nip de silicium, l'énergie moyenne d'ionisation étant supposée égale à 3,50 eV.)

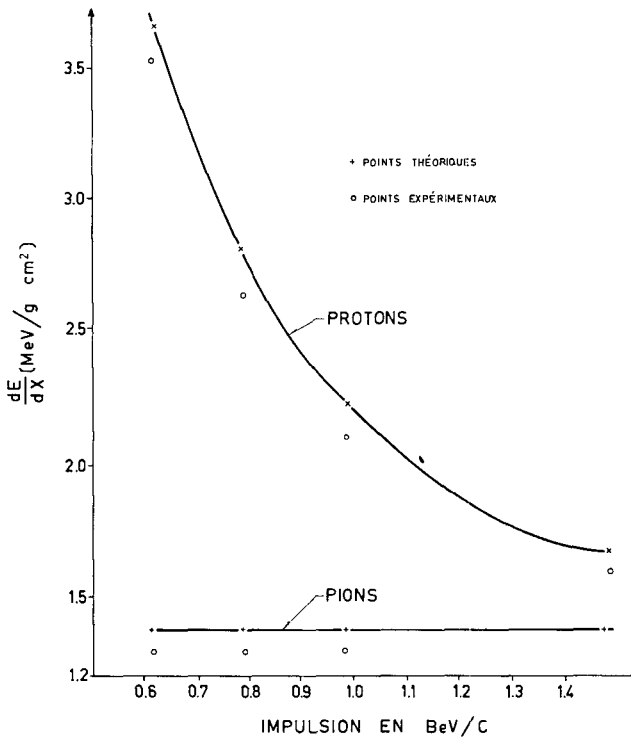


Figure 8

Perte d'énergie la plus probable des pions et des protons en fonction de l'impulsion.

+ Points théoriques
o Points expérimentaux

HEIMER [10]. Le potentiel d'ionisation I qui intervient dans les formules utilisées a été pris égal à 179,5 eV.

On constate un écart systématique entre les valeurs expérimentales et les valeurs calculées, ces dernières étant supérieures de 5% en moyenne. L'origine de cette erreur systématique est probablement la divergence du faisceau de particules (environ 5°), qui amène un déplacement vers les valeurs inférieures du maximum du spectre.

DISCUSSION DES RÉSULTATS

Les valeurs expérimentales ont été obtenues en supposant que l'énergie moyenne de création d'une paire électron-trou dans le silicium était la même (3,50 eV) pour les particules relativistes considérées que pour des particules α de quelques MeV. En effet, le dispositif de mesure a été étalonné en énergie en prenant comme référence le nombre de paires électrons-trous produites par un rayon α de 5,147 MeV dans un cristal de silicium. Certaines raisons théoriques [11] et expérimentales [12] laissent en effet penser que la valeur de 3,50 eV par paire est indépendante de l'énergie et de la nature de la particule incidente. Une différence de quelques pour cent sur cette valeur n'est cependant

pas exclue: elle expliquerait en partie la différence constatée entre les résultats expérimentaux et les valeurs calculées.

Nous n'avons pu vérifier avec une bonne précision que la forme de la répartition spectrale obtenue correspondait bien à la forme théorique prévue par Landau, en particulier du côté des basses énergies, à cause des effets parasites cités plus haut et des effets de bord du détecteur.

Des courbes expérimentales autres que celles qui sont indiquées sur les figures 5, 6 et 7 ont été tracées, en particulier avec la diode nip épaisse au lithium citée plus haut. Les résultats ont la même précision qu'avec les détecteurs au silicium, à cause de la prépondérance de ces effets parasites.

Conclusions

Les diodes à jonction nip utilisées par la tranche permettent la mesure précise de faibles énergies, ou de faibles pertes d'énergie telles que celles que subissent les particules au voisinage du minimum d'ionisation.

Par ailleurs, les diodes au lithium permettent d'obtenir des épaisseurs intrinsèques allant jusqu'à quelques millimètres, ce qui rend possible l'attaque transversale de la diode par le faisceau de particules, plus facile à mettre en œuvre que l'attaque longitudinale.

REMERCIEMENTS

Nous remercions le groupe des physiciens des Hautes Energies de Saclay, en particulier P. Falk-Vairant et G. Valladas, pour l'aide précieuse qu'ils nous ont apportée lors de ces expériences.

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DISCUSSION

A. Roberts (United States of America): In view of the importance of the Landau effect, could Mrs. Koch say whether the resolution which it is possible to obtain with the semi-conductor detectors is any better than it is, say, with a scintillation counter and a photomultiplier? The limiting factor seems to be the spread in energy loss due to the Landau effect.

Mrs. L. Koch (France): No, I do not think we can obtain a better resolution with a semi-conductor detector, precisely because of the spread due to the Landau effect; this represents a dE/dx spread of 30% for a particle of momentum 1 GeV/c. It was not the aim of the experiment to obtain better resolution. We wished to verify that we could

discriminate between high-energy particles, using semi-conductor detectors, and we wished also to verify that in silicon the energy loss was that to be expected from the theoretical calculations of B. Rossi.

H. E. Wegner (United States of America): In connection with the previous question, Cranshaw discusses this problem in detail and points out the relationship for resolution in terms of the energy lost in the detector and the ionization efficiency. A simple formula is obtained for losses of 10% or more; for smaller losses, what is normally involved is the statistics of the delta rays produced in the solid material, not the ionization efficiency of the material or the light efficiency or anything else. The conclusion is that most dE/dx detectors will have equivalent resolution capabilities.

CHARGE COLLECTION IN SEMICONDUCTOR RADIATION DETECTORS

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Abstract — Résumé — Аннотация — Resumen

Charge collection in semiconductor radiation detectors. Semiconductor particle-detectors operate like ion chambers by collecting the charge liberated by an incident-ionizing particle. However the mechanism of charge collection is much more complicated than that of the ion chamber, depending in detail on the properties of the semiconductor, the potential distribution in the device and the ionization density along the initial track. Loss of charge can be attributed to two effects—recombination along the initial track and subsequent trapping of the moving carriers. These effects can be separated by using particles of widely differing ionization densities. Such investigations have been carried out for various silicon devices fabricated in different ways and covering a wide range of resistivities. Analytical results have been derived applicable to the general case of charge loss through trapping, and some results have also been obtained concerning recombination loss.

Collection de la charge dans les détecteurs de rayonnements à semi-conducteurs. Les détecteurs de particules à semi-conducteurs fonctionnent comme des chambres d'ionisation du fait qu'ils collectent la charge libérée par une particule ionisante incidente. Cependant, le mécanisme de collection est beaucoup plus compliqué que dans le cas de la chambre d'ionisation; il dépend étroitement des propriétés du semi-conducteur, de la distribution du potentiel dans le dispositif et de la densité d'ionisation le long du parcours initial. La perte de charges peut avoir deux causes, savoir: la recombinaison le long du parcours initial et la capture ultérieure des porteurs de charge. On peut distinguer ces causes en utilisant des particules à densités d'ionisation extrêmement différentes. Des études de ce genre ont été effectuées pour toute une gamme de dispositifs au silicium, construits de diverses façons et ayant des résistivités très différentes. Ils ont obtenu des résultats analytiques qui sont applicables au cas général de la perte de charges par capture; ils ont également trouvé quelques résultats relatifs à la perte par recombinaison.

Накопление заряда в полупроводниковых радиационных детекторах. Полупроводниковые детекторы частиц действуют как ионные камеры, собирая заряд, высвобождаемый случайными ионизирующими частицами. Но механизм сбора заряда является гораздо более сложным, чем в случае с ионной камерой, завися в деталях от свойств полупроводника, потенциального распределения в приборе и плотности ионизации вдоль первоначального трека. Потеря заряда может быть отнесена за счет двух эффектов: рекомбинации вдоль первоначального трека и последующего захвата двигающихся носителей. Эти воздействия можно разделить, если использовать частицы совершенно различных плотностей ионизации. Такие исследования проводятся для различных кремниевых приборов, изготовленных различными способами и охватывающих самые различные сопротивления. Были получены аналитические результаты, применимые к общему случаю потери энергии посредством захвата, а также некоторые результаты по потере рекомбинации.

Recolección de cargas eléctricas en detectores de radiación a base de semiconductores. Los detectores de partículas a base de semiconductores trabajan, lo mismo que las cámaras de ionización, recogiendo la carga liberada por una partícula ionizante incidente. Sin embargo, el mecanismo de recolección de la carga es mucho más complicado que en el caso de la cámara

de iones, ya que depende en particular de las propiedades del semiconductor, de la distribución del potencial en el dispositivo, y de la densidad de ionización a lo largo de la traza inicial. La pérdida de carga puede atribuirse a dos efectos, a saber, a una recombinación a lo largo de la traza inicial y a una ulterior captura de los portadores en movimiento. Es posible separar ambos efectos recurriendo a partículas de densidades de ionización muy diferentes. Los autores llevaron a cabo tales experimentos con una serie de dispositivos a base de silicio preparados en diversas formas cubriendo una amplia gama de resistividades. Alcanzaron resultados analíticos aplicables al caso general de la pérdida de carga por captura y también lograron algunos resultados en lo referente a la pérdida por recombinación.

I. Introduction

Consider an ionizing particle incident on a semiconductor detector as shown in Fig. 1. In general the particle has to traverse a surface of the detector and this surface may or may not exhibit a "dead layer" effect; i.e. extract energy from the particle without giving any corresponding contribution to the signal. This dead layer effect is not discussed here. Once inside the detector, the particle produces a certain number of hole-electron pairs corresponding to the energy that it loses in this region. This charge constitutes the signal information and its motion in the electric field across the device produces the signal current in the external circuit. Suppose that Q_L is the liberated charge, given by

$$Q_L = \frac{qE}{\varepsilon} \times 10^6 \quad (1)$$

where E = energy in MeV lost by the incident particle,

ε = average energy in eV required to form a hole-electron pair,

q = electronic charge.

And suppose that Q_C is the collected charge: then one can denote the collection efficiency, η , by [1]

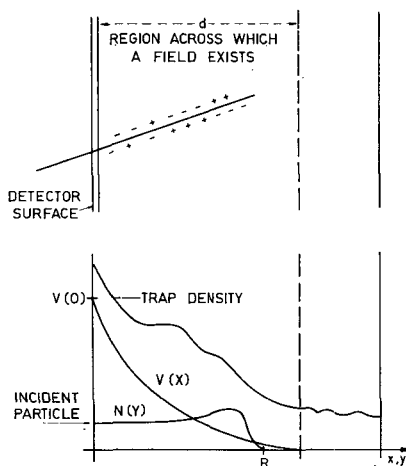
$$\eta = Q_C/Q_L \quad (2)$$

Furthermore, it is easy to show that the collected charge is the liberated charge multiplied by the fraction of the voltage across the device traversed by the charge, i.e.

$$Q_C = Q_L \frac{\Delta V}{V} \quad (3)$$

From this it follows that the basic mechanism responsible for the inefficient charge collection is the prevention of the charge carriers from traversing the entire voltage across the device. This can occur in two ways. Either carriers can be trapped in transit across the device or else they can recombine along the initial track. These two processes will be discussed in detail, but first a general remark will be made regarding equation (3). Given any particular detector, the voltage across it will be some function of the distance $V(x)$. It follows from (3) that the most important regions of a detector are in the neighbourhood of any maximum of $V(x)$. It is well known that the voltage distribution across a p-n junction, of the kind most often used for particle detection, is parabolic; hence the most important region of such a detector regarding trapping or recombination is near the extreme front surface. This is an unfortunate fact since

it is just this region that is most likely to possess the highest density of traps and recombination centres due to the diffusion of impurities from the crystal surface. It is worth emphasizing that, in consequence, detectors not made by high-temperature processes, e.g. surface barriers and devices produced by low-temperature diffusions, possess inherent advantages in this respect.



Figs. 1 and 2

Situation in semiconductor particle detector

The effects of incomplete charge collection manifest themselves in a number of ways. One is that it is sometimes found, particularly in devices produced by high-temperature diffusion, that mono-energetic particles produce a spectrum consisting of a number of closely spaced peaks when displayed in the usual way on a multichannel analyser. This effect has been referred to as "multiple peaking." In other cases a detector can exhibit poor resolution, while showing no resolved structure, even though the noise-line width may be very narrow. This effect can be regarded as unresolved multiple peaking. Multiple peaking can be caused by non-uniform sheet resistance at the detector surfaces [2]. However, a more serious source of this difficulty arises from an inhomogeneous charge collection within the detector. The latter is the effect that will be considered here.

The effects of trapping and recombination can be separated in some cases in semiconductor detectors. This depends on the fact that in a diode, for example, there are practically no carriers in the depletion layer except for the small number in transit that constitute the bulk leakage current. Thus a single trapped carrier practically never sees a carrier of the other sign with which to recombine. However, if a carrier is trapped in the immediate vicinity of the initial highly ionized track of a heavy energetic incident particle, it may find a suitable carrier nearby with which to annihilate. Thus the effect of recombination may be expected to be important for fission fragments, while trapping may be expected to be the dominant source of charge loss for minimum ionizing particles.

Throughout it will be assumed that the situation investigated is that shown in Fig. 1, i.e. the collection process is being investigated only where an electric field exists. This excludes the case in which a particle traverses the depletion layer of a diode and produces ionization in the bulk undepleted material. The process of charge collection by diffusion from outside the depletion layer, exemplified by this case, can be treated by solving the diffusion equation [3].

II. Loss of carriers through trapping

In this section it will be assumed that the only mechanism leading to imperfect charge collection is trapping. The kind of detector investigated is shown schematically in Fig. 2. Particles are assumed to be entering normally through the surface of the device from the left of the diagram, and this surface is assumed to be positive.

Let $N(y)$ = initial density distribution of hole-electron pairs produced by the incident particle

$V(x)$ = voltage distribution across the device

$\tau_{e,h}$ = electron and hole lifetimes

$\mu_{e,h}$ = electron and hole mobilities

$E = -\frac{dV}{dx}$ = electric field

R = incident particle range

d = distance over which an electric field exists;

then it can be shown that the charge collected due to the motion of holes and electrons respectively is given by

$$Q_c(h) = \frac{q}{V(0)} \int_0^R N(y) \int_y^d \exp\left(-\int_y^x \frac{dx}{\mu_h \tau_h E}\right) E dx dy \quad (4)$$

and

$$Q_c(e) = \frac{q}{V(0)} \int_0^R N(y) \int_0^y \exp\left(-\int_x^y \frac{dx}{\mu_e \tau_e E}\right) E dx dy. \quad (5)$$

The total collected charge, Q_C , is given by the sum of these.

These expressions are quite general and cover the case in which the only loss mechanism is trapping. It is assumed here that μ and τ are functions of the distance from the front surface. In general, of course, they also vary from point to point over the front surface. However only the simplest cases will be investigated here since the extension to more general ones is cumbersome and not very useful.

Two special cases will be examined, those of a conductivity counter and an abrupt junction diode.

CHARGE COLLECTION IN A CONDUCTIVITY COUNTER

Consider for example a gold-doped silicon, single-conductivity counter being used to detect α -particles. In this case one can set $N(y) = N \delta(y)$, where $\delta(y)$ is the delta

function, provided that the thickness, w , of the device is much larger than the α -particle range. Also $\frac{dV}{dx} = \text{constant} = E$ since the voltage drop across the device is linear.

Furthermore it is reasonable to take both μ and τ to be constants since the material is homogeneous. Substitution in (4) then gives immediately [4]

$$Q(h) = Q_c = Q_L \frac{\mu_h \tau_h E}{w} \left\{ 1 - \exp \left(- \frac{w}{\mu_h \tau_h E} \right) \right\}. \quad (6)$$

This contribution from the holes comprises the total signal since it can be shown that the electron contribution vanishes.

The quantity $\mu_h \tau_h E$ has the dimensions of a length and is referred to as the "hole-trapping length," the definition being exactly analogous to that of the diffusion length. It is clear from (11) that the condition for efficient collection is that the trapping length should be large compared with w .

The dependence of Q_c on E allows (6) to be employed to determine the lifetime for holes in gold-doped silicon [5]. Strictly speaking, this method only yields the mobility lifetime product, but μ_h can be determined separately to allow τ_h to be evaluated. Also by reversing the polarity of the applied electric field the contribution from (4) vanishes and (5) yields a result identical in form with (6), differing only in that $\mu_e \tau_e$ replaces $\mu_h \tau_h$. Hence τ_e may also be found.

The extension to the case of minimum ionizing particles is simple and can be found in the obvious way by setting $N(y) = \text{constant}$ in (4), (5) and proceeding as before.

CHARGE COLLECTION IN DIODES

The field distribution, assuming a step junction, is given by

$$E(x) = \frac{E_m}{w} (w - x) \quad (7)$$

where E_m is the maximum electric field and w is the width of the depletion layer. The factors involving the exponentials take the form

$$I = \exp \left(- \frac{1}{\mu \tau} \int_x^y \frac{dx}{E(x)} \right), \quad (8)$$

if it is assumed that $\mu \tau$ is a constant. This approximation will hold for example for surface barriers where the material should be homogeneous but may break down for diffused devices where a marked lifetime gradient can exist. If τ^{-1} is not constant but has for example some kind of error function dependence, the final expressions for the collected charge become too complicated to be useful.

Employing (4), (5), (7) and (8) one obtains

$$Q_c(e) = \frac{E_m q}{w V(0) (2 + \gamma_e)} \int_0^R N(y) \left\{ (w - y)^2 - w^2 + \gamma_e (w - y)^{-\gamma_e} \right\} dy \quad (9)$$

and

$$Q_c(h) = \frac{E_m q}{w V(0) (2 + \gamma_h)} \int_0^R N(y) (w - y)^2 dy \quad (10)$$

$$\text{Where } \gamma = w / \mu \tau E_m \quad (11)$$

These expressions are as far as one can go without making some definite assumption concerning $N(y)$, the ionization density along the track of the incident particle. A useful case to consider is that of uniform ionization along a track of length R containing a total of N pairs, i.e.

$$N(y) = \begin{cases} N(R), & 0 \leq y \leq R \leq w \\ 0, & R < y. \end{cases} \quad (12)$$

Two interesting cases now arise, those of $R \ll w$ and $R \gg w$. The first of these includes for example fission fragments incident on a thick counter and the second, $\frac{dE}{dx}$, and minimum ionizing detectors. These will be discussed in turn under the titles of "short" and "long" range, it being understood that here the range is being compared to the depletion length.

SHORT-RANGE PARTICLES. $R \ll w$

Using (10), (11) and (12) one obtains in the limit as $R/w \rightarrow 0$ the very simple form

$$\eta_h = \frac{2}{2 + \gamma_h}. \quad (13)$$

It is easy to see also that in this case $Q_c(e) = 0$. Hence the entire charge-collection efficiency is given by (13). Of course the appearance of γ_h here reflects the fact that at the outset it was assumed that the junction was n^+p . In the case of a p^+n surface barrier, for example, the situation would be reversed, the electrons making the long trip and γ_h being replaced by γ_e in (13).

It is instructive to examine the way in which (13) depends on the applied bias voltage.

Using the fact that for n^+p junctions w in microns is given by $\sim \frac{1}{3} \sqrt{\rho V(0)}$ where ρ is the resistivity of the p region in ohm cm, one obtains

$$E_m \simeq 6 \times 10^4 \sqrt{V(0)/\rho}. \quad (14)$$

Hence

$$\gamma \simeq 6 \times 10^{-10} \left(\frac{\rho}{\mu \tau} \right) \quad (15)$$

with appropriate choice of μ and τ for γ_e or γ_h . The remarkable thing about this expression for γ is that it is independent of bias. Hence from (13) the collection efficiency also is independent of bias. Furthermore this indicates why lower resistivity materials generally tend to make better counters. This is, of course, physically obvious since the

electric field is increasing, making the carriers move faster, and simultaneously w decreases so the carriers do not have so far to go. Both these factors tend to improve the collection efficiency and this is indicated by (13) and (15). On substituting reasonable numbers it becomes clear that charge loss due to the mechanisms discussed here should be generally quite small. For example, in a diffused junction with $\rho \sim 10 \text{ k}\Omega \text{ cm}$ and a lifetime as short as $1 \mu\text{s}$, only $\sim 0.5\%$ charge loss will occur. On the other hand, as soon as τ becomes really small, for example in a damaged region of the crystal or in gold-doped material where the lifetime may be measured in nanoseconds, this mechanism takes hold and can lead to low collection efficiencies.

A point worth noting in deriving (13) is that the assumption has been made that the field is sufficiently low so that the mobility is field independent [6]. This therefore imposes a restriction on E_m . In fact, if one assumes linearity holds up to carrier velocities of $\sim 10^6 \text{ cm s}^{-1}$, then this implies E_m must be less than $2 \times 10^3 \text{ V cm}^{-1}$. Using (14) this means that the analysis is only valid if

$$\sqrt{V(0)/\rho} < \sim \frac{1}{10}. \quad (16)$$

Violation of this condition will lead to a decrease in η below that given by (13) and (15). Hence, in a low resistivity counter with very poor lifetime, one might even expect the collection efficiency to *decrease* monotonically with increasing bias for sufficiently high biases. However the analysis presented here should be applicable to high ρ devices.

LONG-RANGE PARTICLES. $R \gg w$

Using (9) through (12) and setting $R = w$, one finally obtains

$$\eta = \frac{1}{3} \left(\frac{2}{2 + \gamma_h} \right) + \frac{2}{3} \left(\frac{2}{2 + \gamma_e} \right). \quad (17)$$

At first sight this result is surprising because it implies that two-thirds of the signal comes from the motion of the electrons and only one-third from the holes. However the reason for this can be shown to arise from the asymmetry of the potential distribution across a diode.

A consequence of (17) is that the signal from a minimum ionizing detector should be exactly proportional to its thickness no matter how poor its collection. Hence, for example, even for a gold-doped silicon surface-barrier diode (low τ_e and τ_h) one would expect the signal size to be accurately proportional to $\sqrt{V(0)}$. This is, of course, only true until the device is depleted clear through to the back contact; after that it is necessary to return to (4), (5) and use the appropriate new field distribution in place of (7) to find η .

The detection of γ -rays using semiconductor detectors certainly falls within the domain of the low-ionization density case. It is interesting to note that a device exhibiting a 6.8-keV line width for 120-keV γ -rays [7] was a poor α -counter and furthermore exhibited extremely bad collection efficiency for fission fragments. Since numerical estimates are made in a later section showing that if the fission results were attributed to trapping alone the trap density would be so high that it would markedly affect the

γ -results, this is taken as evidence that the mechanism of charge loss is different in the two cases.

However in some materials the trapping length itself is so short that it controls collection. Quite marked effects of this kind have been observed in diodes fabricated by diffusing zinc into $10^8 \Omega\text{-cm}$ GaAs. Shining light on these devices was found to increase η by as much as 30%. This can be attributed to the filling of some of the traps with optically generated carriers, thus rendering them ineffective and consequently increasing the electron trapping length.

Similar effects have also been reported in certain diffused silicon detectors [8].

On the whole, however, it can be safely asserted that if a detector is exhibiting low values of η it will probably have very poor resolution. This would not be the case if the device were extremely homogeneous, for example even $\eta = \frac{1}{2}$ in such a case would only reduce the resolution by $1/\sqrt{2}$. However it is always found in practice that very poor resolution results. This is interpreted as evidence for the existence of marked inhomogeneities on a small scale.

III. Loss of carriers through recombination

In this section it will be assumed that the only mechanism of charge loss is recombination. Recombination processes require the presence of carriers of both signs and hence depend strongly on the densities of both holes and electrons. The region of highest electron-hole pair density is in the vicinity of the incident particle track immediately after its passage. If the ionization density is high enough the resulting dense conducting plasma may be held together by its own electrostatic forces for a time of the order of nanoseconds [9]. Destruction of this plasma is assumed to take place by ambipolar diffusion inside its volume, which is a substantially field-free region, and erosion at its surface due to the presence of the external field. During the short time that the plasma is held together recombination processes may be important.

With the possible exception of electrons, it is usually the case that an incident particle produces a hole-electron density along its track that is large compared to (p_0, n_0) , the initial concentration. In such a case the rate of loss of carriers by recombination can be written

$$-\frac{dn}{dt} = \frac{n_x}{\tau_x} + np\sigma v + \frac{n}{\tau} \quad (18)$$

where the three terms on the right refer to different mechanisms; recombination via excitons, direct radiative recombination, and recombination on recombination centres, respectively. Definitions of the symbols in (18) will be given in the section devoted to each process.

RECOMBINATION VIA EXCITONS

An exciton is a positronium-like complex formed by the association of a free electron and hole. The relationship between the concentration of excitons and free carriers will first be examined. Let (n_T, p_T) be the electron and hole concentration produced by the incident particle, (n, p) be the free electron and free-hole concentration and n_x the exciton concentration. Then, since the charges are produced in pairs, $n_T = p_T$ and $n = p$. Furthermore it is clear that the total carrier concentration is given by

$$n_T = n + n_X. \quad (19)$$

At low total carrier-concentrations the relative populations in the conduction, valence and exciton bands can be shown on the basis of Boltzmann statistics to be connected by

$$\frac{n_x}{n_p} = \frac{N_x}{N_c N_v} e^{\epsilon_x/kT} \quad (20)$$

where the capital N 's denote the density of states in the exciton conduction and valence bands, and ϵ_x is the exciton binding energy. Assuming $N_x = N_c$ and using (19) results in

$$n_x = n_T + \frac{1}{2} N_v e^{-\epsilon_x/kT} \left[\frac{1}{2} \left(\frac{\epsilon_x/kT}{N_v e^{-\epsilon_x/kT}} \right)^2 + 4n_T N_v e^{-\epsilon_x/kT} \right] \quad (21)$$

for the exciton concentration as a function of n_T . This predicts that n_x increases with n_T in such a way that $n \ll n_T$ for high concentration. However for concentrations above about 10^{18} cm^{-3} the excitons formed begin to overlap and interact due to their large radii ($\sim 100 \text{ \AA}$). As the carrier concentration continues to increase it becomes meaningless to consider the binding of holes and electrons in exciton states. Using equation (21), setting $\epsilon_x = 0.008 \text{ V}$ [10], assuming $N_v \sim 10^{19}$ and modifying the result for the expected qualitative behaviour at high densities, results in Fig. 3. The exciton concentration at values of n_T greater than 10^{18} is not known in detail. However, for the present discussion, it is sufficient to say that n_x/n_T is not expected to continue to increase as the total carrier concentration increases above $\sim 10^{18} \text{ cm}^{-3}$ and for concentrations greater than $\sim 10^{19}$ the free carrier concentration can be equated approximately to the total carrier concentration.

Returning to the first term in equation (18), the fraction of pairs lost through exciton recombination is given by

$$\frac{\delta n}{n_T} = \left(\frac{n_x}{n_T} \right) \frac{\delta t}{\tau_x}. \quad (22)$$

Taking the extreme case of a plasma being held together for 10^{-8} s , the maximum $\frac{n_x}{n_T}$ from Fig. 3 and the measured exciton lifetime [10] τ_x of $6.5 \times 10^{-5} \text{ s}$ still results in less than a 0.001% carrier loss. Hence charge loss by recombination via excitons can be neglected.

DIRECT RADIATIVE RECOMBINATION

The second term in equation (18) concerns the direct radiative recombination of electrons and holes. Since this process depends on the np product it will have its largest effect at high carrier densities. Assuming the extreme case of a carrier density of $\sim 10^{20} \text{ cm}^{-3}$, roughly the highest value that can be produced by a fission fragment [11], assuming the hot carriers to be thermalized in $\sim 10^{-12} \text{ s}$ [11], using a cross-section [10] [12] of 10^{-21} cm^2 and a plasma time of 10^{-8} s , still only 1% of the pairs formed will be lost. This can be regarded as an extreme upper limit, and hence it is improbable that this

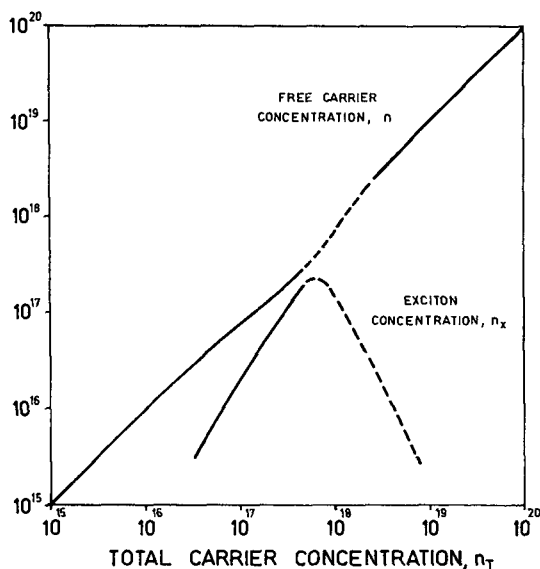


Fig. 3
Free carrier and exciton concentrations

mechanism can make a significant contribution to the large losses which have been observed.

RECOMBINATION ON RECOMBINATION CENTRES

The last term in equation (18) describes recombination via centres within the forbidden energy gap. The fractional carrier loss by this process is given by

$$\frac{\delta n}{n_T} = \frac{n}{n_T} \cdot \frac{\delta t}{\tau} = \frac{n N_R \sigma V}{n_T} \delta t \quad (23)$$

where N_R denotes the density of recombination centres, σ the recombination cross-section and V the thermal velocity of the carriers.

Due to lack of information on recombination centres in silicon it is not possible to calculate the expected carrier loss for the general case. The problem is complicated still further in devices made by high temperature diffusion by the introduction of gradients of known and unknown impurities. For this reason attention will be focused on the special case of a surface barrier detector made from high purity homogeneous n-type silicon. Significant carrier losses have been observed in such detectors by a number of workers, especially for fission fragments [13]. The previous argument will be reversed and σ will be computed from the measured charge loss for fission fragments.

Assume the detector to have 10^{14} cm^{-3} phosphorus donor levels. From Fig. 3 $n \approx n_T$. Assuming a plasma time of $2 \times 10^{-9} \text{ s}$ and a thermal velocity of 10^7 cm s^{-1} , a 10% charge loss results in $\sigma = 5 \times 10^{-14} \text{ cm}^2$.

The recombination process takes place in two stages, first the positively-charged, ionized-phosphorus atom captures an electron and then the resulting neutral complex

captures a hole. It is expected that the cross-section for the first step is much larger than that for the second because of the initial Coulomb attraction. The second step is therefore expected to be the rate limiting one. The estimated value of $5 \times 10^{-14} \text{ cm}^2$ appears reasonable in terms of presently available information for carrier capture by a neutral centre. For example a cross-section of $1 \times 10^{-14} \text{ cm}^2$ has been estimated for capture of an electron at room temperature by an indium impurity level in silicon, which had been previously neutralized by capturing a hole [14].

This mechanism may reasonably explain the observed carrier loss without having to invoke the presence of any other centres than are already known to exist in the base material. An important factor to be noted is that the *total* phosphorus concentration is important, not just the uncompensated part that leads to the observed conductivity. The compensating acceptors also may be expected to contribute their share to the recombination process. This mechanism may explain the large observed variations in collection efficiency between different materials having similar resistivity and lifetime.

This mechanism can be further investigated in a different way that does not involve direct knowledge of the capture cross-sections. This depends on the fact that the recombination lifetime is a function of the carrier density, given by [15]

$$\tau = \tau_0 \left(1 + \frac{n_T (\tau_{p0} + \tau_{n0})}{\tau_{p0} (n_0 + n_1) + \tau_{n0} (p_0 + p_1)} \right) / \left(1 + \frac{n_T}{n_0 + p_0} \right) \quad (24)$$

where τ_0 is the lifetime for very low injected carrier concentrations, τ_{p0} and τ_{n0} are the mean lifetimes for the capture of holes and electrons respectively on the centres of interest, and n_1, p_1 are the equilibrium electron and hole concentration that would exist if the Fermi level were located at the centre of interest. Making the assumption $\tau_{n0} = \tau_{p0}$ one can calculate τ/τ_0 as a function of n_T for centres at different distances from the band edges. The results of such a calculation for two levels are shown in Fig. 4. Centres near the middle of the gap, such as Au, Fe, etc. show little or no change in lifetime as n_T is increased.

Applying this information to recombination on phosphorus centres and taking $\tau_0 \approx 10^{-3} \text{ s}$, the longest reported lifetime in Si, Fig. 4 gives $\tau = 4 \times 10^{-8} \text{ s}$. Assuming

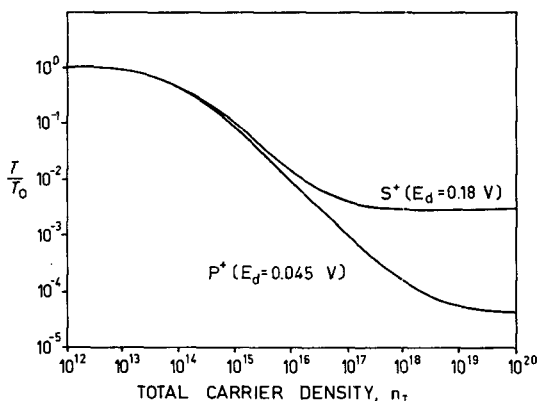


Fig. 4
Relative recombination lifetimes for two levels

a plasma time of 2×10^{-9} s, equation (23) indicates that the charge loss would be $\sim 5\%$. Again this is of the order of observed losses in surface barrier fission fragment detectors.

IV. Measurement of collection efficiency

Measurements were carried out using an integrating preamplifier [16] [17] which exhibited an input capacitance of ~ 30000 pF. A long clipping time, up to $20 \mu\text{s}$, was employed in the main amplifier to ensure that any charge having an effectively much lowered mobility due to multiple trapping and untrapping had time to be collected. The same long clipping time also enabled the full open-loop gain of the preamplifier to be effectively employed in integration.

Fission fragments were obtained from a 2000 fission per minute Cf^{252} source deposited on a thin Ni backing. Both the Cf^{252} α -particles and a calibrated mercury pulser were employed for charge calibration.

Scanning of the surface of detectors was carried out using a thin ThB source collected electrostatically on the polished end of a 30-mil Pt wire. A collimator was made by wrapping a few turns of thin Al foil around the platinum wire and adjusting its position as required.

A noteworthy feature of the kind of collection-efficiency measurements carried out here is that they can be made with quite high accuracy even with broad lines. This is because the measurement of the peak shift is practically always the quantity of interest, and this can be determined even when the resolution is very poor. In the case of fission spectra experiments in particular, it has been found very advantageous to run collection-efficiency curves to determine system performance [18].

V. Collection efficiency of diffused junction detectors

Charge collection in a number of different types of detectors have been investigated. Representative data on the main types of devices examined will now be presented.

PHOSPHORUS "PAINT-ON" n^+p DEVICES

In this process a thin layer of P_2O_5 dissolved in some suitable solvent, e.g. ethylene glycol monoethyl ether, is painted on the etched surface of a p-type silicon wafer. Phosphorus diffusion is carried out by heating for approximately 10 min at 900°C . This is followed by slow cooling, masking, etching, etc. to produce a usable detector. The resulting devices have n^+ layers about 0.1μ thick.

Inevitably in this high-temperature process some unwanted impurities also diffuse into the device from the silicon surface. It is reasonable to suppose, and is borne out experimentally, that the hotter and more prolonged the heating the greater the degradation of the material.

Experimentally it is found that devices that are excellent diodes but poor counters can be produced by double diffusion, i.e. a repetition of the paint-on process. Collection-efficiency results for such a representative device made from $10 \text{ k}\Omega$ p-type material are shown in Fig. 5. In this diagram the percentage charge collected has been plotted as a function of bias for Cf^{252} fission fragments incident normally and at 45° to the

n^+ surface. In view of the short range of these particles, $\sim 30 \mu$, it is clear that, provided the bias is two volts or more, the incident particles come to rest within the depletion layer. In consequence, for all biases greater than this value the process under investigation is that envisaged in section I, i.e. collection from a region having an electric field across it.

A number of features of Fig. 5 are noteworthy. First, the fact that η is as low as 0.8 for zero bias indicates that τ is short. This follows from the fact that since such a long clipping time is being used in the main amplifier any minority carriers created in the undepleted material should have ample time to diffuse to the depletion layer and be collected. In fact, from the known diffusion constants of carriers in silicon it should be possible to collect the entire charge by diffusion in less than $1 \mu s$. However, if a short lifetime were the only culprit, one might expect that, for biases greater than 2.0 V, the collection should be almost perfect. That this is not the case is clearly indicated, η only levelling off around 10 V. At this bias the depletion-layer thickness is approximately four times the particle range.

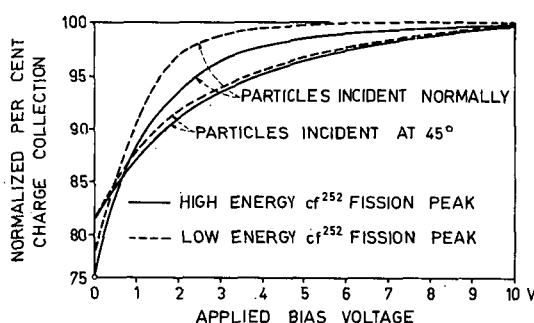


Fig. 5

Charge-collection efficiency of a phosphorus paint-on detector

Another conclusion that can be drawn from Fig. 5 is that though there clearly exist marked angle effects in this device they are not due to a dead layer. This follows from the fact that the curves tend to move together at high biases. The difference in η at normal incidence for the two fragments at low biases can be partly ascribed to their difference in range, the lower energy fragments coming to rest within the depleted region when the higher ones do not. However, on injection at an angle, η drops sharply for both fragments, the lower energy ones being more markedly affected. This is consistent with the existence of a collection-efficiency gradient at the front of the device. The fact that at 45° the two curves are almost coincident is fortuitous. These results are typical of poor diffused devices.

It is instructive to consider what Fig. 5 would imply if interpreted entirely on the basis of trapping. The high-energy fragment has an energy of ~ 100 MeV, and from measurement of the collected charge produces $\sim 3 \times 10^7$ pairs. Taking the most pessimistic case of a fragment incident almost parallel with the junction surface and assuming that dE/dk is uniform, it would give a thread of pairs uniformly spaced along $\sim 3 \times 10^{-3}$ cm. These carriers are swept apart, the ones making the long trip traversing

a distance of $\sim 5 \times 10^{-3}$ cm. While moving across the junction the carriers are also diffusing sideways; and again making the most pessimistic estimates they would diffuse at most 5×10^{-4} cm. Hence these carriers sweep out a wedge-shaped slice of the depletion layer, the volume of this wedge being $\frac{1}{2} \times 5 \times 10^{-4} \times 3 \times 10^{-3} \times 5 \times 10^{-3} \approx 4 \times 10^{-9}$ cm³. However, since $\sim 10\%$ of the charge is lost according to Fig. 5 for the chosen bias, this means that $\sim 3 \times 10^6$ carriers would have to be trapped in this volume. Since the worst that a trap could do is to trap and hold a carrier for a time longer than roughly the amplifier clipping time, i.e. one trap can only be effective once during one fission-fragment pulse, this implies that the minimum density of traps must be $\sim 10^{15}$ cm⁻³. This trap density is several orders of magnitude higher than could reasonably be expected.

This same double-diffused device exhibited very poor α -resolution and partially resolved multiple peaking. Exploring the surface with a small collimated ThB source we exposed marked area effects, with α -peak energies shifting as much as 120 keV from place to place. It is not known to what extent results such as these reflect bulk properties of the starting crystal or contamination differences during diffusion.

It is clear from the results of Fig. 5 that a diode fabricated by high-temperature double-diffusion on high-resistivity base material is a poor fission counter. It was for this reason that it was investigated. Such counters, as is scarcely surprising, give fission spectra in poor agreement with time-of-flight data.

By optimizing fabrication techniques it is possible to make good fission fragment counters by diffusion. For example, Fig. 6 shows a representative Cf²⁵² spectrum obtained with a $\sim 100 \Omega\text{-cm}$ device of 3 cm² operating at 150 V. This detector was produced by a very clean phosphorus gaseous diffusion at 600° C. Comparison with the time-of-flight data was made at the 15 points shown; agreement being indicated by the associated linearity plot. The agreement in shape between the two is clearly good, even though a mercury pulser calibration indicated a pulse-height defect of ~ 10 MeV per fragment. On increasing the bias the defect decreased but the shape did not change significantly. It has not proved possible to answer the question of whether ϵ for fission fragments is accurately the same as for other particles. The reason for this is that η goes on increasing slowly with bias right up to the point at which avalanche multiplication sets in, giving ϵ an apparently low value. Since the onset of the multiplication process is smooth it is hard to know exactly where it starts and it is by no means clear whether ϵ would have plateaued as was expected had this process not intervened.

The fact that η goes on increasing for increasing bias for fission fragments further indicates that the loss mechanism cannot only be due to trapping, for the counter of Fig. 6 η still increased slowly with peak fields as high as 10^5 V/cm. The carrier velocity, and hence the trapping length, have long since reached their limiting values. Consequently, by the arguments of Section II, one would expect, if anything, that η would decrease rather than increase with further increases in bias. However this data is consistent with the plasma theory, i.e. it is not the trapping but the initial recombination that is being reduced.

In order to try to eliminate the effects of possible processing differences a group of counters of various resistivities were diffused simultaneously. Collection-efficiency curves, plotted against depletion-layer thickness, are shown in Fig. 7. Apart from the inversion of two of the low-resistivity curves it is apparent that the results fall into two groups corresponding to high and low-resistivity base material.

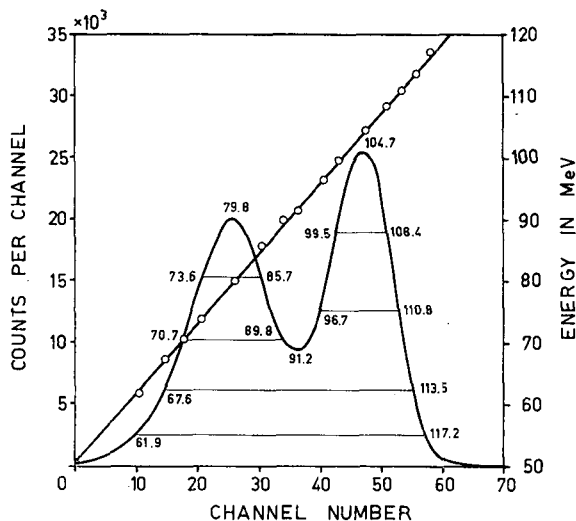


Fig. 6

Spectrum of Cf^{252} obtained with a phosphorus gaseous diffusion detector

LOW-TEMPERATURE GASEOUS DIFFUSIONS

Phosphorus gaseous diffusions have been carried out at 600°C . The resulting junctions again have n^+ layers $\sim 0.1\ \mu$ thick, as demonstrated by an anodic oxidation and etching investigation. Collection efficiency data for these devices is similar to that presented in the previous section, though their performance is usually superior to that obtained using the paint-on technique.

GALLIUM DIFFUSED COUNTERS

Devices produced by the diffusion of gallium into n-type base material have been used by a number of workers in France [19]. One of these detectors was examined and found to exhibit collection-efficiency behaviour similar to that obtained with high-temperature phosphorus-diffused devices.

SURFACE BARRIERS

Surface barrier detectors have been extensively investigated by others [13] [20] [21] and, as with diffused devices, it is usually found that the resolution is limited by factors other than the noise. Collection-efficiency results are similar in form to those of Fig. 5 except that the angle effect is very much smaller, or negligible. This is to be expected since the base material is much more homogeneous. Together with the results for diffused detectors, this is evidence for the existence of lifetime gradients inside diffused devices.

Multiple peaking effects have also been observed in poor surface barrier detectors, presumably reflecting inhomogeneities in the base material.

VI. Discussion

At the high and low ends of the ionization-density range, exemplified by fission fragments and high-energy electrons respectively, it seems possible to obtain some understanding of the mechanism of charge loss. The process of recombination on shallow centres in the initial plasma discussed in Section III seems capable of explaining both the magnitude of the charge loss for heavily ionizing particles and also its dependence on ionization density. In addition, this offers a simple explanation of the poor resolution that exists even in apparently quite homogeneous devices since any given particle track will contain a certain number of recombination centres, and it is the fluctuation in this number that controls the resolution. Furthermore, the results exemplified by Fig. 7 can be explained on the basis of the higher electric field eroding the plasma surfaces more rapidly, and hence reducing the plasma time. Extension of these arguments would indicate that heavily compensated, lithium-drifted counters [22] might be expected to be poor α and fission detectors, while a thin p-i-n surface barrier should be a good detector provided that the intrinsic region were uncompensated.

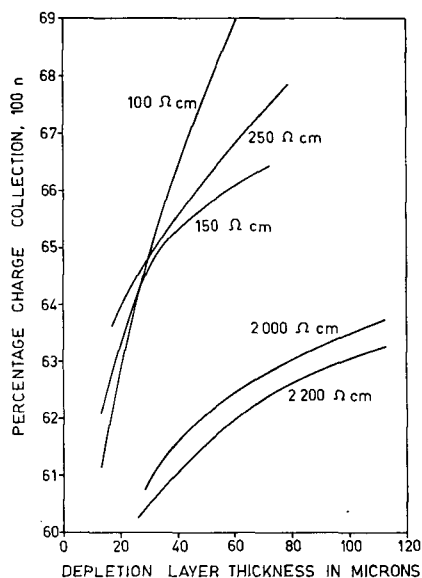


Fig. 7
Collection-efficiency curves of counters of various resistivities

The overall picture cannot be regarded as satisfactory until collection efficiency, electric field and charge-collection time have been further correlated, since this is crucial for the arguments presented here. In addition the question of lifetime gradients in diffused devices needs investigation. It may turn out that this gradient is simply due to the donor or acceptor material itself which is intentionally diffused into the crystal surface, although one cannot be confident of such a conclusion due to the possible simultaneous diffusion of other impurities during heating.

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DISCUSSION

H. E. Wegner (United States of America): Would you care to describe the construction and the operating conditions of the counters used in the back-to-back fission experiment?

G. L. Miller (United States of America): The special features of these counters were as follows: they were made with 300 Ω -cm p-type material. This was in order to obtain a high electric field. The diffusion was carried out by a reverse-flow gaseous technique at 600°. The diffusion depth was 1/10th of a micron; the area was 3 cm². The counters were mounted on lead backings. The front contact was a spring contact with a fine phosphor-bronze wire. The whole assembly was mounted on lucite, and the counters and the fission foil were surrounded by a lucite beta shield, which kept out beta rays from the aluminium can. As a result of these precautions we had no trouble whatsoever from spurious pulses. We operated at various biases, but the curve shown is for 150 V, and that corresponds, I think, to a peak electric field in the counter of about 70000 V/cm. We have tried operating at higher voltages, but then one starts getting avalanche multiplication in the counters and this leads to a spurious peak on the correlated fission spectrum.

R. J. Griffiths (United Kingdom): Would Mr. Miller like to comment on the relative importance of trapping and re-combination in his detectors?

G. L. Miller: Re-combination is only of importance along the initial, highly ionized track. It is of no importance later on, because if a carrier gets trapped it never sees a carrier of the other sign with which to re-combine. So re-combination only matters at the beginning—when the particle first enters and leaves its dense trail of hole-electron pairs. As an example of this, we have obtained with 120-kV gammas a line width of 6.8 V. If one used the same counter to count alpha particles, the line width was extremely bad, about 70 kV. The difference is simply that the trapping is low, as can be seen from the paper. Something which interests me greatly is why things like these lithium-drifted counters give, on the whole, such bad resolution for gammas, because the resolution ought to be good—according to our calculations it ought to be almost exactly equal to what would result from the system noise level.

C. G. Clayton (United Kingdom): Would Mr. Miller like to comment on the specific nature of the re-combination centres?

G. L. Miller: Well, one of the difficulties is that one does not know what the re-combination centres are. We have definite evidence to show that there is a re-combination lifetime gradient inside diffused detectors. This is shown by the angle effect seen on the second slide. If one repeats this experiment with a surface barrier detector, which is homogeneous, one does not get the same angular dependence—which indeed one would not expect. This is taken as evidence that a re-combination lifetime gradient exists. We have not been able to decide whether this gradient is entirely due to the donor material, which is diffused in in order to make the junction. It may be, but on the other hand there may be additional materials diffused in at the same time, which act as re-combination centres.

J. V. Kane (United States of America): Is it your opinion that surface barrier counters would be better for fission fragments because they would show less re-combination effect?

G. L. Miller: That is a very good question. I think they should. There is one disadvantage that surface barriers have, although I think it is by no means inherent: at present they have to be made on n-type material. What this analysis shows, if it is right, is that one wants to have the purest possible material with the highest possible electric field. The ideal solution would be if somebody could find a way of making a surface barrier on a very thin slice of very pure p-type material, so that you could get a high electric field across it; thus an epitaxial construction of p^- with n^+ surface barrier and a p^+ back would be an ideal device. The main reason that we did these experiments with diffused junctions is that we have always worked with diffused junctions. I know people at Oak Ridge have had good results for fission spectra with surface barriers, and I see no reason why they should not be at least as good as diffusion devices.

J. Labeyrie (France): I did not quite understand what was the order of magnitude of the deviation caused by the fine structure on the XYZ plot in relation to the curve $N - f(E)$.

G. L. Miller: The fine structure on the XYZ plot corresponds in energy to a few mega-electron-volts. The same effects have not been observed with the time-of-flight data, but not with such a high resolution,

W. L. Hansen (United States of America): Have you been able to relate the satellite upper peak, which is very often seen with alpha particles on diffused junctions, to trapping or re-combination centres?

G. L. Miller: You mean this multiple peaking. We have worked very hard on this. We have scanned the surfaces of detectors with very thin alpha sources—thorium B collected electrostatically and so on—and we can see from place to place gross differences in collection efficiency for alpha particles. On the basis of this analysis it is our belief that this is due to differences in the density of re-combination centres. However, we do not know how these differences arise. One thing we thought might be the origin was crystal damage at the surface, so we tried making a detector with an intentionally damaged surface, damaged to a depth of one micron diffusing into that, and then looking for multiple peaking. We did not find it. We explained that by saying that the diffusion would proceed very fast through the damaged region and therefore the junction was just deeper. To re-investigate it, we took another piece of n-type silicon and optically polished it, which damaged it to one micron; we then made a surface barrier and that gave the worst multiple peaking we have ever seen. I think all that one can say is that it is a materials problem, but we have not really been able to nail it down and we do not really know how to get rid of it.

W. L. Hansen: Did you get rid of the multiple peaking with the low-temperature diffusion?

G. L. Miller: The multiple peaking is apparently reduced with low-temperature diffusion, but we have very little statistical data on this. With low-temperature diffusions we have only made about ten counters, and these have all been investigated in detail only for fission fragments. They are all detectors which have huge capacitances; they intentionally have these high electric fields—in very thin depletion regions—and they run with capacitances of several hundred micromicrofarads, so one can look at an alpha line width and compare it with the pulser width and they are both rather poor, owing to this big capacitance. Hence, these are inherently poor devices in which to investigate multiple peaking.

Mrs. L. Koch (France): When potential differences as low as 2 V are applied to the crystal, the pp^+ barrier at the back of the crystal represents a certain capacitance in series with the capacitance of the pn barrier. Do you not think that the fact that these two capacitances are in series reduces the amplitude of the measured pulse?

G. L. Miller: I do not agree exactly with what you say. It seems to me that in junctions of this kind there is only one capacitance, and that is the capacitance across the junction region. The region from the back of the depletion layer, moving towards the back contact, simply looks like a high resistance, but this is the resistance of the bulk undepleted material. Perhaps we could discuss this privately.

Mrs. L. Koch: We have taken various measurements sending alpha particles parallel to the np and pp^+ junction planes* and we noted that the amplitudes of the pulses obtained were split into two peaks; the first of these corresponded to a fast pulse rise-time and the second to a very slow rise-time, which could not be explained by a diffusion phenomenon. However, the amplitudes of the peaks did correspond to this capacitance effect, and the apparent loss of collection of about 20% corresponded to the capacitance of the pp^+ barrier in the back of the crystal which was 14 pF/cm² for a zero difference of applied voltage.

* MESSIER, J. and VALIN, J. J., *Nucl. Instr.* (in press).

PRELIMINARY EXPERIMENTS WITH A SOLID-STATE IONIZATION CHAMBER

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Abstract — Résumé — Аннотация — Resumen

Preliminary experiments with a solid-state ionization chamber. A solid-state ionization chamber has been made by diffusing phosphorus into high-resistivity silicon to form ohmic contacts. Such a detector has been successfully used to detect 30-MeV protons.

Preliminary results are given and discussed.

Expériences préliminaires au moyen d'une chambre d'ionisation à milieu solide. Une chambre d'ionisation à milieu solide a été réalisée par diffusion de phosphore dans du silicium de haute résistivité pour former des contacts ohmiques. Un détecteur de cette nature a été utilisé avec succès pour détecter des protons de 30 MeV.

Les auteurs présentent les résultats préliminaires obtenus.

Предварительные опыты с твердой ионизационной камерой. Твердая ионизационная камера изготовлена путем включения фосфора в кремний с высокой удельной сопротивляемостью для образования омических контактов. Такой детектор успешно применяется для обнаружения протонов в 30 мэв.

Представлены и обсуждаются предварительные результаты.

Experimentos preliminares con una cámara de ionización en estado sólido. Se ha construido una cámara de ionización en estado sólido, por difusión de fósforo en silicio de elevada resistividad para formar contactos óhmicos. Con esta cámara se han logrado detectar protones de 30 MeV.

Los autores presentan y examinan los resultados preliminares obtenidos.

I. Introduction

I wish to describe briefly some preliminary experiments we have been making with a new type of semiconductor counter. These counters were made by Mr. Gibbons and Dr. Northrop at the Services Electronics Research Laboratory (SERL) whilst the experiments to be discussed were performed, using the Rutherford Laboratory 30-MeV Proton Linear Accelerator, by Dr. Griffiths, Mr. Gibbons and Dr. Batty.

The detector to be described differs from the usual junction-type of detector in which the applied voltage is dropped mainly across the rectifying barrier, and the high-resistivity, ionization-sensitive depletion layer extends only a short way into the crystal. In bulk detectors ohmic contacts are applied to the two faces to give a uniform field throughout the counter, so that all parts are equally sensitive to ionization. In the case of silicon it is necessary to cool the counter to 90° K to reduce current noise to an acceptable level. The greater depth of high-resistivity silicon allows higher energy particles to be detected.

II. Production

The counter on which these measurements were made consisted of a 6-mm cube of n-type silicon whose resistivity at 90° K was $10^9 \Omega \text{ cm}$. Phosphorus, which is an n-type impurity in silicon, had been diffused about 25μ into two faces of the cube to give ohmic contacts. Fields up to 1000 V/cm could be applied to the crystal to separate and collect the electron hole pairs.

III. Experiments

The detectors were mounted in a vacuum of better than 10^{-5} mm Hg, on a copper rod, one end of which dipped into liquid nitrogen. The detector was exposed to a 2-mm diam. beam of 30-MeV protons from the Linear Accelerator. The pulses were detected using the circuit shown in Fig. 1 and, after amplification by an AERE Type-1430 amplifier and head amplifier, were displayed on a 100-channel pulse-height analyser.

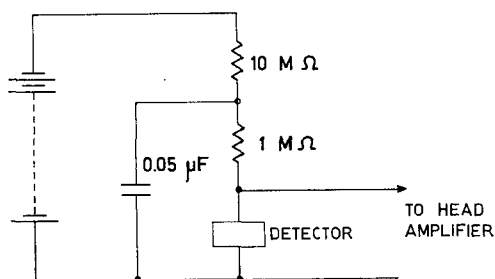


Fig. 1
Circuit used for pulse detection

A typical pulse-height spectrum obtained, using one of these detectors, is shown in Fig. 2. This was obtained using —300 V bias giving a field of 500 V/cm. The resolution,

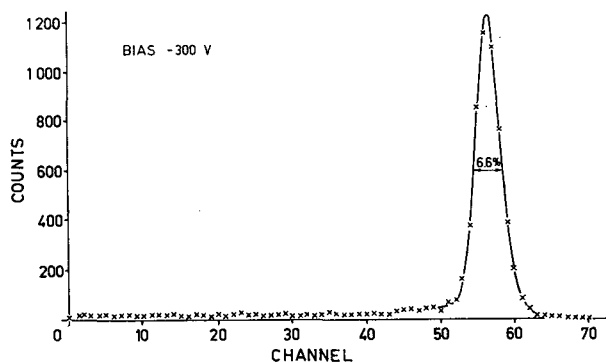


Fig. 2
Typical pulse-height spectrum of bulk detector with 30-MeV protons

full-width at half height, is 6.6%. The resolution and position of the peak were then measured as a function of bias applied to the detector (Table I).

TABLE I
BULK DETECTOR PERFORMANCE AS A FUNCTION OF APPLIED FIELD

Bias	Field	Resolution	Peak Position (Ch. No.)
— 150 V	250 V/cm	8.6%	58
— 300 V	500 V/cm	7.7%	59½
— 480 V	800 V/cm	7.7%	60½

Both the resolution and pulse height tend to saturation at the largest bias voltages, indicating that the majority of the available charge carriers are being collected. By moving the collimator, the beam was moved to different positions on the detector. The resolution and pulse height remained essentially independent of the beam position except at the very edges. This would indicate that the detectors are macroscopically uniform.

The detector noise was 1.2 V peak-to-peak with — 300 V bias. 30-MeV protons gave 29.5-V pulses. This corresponds to 10 mV across the 35-pF input capacity of the amplifier. This amount of noise, which originates mainly in the detector is rather large and we hope to reduce it by more efficient cooling arrangements in future experiments.

Some experiments were also performed, reversing the bias, so that protons entered at the face which is positive. A comparison of the spectra obtained is shown in Fig. 3. The bias was + 480 V and we see that the pulse height had decreased and the resolution is much worse. Since the ionization is greatest for the incident particle at the end of its range, these results would seem to indicate that appreciable electron trapping and/or recombination takes place, since the electrons now have to travel a greater distance. This is borne out by the measurement of the gain of the system which indicated that

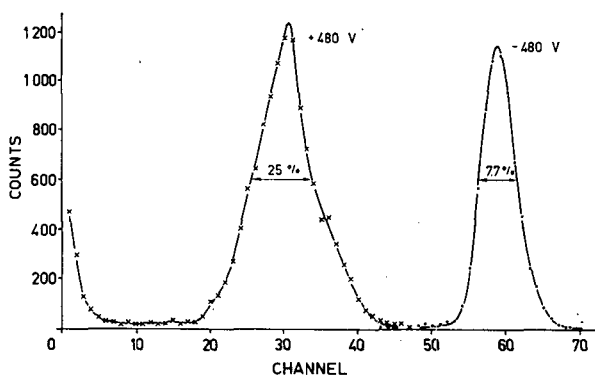


Fig. 3
Effect of reversing the bias on bulk detector

only 12% of the electron hole pairs were collected. It is known that the silicon used had a very high dislocation density and this may be responsible for the large amount of trapping taking place.

IV. Future developments

In future experiments we hope to use detectors made from silicon with a lower dislocation density which should help to reduce electron trapping and hence improve the resolution. It is also hoped that, with an improved cooling system, the detector noise will be reduced. Experiments have been planned using different energy protons to measure the linearity and to explore different depths in the crystal. By a detailed examination of the pulse shape it is hoped to gain information about the fundamental processes taking place in the crystal.

PROPERTIES OF SOLID-STATE DETECTORS

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Abstract — Résumé — Аннотация — Resumen

Properties of solid-state detectors. Conventional surface-barrier counters have been made from high-resistivity n-type silicon, and these have been capable of resolutions of $0.4\% \pm 0.1\%$ (electronics plus counter contributions) at room temperature with 5-MeV alpha particles. Results will be presented on the performance of these counters with alpha particles (5 MeV), soft X-rays, and 60—1200 keV electrons from a beta spectrometer. Parameters relating to counter performance, such as dead layer, linearity, resolution, noise and depletion-layer thickness constitute the bulk of the results.

Experience with a process (which was originally described by the Service Electronics Research Laboratory (SERL), Baldock) for making junctionless conductivity counters from high-resistivity p-type silicon will be discussed, together with considerations of the relative importance of various semiconductor properties in this application. Some preliminary tests on the performance of these counters, especially in relation to their potential as spectrometers for energetic gamma rays, will be included.

Propriétés de l'état solide comme milieu de détection. Les auteurs ont construit des compteurs classiques à barrière de surface en silicium du type n de grande résistivité; ces compteurs ont un pouvoir de résolution de $0,4 \pm 0,1\%$ (compteurs et électronique associée) à la température ambiante pour des particules gamma de 5 MeV. Ils présentent les résultats obtenus sur le fonctionnement de ces compteurs avec des particules alpha (5 MeV) de rayons X mous et des électrons de 60 à 1200 keV en provenance d'un spectromètre bêta. Ces résultats portent essentiellement sur les paramètres de fonctionnement tels que la couche morte, la linéarité, le pouvoir de résolution, le bruit et l'épaisseur de la couche d'appauvrissement.

Le mémoire contient l'exposé d'un procédé (décrit à l'origine par S.E.R.L., Baldock) employé pour construire des compteurs à conductivité sans jonction en silicium du type p de grande résistivité, ainsi que des considérations sur l'importance relative des différentes propriétés des semi-conducteurs dans cette application. Les auteurs font l'exposé de plusieurs essais préliminaires sur le fonctionnement de ces compteurs, notamment en ce qui concerne leur emploi éventuel comme spectromètres pour des rayons gamma énergiques.

Свойства твердых детекторов. Из кремния типа „n“ с большим удельным сопротивлением были построены обычные счетчики с поверхностным барьером; для альфа-частиц с энергией в 5 мэв при комнатной температуре разрешающая способность этих счетчиков была порядка $0,4 \pm 0,1\%$ (электроны плюс фон счетчика). Будут представлены результаты работы этих счетчиков с альфа-частицами (5 мэв), мягкими рентгеновскими лучами и электронами с энергией от 60 до 1200 кэв из бета-спектрометра. Главная часть результатов состоит из параметров работы счетчика, как, например, данных о мертвом слое, линейности, разрешающей способности, шумов и толщины слоя обеднения.

Будет рассмотрен опыт (первоначально описанного S.E.R.L., Балдоук) построения счетчиков с беспереходной проводимостью из чистого кремния типа „p“ с большим удельным сопротивлением, а также соображения относительно важности различных свойств полупроводников при таком использовании. Будут даны некоторые результаты предварительных испытаний работы этих счетчиков, в особенности в связи с перспективным использованием их в качестве спектрометров гамма-лучей большой энергии.

Propiedades de los detectores sólidos. Los autores han fabricado, con un silicio tipo n de gran resistividad, contadores normales de barrera superficial, dotados de un poder de resolución

de $0,4 \pm 0,1$ por ciento (contribuciones de los circuitos electrónicos y del contador) a la temperatura ambiente para partículas α de 5 MeV. Presentarán los resultados obtenidos al probar estos contadores con partículas α (5 MeV), con rayos X blandos, y con electrones de 60 a 1200 keV procedentes de un espectrómetro β . Los resultados, en su mayor parte, consisten en parámetros relativos al rendimiento del contador tales como la capa «muerta», la linealidad, el poder de resolución, el ruido y el espesor de la capa de detención.

Se describirán los experimentos realizados para fabricar contadores de conductividad, sin uniones, a base de silicio tipo p de gran resistividad (proceso descrito por primera vez por S.E.R.L. Baldock), y se discutirá la importancia relativa de varias propiedades de los semiconductores cuando se aplican con estos fines. La memoria describirá también algunos ensayos preliminares del rendimiento de estos contadores, especialmente en relación con la posibilidad de utilizarlos como espectrómetros para rayos γ de elevada energía.

A. Surface-barrier counters

FABRICATION TECHNIQUES

High-resistivity, n-type silicon of 500–2000 Ω cm has been used to construct conventional gold-silicon surface-barrier counters. The procedure of etching, gold-evaporating and lead-connecting described by DEARNALEY [1] has been used, but with the following modifications. To prevent both surfaces becoming diodes (in which case the back one would act as a noise source), only the front face and edges of the silicon are etched before gold evaporating. The back surface is protected from the etch by holding the disc by vacuum suction on to an "O" ring mounted in a polythene beaker full of etchant, or else by painting the back surface with a protecting solution of polystyrene and chloroform. Contact to the evaporated gold (which is usually about 1½ cm diam.) both on the front surface and on the unetched back surface, is made by a high-conductivity, cold-setting epoxy resin HYSOL 6250. The thickness of the front evaporated gold is usually 50–100 $\mu\text{g}/\text{cm}^2$, though down to 5 $\mu\text{g}/\text{cm}^2$ has been successfully used. Recently an attempt has been made to make smaller stopping-power dead-layers by evaporating aluminium instead of gold, but the aluminium adversely affected the properties of the surface barrier.

PERFORMANCES AND APPLICATIONS

(a) Alpha-particles

The performances attained are illustrated by a recent batch of twelve counters, of which nine yielded (with 5.5-MeV alpha-particles) resolutions better than 1% (55 keV), with one being 0.4% (22 keV). One of the chief contributions to overall resolution limitation is electronics drift and amplifier noise, which account for about half of the overall typical performance of ½% (27 keV). The counters themselves do not contribute more than about 0.1–0.25% (5–13 keV). In general, the best counters have come from 1300–2000 Ω cm n-type silicon obtained from the United States of America (Merck Co.). Reverse currents observed are usually about 0.2 μA per 100-V back bias, but diode characteristics are found to be not always a reliable criterion of counter performance.

Fig. 1 shows the fine structure of the Am^{241} 5.477-MeV alpha-particle line, as obtained from a surface-barrier counter made from 600- Ω cm n-type silicon. The sensitive evaporated gold area was 0.5 cm diam. The spectrum was taken at room temperature, with a reverse bias of 160 V.

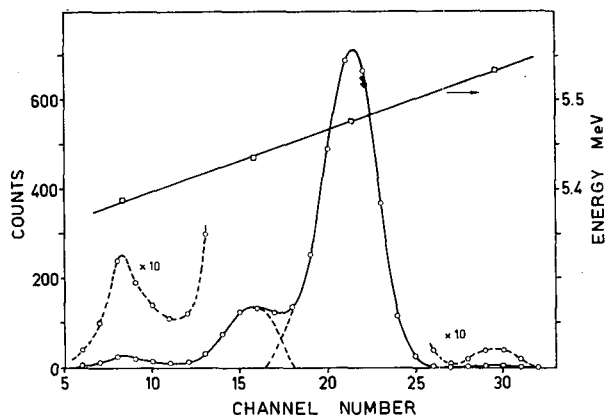


Fig. 1

Am^{241} spectrum by surface-barrier counter; showing also the linear relationship between the channel numbers and alpha energies

The electronics used was a Brookhaven preamplifier [2] built at AWRE, in conjunction with a 1430A main amplifier ($0.8 \mu\text{s}$ ITC, $1.6 \mu\text{s}$ DTC) which was modified to have less HT ripple. The preamplifier heaters were supplied from a 12-V accumulator. It was found that this preamplifier was 100% charge-sensitive for input capacities between 10 and 1000 pF. The equivalent noise level of the preamplifier plus main amplifier was 11.5 keV full-width half maximum (FWHM), and of the amplifiers plus counter, with 160 V bias, 16.0 keV (FWHM). This was measured by feeding in an accurately known voltage pulse across a known capacity, and measuring the pulse and rms noise of the amplifier output.

The overall resolution obtained from Fig. 1 with Am^{241} alpha-particles is 25 keV (FWHM). This is larger than would be expected from the equivalent noise of the counter plus amplifiers—the excess is due to drift, especially in the 30 mV/channel, 100 channel, CDC kicksorter, which can drift by 2–3 channels during a count.

(b) Beta-particles

Mono-energetic electrons of 60–1200 keV supplied from a $\text{Sr}^{90}\text{-Y}^{90}$ source in a Siegbahn-Slätis intermediate-image beta spectrometer, have been used to examine the performance of surface-barrier counters for beta-particles. The experiment is similar to one carried out by McKENZIE and EWAN [3] with diffused junction-type counters. The momentum resolution of the spectrometer was 1% and the electrons reached the counter at an angle of $\sim 40^\circ$ from the normal. An energy sweep was carried out to determine the number of electrons counted at various energies by the conventional central end-window Geiger counter. This Geiger counter was then replaced by the surface-barrier counter and another energy sweep carried out. The electronics used was the same as described above.

The results are similar to those obtained by McKenzie and Ewan and no differences in behaviour between diffused junction counters and surface-barrier counters have been detected. Fig. 2 shows the response of the counter to electrons of from 60 to 1200 keV

at a reverse counter bias of 160 V. The curves are normalized to make the number of electrons reaching the counter at each energy constant. At 160 V reverse bias, about 200 keV electrons will be stopped in the depletion layer. Up to this energy, the electrons expend all their energy in the depletion layer and hence the absorption peak heights (Fig. 2) are constant. The tails on the low-energy sides of these peaks are due to back scattering of the particles out of the counter (higher than for anthracene, since anthracene has lower Z). At higher energies, progressively more electrons pass through the depletion layer, expending in it about 120 keV of their energy. These produce a minimum ionizing peak (Fig. 2)—i.e. due to particles passing straight through the depletion layer with minimum scattering. Those electrons which do undergo multiple scattering in the depletion layer so that all their energy is expended there, produce a reduced total-absorption peak. The height of this absorption peak diminishes with energy and disappears at 1200 keV. Fig. 3 gives pulse height in each absorption peak (i.e. peak position on Fig. 2) *versus* energy and this is linear as expected. If, at each reverse bias, the electron energy at which the count-rate commences to fall is related to depletion-layer thickness by means of known electron range-energy data in silicon, it is found that depletion-layer thickness varies as the square root of the reverse bias within experimental error.

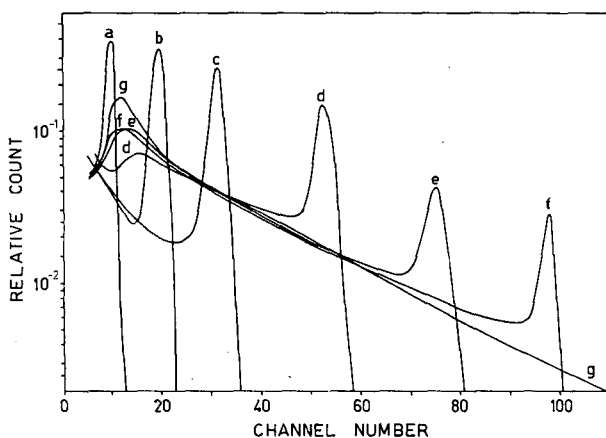


Fig. 2

Surface-barrier counter: Response to mono-energetic electrons: Counts per channel relative to the counts found in a G-M tube at the same position, plotted against kicksorter channel number for various electron energies. (a) 80 keV, (b) 150 keV, (c) 254 keV, (d) 396 keV, (e) 562 keV, (f) 790 keV, (g) 1.22 MeV; no peak detected at higher channel numbers

Table I shows the response of the counter to various energy electrons at several counter bias voltages. The figures are the counts in each peak divided by the counts detected by the Geiger counter, at that energy. It will be seen that the fraction of electrons stopped in the depletion layer decreases with increasing energy and also that at the higher energies, the fraction of electrons stopped in the depletion layer increases with counter bias voltage (i.e. with increasing depletion-layer thickness). At the lower energies, all energy is absorbed in the depletion layer even at low bias.

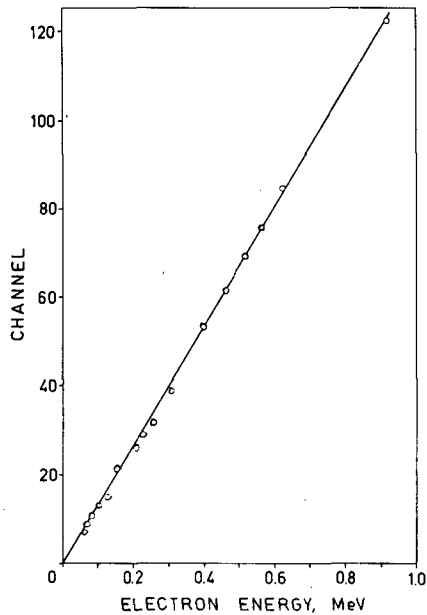


Fig. 3

Surface-barrier counter: relationship between channel number of the total absorption peak and electron energy

TABLE I

RESPONSE OF COUNTER AT VARIOUS BIAS VOLTAGES TO DIFFERENT ENERGY BETA PARTICLES

Counter Bias Volts	Electron Energy, keV				
	126	207	396	562	616
410	1.11	1.16	1.08	0.47	0.38
320	1.29	1.16	0.88	0.42	0.29
160	1.27	1.13	0.53	0.18	0.12

(c) *Soft X-rays*

One novel application which surface-barrier counters are finding at AWRE is the measurement of instantaneous electron temperature at successive stages of a fast discharge in a CTR plasma. This can be calculated from the instantaneous energy spectrum of the soft X-rays (~ 1 keV) emitted from the plasma. It is hoped to obtain this information by placing inside the discharge vessel a small surface-barrier counter which has its sensitive area divided into four separate $\frac{1}{8}$ -in diam. regions, each having a different absorbing window thickness (50, 100, 250 and 500 $\mu\text{g}/\text{cm}^2$). At a given instant during the discharge, information on the energy distribution in the X-ray flash can be

obtained from the relative intensities of the current pulses from each counter section and from knowledge of the stopping powers of the windows. These counters offer the most compact form of detectors which are capable of rapid response and which are insensitive to transient magnetic fields, and once they are calibrated and the linearity of their energy response established, this application to instantaneous soft X-ray spectra should prove useful. Tests with a single counter have so far yielded a very good signal-to-noise ratio (since the energy deposition is enormous), and certainly the counter response has proved to be fast enough.

B. Junctionless conductivity counters

Solid-state detectors possessing p-n junctions are limited in their applications as energy spectrometers to those types of radiation which can be made to lose all their energy in the depletion layer. Since depletion layers cannot be made greater than about 1 mm of silicon, high-energy gamma-ray spectroscopy is not possible. For this application, a large crystal with adequate stopping power for the gamma-rays concerned, with a resistance high enough to keep ohmic noise small, with efficient charge collection throughout its bulk, and with proportionality to energy, is required. While diamonds are capable of counting single gamma-ray events, their application is severely limited by such difficulties as space-charge build-up. In recent years, it has become usual to use materials possessing intermediate resistivities, such as semiconductors, and to apply a charge-collecting field of about 500 V/cm. These materials show promise as gamma-ray spectrometers capable of energy resolutions better than the 6–7% from the best and largest NaI scintillators.

FACTORS INFLUENCING CHOICE OF MATERIAL

Two obvious properties which come to mind are low-band gap (in order that the radiation energy necessary to produce each electron-hole pair is small), and high stopping power (which is governed by the average Z of the material, and the size in which crystals of that material can be produced).

A most important requirement is low-carrier density, for otherwise the limitation on energy resolution imposed by Shott noise becomes very large. For example, if the total number of holes in a cooled silicon crystal is $N = 10^6$, then the energy spread due to Shott noise is $\Delta E \sim 3.5 \sqrt{N} = 3.5 \text{ keV}$. The limitation imposed on resolution by thermal noise (which applies to junction counters also) is less. For example, for silicon

$$\begin{aligned}\Delta E &= 3.5 \times 2 (kT_{\text{carriers}} C)^{1/2} t^{1/2} / \tau_{1/2} e \\ &= 3.5 \times 400 \sqrt{C} \\ &= 1.4 \text{ keV for } C = 1 \text{ pF}\end{aligned}$$

Here t is the integrating time necessary to collect the whole pulse, C is in pF, T is room temperature, and τ is the time constant.

It is also important to have a low trap density. If, for example, the holes are trapped for a much longer time than the dielectric relaxation time, then the conductivity of the crystal will increase due to electrons compensating these holes and this will result in the integrated area under the pulse being no longer proportional to incident energy. If the trapping time is short compared to the dielectric relaxation time, then the integrated area under the pulse will be proportional to energy, but since μ_h is less than μ_e (the μ 's

being mobilities), the pulse shape and length will depend on where in the crystal the radiation enters. The mobility of carriers should be as high as possible so that the transit time (i.e. pulse length) can be kept low. For example, for silicon, electron transit time $= \frac{x}{\mu_e E} \sim 1 \mu\text{s}$ for $x = 1 \text{ cm}$ and $E = 1000 \text{ V/cm}$.

Diamond has a very high-energy band-gap (5.2 eV) and has a high trap density. Cadmium sulphide also has a high trap density. Germanium would satisfy all requirements excepting that it has to be cooled to liquid helium temperatures in order to keep the carrier density low. Silicon is much more convenient in this respect, as cooling to liquid nitrogen temperatures achieves a low enough carrier density and high enough mobilities. There is, however, a special form of gallium arsenide which shows promise, namely a type which has a room temperature resistance of greater than $10^6 \Omega \text{ cm}$. Northrop of SERL, Baldock finds that, when growing gallium arsenide crystals, either a low-resistivity-type ($\sim \text{few } \Omega \text{ cm}$) or a material of greater than $10^6 \Omega \text{ cm}$ is obtained, but nothing in between. Presumably some rather exactly balanced compensation process is responsible for producing this high resistivity type. NORTHROP *et al.* [4] of SERL, Baldock, have reported success with Co^{60} gamma-ray counting with this high-resistivity-type gallium arsenide.

At AWRE, we have restricted our investigations to silicon, mainly because the high-resistivity type is fairly easy to obtain and because much larger crystals of silicon than of gallium arsenide are obtainable. There is a slight advantage in using p-type silicon rather than n-type, in that the current for a given carrier density is less than that for n-type of the same carrier density, so that the Shott noise limitation on the resolution attainable is not quite so severe.

FABRICATION TECHNIQUES

There are two main objects in the fabrication process, first to produce non-rectifying, noiseless contacts on each end of the sample and second to raise the resistivity of the material as much as possible by compensation. The starting material we have used has been bars $3 \times 3 \times 19 \text{ mm}$ cut from ingots of 4000–8000 $\Omega \text{ cm}$ Monsanto p-type silicon. Making ohmic contacts on to such high resistivity silicon by the usual methods of soldering or electrodeless nickel plating has been found to be impracticable. The method has been to seal off the clean specimen at $\sim 10^{-6} \text{ mm Hg}$ in a silicon tube containing a piece of pure boron oxide and to heat this tube at 1000°C – 1100°C for about 1–2 hours, followed by slow cooling to about 500°C in order to prevent the carrier lifetime from becoming too short. After dissolving the glossy surface coating of boron oxide with hydrofluoric acid, the resultant resistance is found to be only a few ohms owing to a very low-resistance surface coating of heavily boron-doped silicon. This material may be removed from the sides of the sample by etching in CP 4 for some minutes, but the ends are retained with their boron doped surfaces by protecting them from the etch with wax. After removing this wax, it is found that when the specimen is heated to 400°C on a tantalum strip heater, thin 0.005-in wires of 1% gallium-gold alloy lightly touching these boron-doped ends results in molten gold spreading into the material and forming excellent ohmic contacts. The contacts are sufficiently strong to cause lumps of silicon to come away from the sample if the wires are pulled off.

If the resistivity of the specimen is now examined at room temperature, it is found that it is usually about 2–3 orders of magnitude higher than that of the starting material.

The processing in the oven has presumably resulted in many of the carriers in the bulk of the sample becoming compensated. The two wires from the sample are then soldered up to two supporting leads and the whole sealed up into a cryostat glass tube containing an atmosphere of dry hydrogen. After cooling to 80° K, the cryostat is sealed up with a light-tight, earthed copper shield.

It is usually found that cooling to 80° K raises the resistivity by about another three orders of magnitude, so that the final resistance of the specimen at 80° K is in the range 10^6 – 10^9 Ω . In general, the higher the final resistance attained at 80° K, the better the counter behaves, since the ohmic noise caused by the DC current through the sample is then small. It has been found, however, that it is very difficult to control the compensation process in the oven exactly, since the slightest impurities (1 part in 10^{11}), both inside the bulk silicon and outside if it diffuses rapidly, may affect the exact compensation balance.* Hence, very variable final resistivities have been observed—the best being just over 10^9 Ω at 80° K.

Performance

The field value (~ 500 V/cm) chosen depends, of course, on whether the surface is sufficiently clean to prevent electrical breakdown and whether the resistance is sufficiently large to keep ohmic noise low. The electronics used has been a "Tennelec" Model 100 Charge Sensitive Preamplifier, followed by a standard 1430A main amplifier, followed by a 100-channel, 30 mV/channel, CDC kicksorter. The overall electronics noise, with the sample in the circuit and with the field applied, was about 1.3×10^3 electrons rms, which gave a resolution limitation of about 12 keV (FWHM).

The counters were found to count alpha-particles (Am^{241}), Co^{60} gamma-rays, and Hg^{203} gamma-rays. With Co^{60} , the signal-to-noise ratio at about the 1 MeV Compton edge was 150:1, but with Hg^{203} (279 keV gamma) the charge collected per pulse was about four times less. The value of 3.5 eV per electron-hole pair for silicon checked up with both cobalt and mercury gamma-rays. The pulse lengths were about 1–2 μs . These results are all very similar to those reported by GIBBONS and NORTHROP [5] for Co^{60} gamma-rays in silicon counters, though we have apparently observed a better signal to noise ratio.

Northrop of SERL, Baldock, has found that the higher the field applied, the sharper is the Compton edge in the pulse-height spectrum and under these conditions he has observed two humps in the Co^{60} spectrum just on this Compton edge (private communication). This he interprets to be due to resolution of the two 1.1 and 1.3-MeV Co^{60} Compton edges.

We have searched for this double Compton edge with Co^{60} , but at the time of writing have observed only a steady fall off in pulse height with increasing channel number, even with 900 V/cm field and even with a cylindrical silicon counter 4 cm long and 2 cm diam. However, with Hg^{203} , we have observed a much sharper cut-off (i.e. sharper Compton edge), but still no photopeak. We feel confident that if we can exactly balance the compensation in one of our large samples so that the overall final resistance at 80° K is greater than 10^8 Ω , and if we can at the same time keep the carrier lifetime

* Too much compensation may even change it to n-type, in which case a p-n junction is formed at the boron-doped surface. When this happens, most of the applied field gets developed across this junction, and the sample no longer works as a bulk conductivity counter.

long then we should observe photopeaks with low energy gamma-rays of about 100 keV, and pair-production peaks with high-energy gamma rays of about 5 MeV. The resolution should not be worse than a few percent. Ion bombardment offers one possibility of making ohmic contacts on high-resistivity silicon without bulk heating and consequent lowering of life-times.

ACKNOWLEDGEMENTS

We are grateful to Dr. D. C. Northrop of SERL Baldock for helpful discussions regarding fabrication difficulties with conductivity counters and to Dr. T. Green and Mr. A. Muggleton of AWRE for providing details of their experiences with using and making surface-barrier counters. Acknowledgement is made to the Director of AWRE for permission to publish.

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DISCUSSION

G. L. Miller (United States of America): I want to ask the last speaker why he thinks the resistivity is raised because the material is compensated.

E. M. Gunnensen (United Kingdom): We do not know very much about this process, but we think it is probably something to do with oxygen trapped in the lattice and producing some compensation process. This has been put forward as an explanation for the gallium arsenide case, but I do not know whether it still applies in silicon.

G. L. Miller: It seems to me that the compensation argument is very unlikely on the following grounds. Assuming that we start with, say, 10000- Ω -cm silicon and we want to take it to 10^9 ; it is then necessary, even at liquid air, to have a degree of compensation of about 10^5 . Whatever was being done in introducing the compensation would have to be done accurately to one part in 10^5 . I think, first, that you are not doing this and, secondly, that it has nothing to do with putting in boron, which is an acceptor.

E. M. Gunnensen: Of course, the boron has nothing to do with the compensation process. There is something very strange about this process, I agree completely, because in the case of gallium arsenide almost exact compensation seems to be obtainable in every case, and this seems almost impossible.

G. L. Miller: We have worked with gallium arsenide and we found it poor material. Our experience is not that it is compensated, but that it is full of traps. The people who make this material claim that its stoichiometry is marvellous, and that it is of high purity, but they admit that it is full of material that traps out the carriers. My guess would be that in both cases this was a phenomenon entirely due to trapping. It seems to me that it would be possible to check this by measuring the extent to which the resistivity of this material is dependent on temperature, because that should show what the activation energy of the levels of interest are.

A. Roberts (United States of America): I would like to take advantage of this opportunity to address a question to several of the previous speakers, although not to any one in particular. I want to point out, as a would-be user of these semiconductor detectors, that there is one type of detector which has not been developed very much as yet, and which would be very useful in high-energy physics, and that is a semiconductor detector with avalanche properties so that it would give out a large pulse independent of the primary ionization—something analogous to a Geiger-Müller counter. Such a device, which would need no amplifiers, would then allow the semiconductor detectors to be used in rather large quantities, as is usually desirable in experiments in high-energy physics. I wonder if anyone would be willing to comment on whether such a device will be available soon.

C. J. Borkowski (United States of America): There was some discussion of this topic at the Ashville Conference. The National Academy of Science has just brought out the proceedings of the Ashville Conference on semiconductor nuclear particle detectors. It was—at least as I recall—the consensus of opinion that the largest avalanche multiplication one could get reasonably was about 20, and I think I would expect the greatest gain to be obtained by transistor action, occurring within the semiconducting material, similar to that described by Williams of RCA, Montreal. I think the future probably is brighter for that type of device than for an avalanche-multiplication process.

K. Kandiah (United Kingdom): I would like to make a comment on Mr. Robert's reference to avalanche multiplication. We did have this question looked at by people who are expert in making junctions of very high accuracy, and it seems that it is impossible to obtain sufficiently uniform multiplication to give the necessary resolution over the kind of area required for a particle detector.

CHANGE OF I-V CHARACTERISTICS OF SiC DIODES UPON REACTOR IRRADIATION

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Abstract — Résumé — Аннотация — Resumen

Change of I-V characteristics of SiC diodes upon reactor irradiation. In search for semi-conductors, which can be used in high-flux reactors in order to measure flux distributions, we irradiated SiC p-n junctions in the Belgium BR-1 reactor. Two types of SiC-diodes of different origin have been irradiated. These junctions are grown in the Lely-furnace.

The change in forward and reverse characteristics have been measured during and after irradiation up to temperatures of 150° C, while measurements up to a temperature of 500° C are in progress.

It has been found that one type resists BR-1 neutrons up to an integrated flux of 10^{15} n/cm², while the other resists irradiation up to a flux of 10^{17} n/cm².

The changes in characteristics are given as well as the result of some annealing experiments.

Modification des caractéristiques I-V de jonctions p-n au SiC du fait d'une irradiation dans un réacteur. En recherchant des semi-conducteurs pouvant servir à mesurer les distributions de flux dans les réacteurs à haut flux de neutrons, les auteurs ont irradié des jonctions p-n au SiC dans le réacteur belge BR-1. Deux types de diodes à SiC d'origines différentes ont été ainsi irradiés. Les jonctions en question sont préparées par étirage dans le four Lely.

Les auteurs ont mesuré les modifications subies par les caractéristiques I-V après et pendant l'irradiation à des températures allant jusqu'à 150° C; ils poursuivent leurs mesures dans la gamme des températures allant de 150° C à 500° C.

Ils ont constaté que l'un des types de diode à SiC résiste aux neutrons du réacteur BR-1 jusqu'à 10^{15} n/cm², tandis que l'autre type résiste à l'irradiation jusqu'à 10^{17} n/cm².

Les auteurs indiquent les modifications subies par les caractéristiques, ainsi que le résultat de certaines expériences de recuit.

Изменения характеристик I-V выращенного в SiC перехода типа p-n после облучения его в реакторе. В поисках полупроводников, которые могли бы быть использованы в реакторах с высокой плотностью нейтронного потока для измерения распределения потоков, мы облучали в бельгийском реакторе BR-1 переходы типа p-n в SiC. Были облучены два типа диодов SiC различного происхождения. Эти переходы выращиваются в печи Лели.

Изменения прямой и обратной характеристик были измерены после и во время облучения вплоть до температуры 150° C; в настоящее время производятся измерения вплоть до температуры 500° C.

Было установлено, что один тип диода выдерживает нейтронное облучение реактора BR-1 вплоть до интегрированного потока 10^{15} нейтронов на кв. см, тогда как другой тип выдерживает облучение вплоть до потока 10^{17} нейтронов на кв. см.

Даются изменения характеристик, а также результаты некоторых экспериментов отжига.

Modificaciones que sufren por irradiación en un reactor las características I-V de uniones p-n en SiC. Los autores están tratando de encontrar semiconductores con los que sea posible medir distribuciones de flujo en reactores de flujo elevado, y con este fin irradiaron uniones p-n del SiC en el reactor BR-1 de Bélgica. Irradiaron dos tipos de diodos de SiC de distintas procedencias. Las uniones se obtuvieron en el horno de Lely.

Midieron las características directa e inversa durante la irradiación, y después de ésta, hasta la temperatura de 150° C. Se están realizando mediciones hasta 500° C.

Han encontrado que uno de los tipos de diodo es resistente a los neutrones del BR-1 hasta un flujo integrado de 10^{15} neutrones/cm², mientras que el otro soporta hasta 10^{17} neutrones/cm².

La memoria indica los cambios de las características, así como los resultados de algunos experimentos de recocido.

I. Introduction

The study of radiation damage on grown SiC p-n junctions (the initial results of which are reported below) has been started by us as part of a programme for the development of a solid-state neutron detector for measuring flux distributions in high-flux reactors. The detector will have to operate at temperatures as high as 500° C and in a radiation field of 10^{14} neutrons/cm² s. SiC diodes maintain their rectifying properties up to 500° C. AUKERMAN *et al.*, [1] and BRYSON [2] have reported a resistance to radiation damage of some orders of magnitude higher than silicon. These authors irradiated alloyed p-n junctions at temperatures of 40° C. On the basis of the results of PRIMAK, FUCHS and DAY [3] who have measured changes brought about by irradiation in the length and density of hexagonal SiC, rapid annealing may be expected at 500° C. In order to investigate the extent to which, at this temperature, the rate of annealing is equivalent to the rate of radiation damage, we irradiated a number of grown SiC junctions of two different types in the Belgian Br-1 reactor and measured the changes in characteristics up to temperatures of 150° C, while measurements at temperatures as high as 500° C are in progress.

II. Grown SiC p-n junctions

The junctions, of which we have received two types and which will be indicated by the letters A and B, are all grown according to a method described by LELY [4].

TYPE-A JUNCTIONS

The properties of the type-A junctions are the same as those described by GREEBE and KNIPPENBERG [5]. The p-region has an acceptor of which the ionization energy is about 0.3 eV. The n-region contains N₂ as a donor of which the ionization energy is 0.08 eV. On the basis of the $q/2 kT$ behaviour of the forward characteristic and of the activation energy of 1.4 eV, Greebe and Knippenberg assume that these diodes have a p-i-n structure, the theory of which is described by HERLET and SPENKE [6]. The forward and reverse characteristics of a type-A junction at room temperature are given in Figs. 1, 2 and 3. The semi-logarithmically-plotted forward characteristic of type-A junctions is composed of two or more regions of different behaviour. The junction is clearly visible and is partly parallel to the surface at a depth of about 100 μ .

The photovoltaic effect was found to be 0.03 V upon irradiation with γ -rays from a 60 K-c cobalt source. The capacity of these junctions is about 100 pF/mm² and is inversely proportional to the cubic root of the bias voltage. Attempts to use this deep-lying junction as a charged particle detector have so far failed.

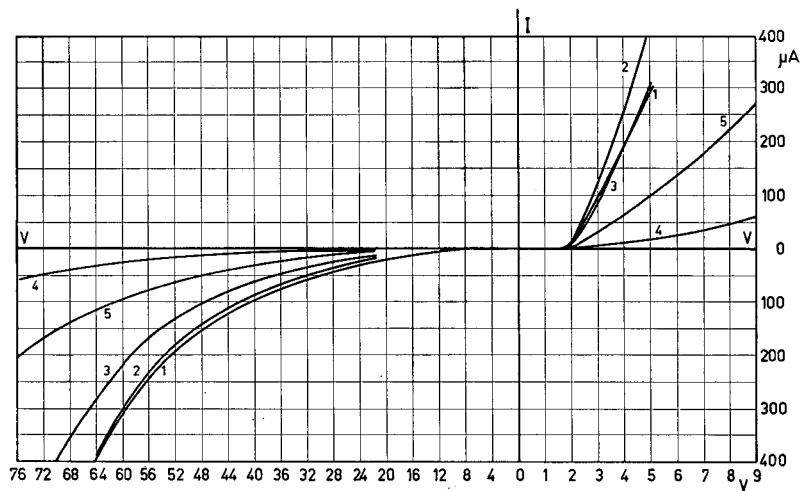


Fig. 1
Change of characteristics after irradiation with various doses and annealing of a type-A SiC p-n junction

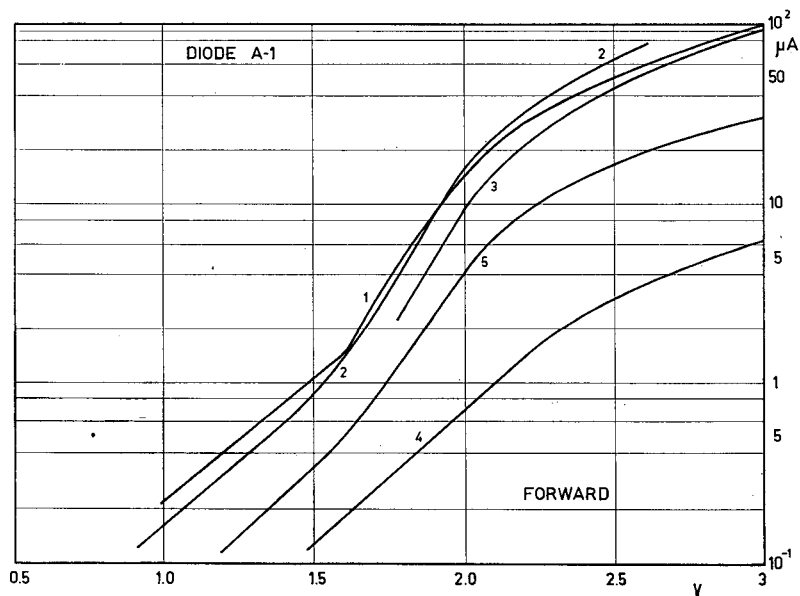


Fig. 2
Change of forward characteristics after irradiation with various doses and annealing of a type-A SiC p-n junction

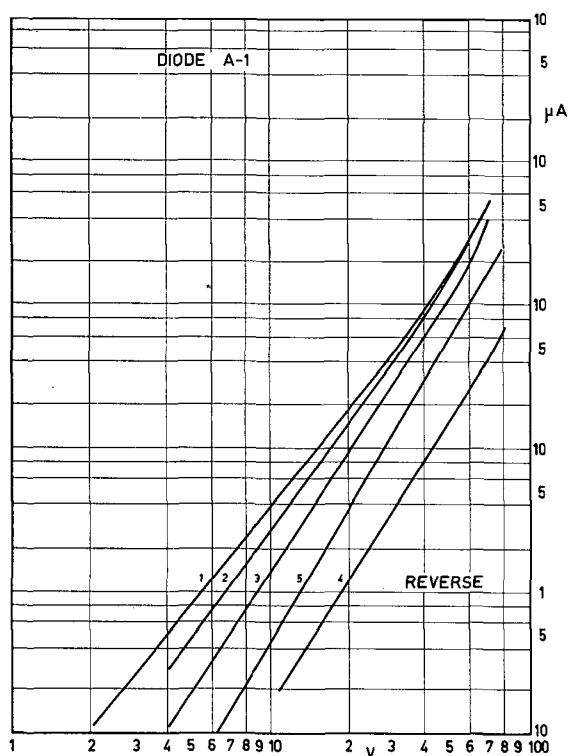


Fig. 3

Change of reverse characteristics after irradiation with various doses and annealing of a type-A SiC p-n junction

TYPE-B JUNCTIONS

The p-region of the junction contains Al as an acceptor and the n-region contains N_2 as a donor. The forward and reverse characteristics for various temperatures are shown in Figs. 4 and 5. The semi-logarithmically-plotted forward characteristics are straight lines with a slope of $q/2 kT$. The crystals are dark in colour and the junction, which is at a right angle to the surface, is not visible. Ohmic contacts on type-A and type-B junctions are made by alloying tungsten or molybdenum strips to the crystals.

III. Experimental

The junctions are sealed in a quartz container under inert atmosphere. The container with the measuring leads is lowered down along a helically wound aluminium tube into a specially designed oven, which is placed into a vertical channel of the BR-1 reactor.

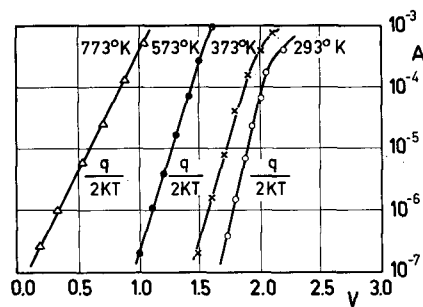


Fig. 4

The forward characteristics of a type-B SiC p-n junction for various temperatures

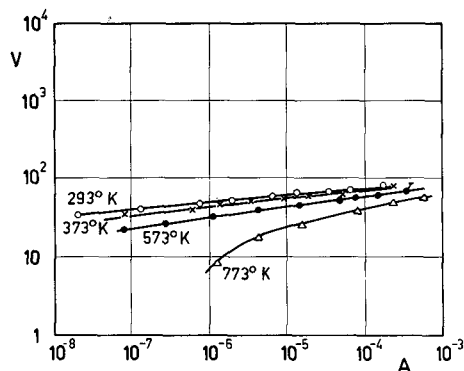


Fig. 5

The reverse characteristics of a type-B SiC p-n junction for various temperatures

The voltage-current characteristics are measured at definite times semi-automatically according to the principle illustrated in Fig. 6. The flux at the position of the junction is 2×10^{12} n/cm² s of which 10% are neutrons with energies greater than 0.1 MeV. No precautions are taken to shield the junctions from thermal neutrons.

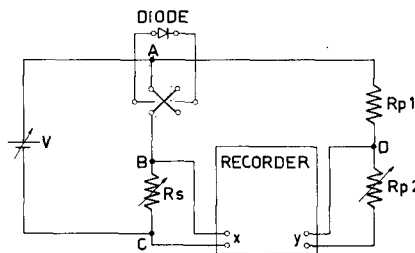


Fig. 6

Circuit for the semi-automatic recording of voltage-current characteristics

A number of junctions are measured at room temperature in the laboratory after irradiation, while others are measured semi-automatically during irradiation.

IV. Results

The experiments, which have so far been performed up to a temperature of 150°C , have not shown any annealing effect. However, junctions which have been heated at a temperature of 500°C for a period of 24 h outside the reactor after irradiation with a dose of 10^{17} n/cm^2 , do show a partial annealing as evidenced in Figs. 1, 2 and 3. In type-A crystals a light brown colour persisted, even after the crystals were heated up to a temperature of 750°C .

Essentially the type-A as well as the type-B junctions show the same behaviour, with the important difference, however, that the characteristics of the type-B junctions up to a dose of 10^{16} n/cm^2 , and the type-A junctions up to a dose of 10^{14} n/cm^2 , do not change.

The change in the characteristics are schematically represented in Fig. 7. Fig. 8 gives a typical example of the change in current at a constant voltage of 2 V in the forward and the reverse direction as a function of the dose. The points have been taken from a sequence of semi-automatically recorded characteristics of a type-A junction.

The forward characteristic does not change up to a certain dose after which it suddenly moves to the current-axis till it reaches a certain position where it remains for some time. The characteristic then starts moving to the voltage-axis, passing its initial position. The reverse characteristic moves monotonically with the dose to the voltage-axis.

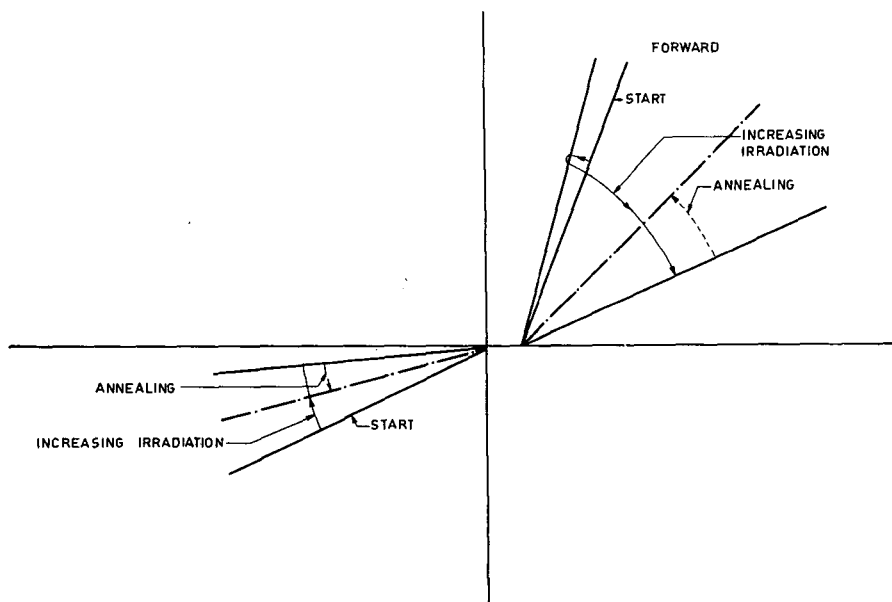


Fig. 7

Schematic representation of the change in the voltage-current characteristics of type-A and B SiC p-n junctions upon irradiation with various doses

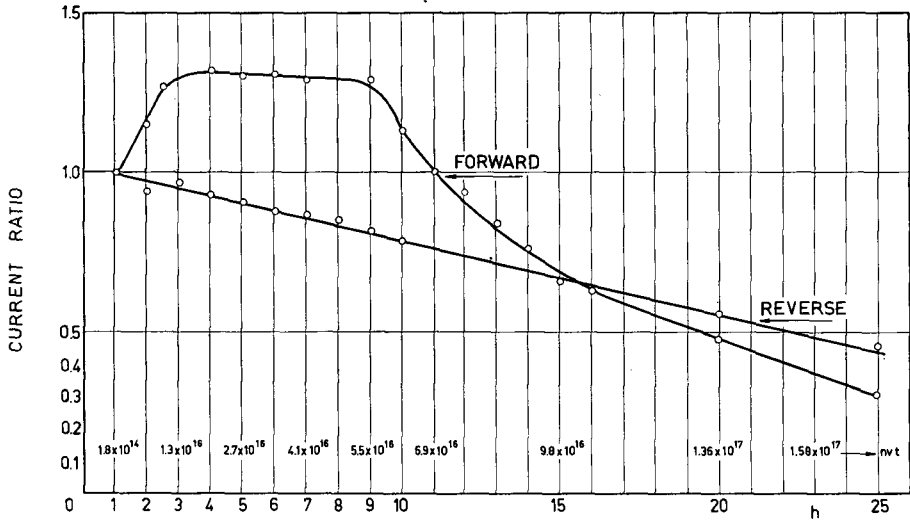


Fig. 8

Change of forward and reverse current at a constant forward and reverse bias of 2 V during irradiation of a type-A SiC p-n junction

Figs. 1, 2 and 8 show an example of the change in the forward and the reverse characteristic of a type-A junction which is measured at room temperature in the laboratory after having been irradiated with various doses.

It was found that the double-logarithmically-plotted reverse characteristics move parallel to themselves to lower currents. The slope of the semi-logarithmically-plotted forward characteristics increased at first, which was observed for all the diodes measured. Upon further irradiation the forward characteristics move to lower currents as well. The extrapolated saturation current decreases with increasing dose. At higher doses the departure from the straight lines sets in at lower currents, which part is no longer quite ohmic.

V. Discussion

The results may be explained by assuming that the junction has a p-i-n structure and that a net amount of donors is introduced per unit-dose of neutron radiation. In type-A junctions the concentration of the acceptors in the p-region is $10^{18}/\text{cm}^3$, the concentration of the donors in the n-region $10^{19}/\text{cm}^3$, while it is supposed that an intrinsic region of a certain width exists between them.

Herlet and Spence have calculated the maximum bias voltages for germanium at which the p-i-n structure changes into a p-s-n structure at different donor concentrations introduced in the originally intrinsic region. The same calculation, which were made for SiC on the assumption that the concentration of the intrinsic electrons and holes at room temperature is $10^{-4}/\text{cm}^3$ [5], shows that the maximum voltage at which the p-i-n structure changes into a p-s-n structure is 2 V for a concentration of 10^{14} donors/ cm^3 . This is about the voltage up to which the characteristics in the forward direction have

been measured. The introduction of this amount of donors does not affect the situation in the p- and the n-region. As a consequence of this change in structure the $q/2 kT$ behaviour of the diode will become a q/kT behaviour or more generally speaking the slope of the semi-logarithmically-plotted forward characteristic will increase, which is exactly what was observed with all the junctions. It was found that for type-A junctions the increase in slope occurs at a dose of about 10^{13} fast neutrons/cm², which means that on the basis of the above-mentioned calculation 10 ionized donors are created per fast neutron.

In the early stage of its formation the p-s-n diode can be considered as if it is composed of a p*-n and an n-n* junction of which the last is of no importance in this consideration. The saturation current of the p*-n junction is proportional to the concentration of the holes in the n-region (originally intrinsic). This concentration decreases with increasing donor concentration and thus with increasing dose. As a consequence the saturation current decreases proportional with the dose as is demonstrated in Fig. 2 and Fig. 8 for the reverse current. This process is going on until the concentration of the holes in the n-region is of the same order of magnitude as the concentration of the electrons in the p-region, at which stage the Fermi-level in this region starts moving, which means that the diode will be destroyed after some time.

It is assumed that the diffusion length, the diffusion coefficient and the lifetime of the different regions did not change, which will certainly take place in the later stages of the radiation damage.

The fact that the type-B junction does not change before it has received a dose of 10^{15} fast neutrons per cm² may be explained by the assumption that this diode already had a p-s-n structure before the irradiation started, which does not however accord with the observation that the slope of the semi-logarithmically-plotted forward characteristic also increases at first.

This work is part of a research programme undertaken at CEN, Mol, on behalf of the Joint Research and Development Program of the agreement for co-operation between the European Atomic Energy Community and the United States of America.

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DISCUSSION

B. de Cosnac (France): Did you use a mono-energetic source of neutrons or a complex spectrum in the experiments which have been carried out?

M. Heerschap (European Atomic Energy Community): These experiments have been carried out in the Belgian BR-1 reactor with a complex spectrum of neutrons, ranging from thermal-neutrons to fast neutrons.

B. de Cosnac: We have irradiated semi-conductors in the reactors of Fontenay-aux-Roses. The results seem to be different with the fast neutron spectrum in the reactors. Does not this completely alter the conclusions drawn from the results? Would it not be better to study each neutron energy separately?

M. Heerschap: From resistivity measurements we have got the impression that donor impurities are introduced into the silicon carbide upon electron and neutron irradiation. I think you are right that one should do this experiment with mono-energetic neutrons, but we are not in a position to do so.

SEMICONDUCTOR COUNTERS AS CHARGED-PARTICLE AND NEUTRON SPECTROMETERS

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Abstract — Résumé — Аннотация — Resumen

Semiconductor counters as charged-particle and neutron spectrometers. Since December 1958, surface-barrier detectors in silicon and germanium have been studied at the Atomic Energy Research Establishment (AERE). A relatively simple and reliable technique has been developed for their construction and results of their performance will be shown.

The best resolution obtained has been 15 keV and linearity has been achieved for protons up to 10 MeV, at which energy the resolution was 50 keV. The detector characteristics depend markedly upon the quality of the semiconductor starting-material. Not all counters attain the resolution figures quoted, due to recombination processes during collection of the carriers. A study of these processes is being made.

The high resolution, excellent linearity, fast rise-time, compactness of size and simplicity of design of these counters make them ideally suited for many applications in nuclear physics.

One such application is the use of a detector as a proton-recoil neutron spectrometer, in which a thin hydrogenous radiator is deposited on the face of a counter. A neutron spectrum is obtained by differentiation of the recoil proton spectrum. Results with regard to resolution and efficiency of such a detector are presented.

Compteurs à semi-conducteurs utilisés comme des spectromètres pour particules chargées et pour neutrons. Depuis décembre 1958, l'AERE étudie des détecteurs à barrière de surface en silicium et en germanium. Il a mis au point un procédé de construction relativement simple et sûr. Le mémoire expose les résultats du fonctionnement de ces appareils.

La meilleure résolution obtenue s'élevait à 15 keV; la linéarité a pu être obtenue pour des protons allant jusqu'à 10 MeV, énergie pour laquelle la résolution était de 50 keV. Les caractéristiques des détecteurs dépendent beaucoup de la qualité du matériau de départ. Etant donné les processus de recombinaison qui interviennent pendant la collection des porteurs de charge, certains compteurs n'atteignent pas les pouvoirs de résolution indiqués. Les auteurs ont étudié ces processus.

En raison de leur pouvoir de résolution élevé, de leur excellente linéarité, de la brièveté du temps de montée, de leurs petites dimensions et de la simplicité de leur conception, ces compteurs conviennent parfaitement à un grand nombre d'emplois en physique nucléaire.

Il y a lieu de signaler notamment l'emploi d'un de ces détecteurs comme spectromètre neutronique à protons de recul, dans lequel un milieu hydrogéné radiatif est déposé en couche mince sur la face du compteur. Il permet d'obtenir un spectre neutronique par différentiation du spectre des protons de recul. Les auteurs exposent les résultats relatifs au pouvoir de résolution et au rendement de ce détecteur.

Счетчики на полупроводниках, используемые в качестве спектрометров для заряженных частиц и нейтронов. С декабря 1958 года в Управлении по атомной энергии Соединенного Королевства изучались поверхностно-барьерные детекторы в кремнии и германии. Был разработан относительно простой и надежный метод их конструкции; результаты работы детекторов будут продемонстрированы.

Наиболее высокая полученная разрешающая способность составляла 15 KeV; была достигнута линейность для протонов до 10 MeV, при данной энергии разрешающая способность составляла 50 KeV. Характеристики детектора явно зависят от качеств исходного материала полупроводника. Не на всех счетчиках достигаются приводимые

цифры разрешающей способности из-за процессов рекомбинации во время накопления носителей. Сейчас осуществляется изучение этих процессов.

Высокая разрешающая способность, отличная линейность, быстрое время нарастания, компактный размер и простота конструкции этих счетчиков делают их идеально подходящими для многих применений в ядерной физике.

Одним из таких применений является использование детектора в качестве нейтронного спектрометра для ядер отдачи протонов, в котором тонкий водородосодержащий излучатель осаждается на поверхности счетчика. Спектр нейтронов получается посредством дифференциации спектра ядер отдачи протонов. Представлены результаты относительно разрешающей способности и эффективности такого детектора.

Empleo de contadores semiconductores como espectrómetros de partículas cargadas y de neutrones. En el Atomic Energy Research Establishment se estudian, desde diciembre de 1958, los detectores de barrera superficial de silicio y germanio. Para su construcción se ha ideado un procedimiento relativamente sencillo y seguro; en la memoria se exponen los resultados de las pruebas realizadas con ellos.

El mejor poder de resolución obtenido ha sido de 15 keV y se ha logrado linealidad para protones de hasta 10 MeV; para esta energía, el poder de resolución es de 50 keV. Las características del detector dependen en grado considerable de la calidad del material semiconductor de partida. No todos los contadores permiten alcanzar un poder de resolución como los citados, debido a los procesos de recombinación durante la colección de los portadores. Se está efectuando un estudio de estos procesos.

El elevado poder de resolución, la excelente linealidad, el breve tiempo de elevación, el reducido tamaño y la sencillez de diseño de estos contadores los hacen ideales para múltiples aplicaciones en la física nuclear.

Una de estas aplicaciones consiste en emplearlos como espectrómetros de neutrones por protones de retroceso, para lo que se deposita una capa delgada de radiador conteniendo hidrógeno en la cara del contador. Por diferenciación del espectro de los protones de retroceso, se obtiene un espectro neutrónico. Se exponen los resultados obtenidos en lo que respecta al poder de resolución y a la eficacia de este detector.

I. Construction of surface-barrier detectors

For over two years surface-barrier detectors in silicon and germanium have been made and studied at AERE, Harwell [1]. A relatively simple and reliable technique has been developed for their construction.

The technique is quite straightforward but requires a vacuum evaporation system and a fume cupboard. Extreme cleanliness is essential at all stages because impurities present in high-resistivity silicon and germanium represent only a few parts in 10^{10} . The crystals should not be touched with bare hands, for instance.

In order to prepare detectors of silicon, zone refined crystals of this material are cut to the required size and lapped to a fine matt finish with aluminium oxide of about $7\ \mu$ grain size. The procedure is then as follows:

(1) The crystal is cleaned before etching by being boiled for a few minutes in concentrated nitric acid.

(2) The crystal is then put in a polyethylene beaker and about 20 cc of CP-4A etch is added, the mixture being kept ice-cold. Etch-pit formation has been observed if the temperature is allowed to rise. CP-4A is a standard solution used in semi-conductor processing, and consists of:

concentrated nitric acid	2 vol.
glacial acetic acid	1 vol.
40% hydrofluoric acid	1 vol.

Chemicals should be of analytical reagent purity, mixed in clean polyethylene apparatus, and allowed to stand for 30 minutes before use. Fresh etch must be made up for each day's requirements. This step must be carried out with due care in a fume cupboard as HF produces serious burns on the skin and is highly toxic if inhaled. Five to ten minutes in the etch bath should be sufficient to produce a mirror-like finish on the silicon surface. In some cases uneven etching has been observed and is attributed to the presence of strain dislocations. Such crystals do not make good detectors. Bubbles which occur on the surface during etching should be removed by occasional agitation and we have recently found supersonic agitation very effective at this stage for removing bubbles.

(3) Demineralized water is run into the etch and the crystal is washed by alternate dilution and decanting, avoiding exposure of the silicon during the early stages of the procedure. A dark stain results if this precaution is not taken. The crystal is transferred to a clean polyethylene beaker and washed several more times with demineralized water. This beaker must be used for no other purpose. A water-conductivity cell can be employed at this stage to verify that the washing is complete. The crystal is then dried on pure tissue and allowed to stand for 1—2 days to undergo the initial oxidation process.

(4) A mica mask is prepared for the evaporation. A convenient shape is the keyhole as shown in Fig. 1, which provides a small gold area for the front contact leaving a circular area free. The purpose of the mask during evaporation is to define the area

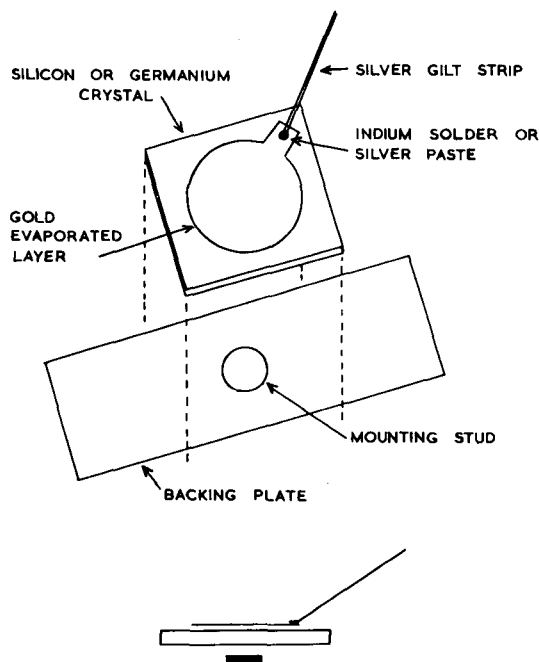


Fig. 1
Method of mounting a surface-barrier detector

of the counter and avoid deposition of gold on or near the crystal edges. The mask is then cleaved to ensure that the faces which are in contact with the crystal are perfectly clean and the crystal is lightly clipped between them.

(5) The masked crystal is then mounted in the vacuum evaporator so as to deposit gold on the face which has the best finish. The gold is evaporated at a pressure of less than 10^{-4} mm of Hg. For most purposes a film of about 75% light transmission, corresponding to 20–40 $\mu\text{g}/\text{cm}^2$, is satisfactory.

(6) The crystal is then removed and placed on pure tissue in a covered box, as it has been found that it is better to age the detectors for a few days after depositing the gold before making the connections. This is presumably to allow the surface oxide to fully develop, a process which appears to take place through the thin gold.

(7) A second gold evaporation is made, this time with the circular counting area shielded, forming a thicker deposit on the small tab to which electrical connection is to be made. This avoids the possibility of the organic binder in the silver paste penetrating and damaging the surface layer.

(8) The crystal is then cemented on to the required mount which may be simply a small plate of metal with fixing holes. Kovar is recommended as it has a coefficient of thermal expansion similar to that of silicon. Johnson, Matthey FSP 43 flake-silver paste has proved satisfactory. In order to give a long-surface leakage path and to avoid the possibility of cement remaining on the edges of the crystal, a dimple can be pressed into the plate or a small spacing disc inserted, as shown in Fig. 1. The silver paste contact is only slightly rectifying, presumably due to the effect of its organic constituents on the surface inversion layer; thus, despite the symmetrical preparation of the etched crystal, the finished unit is a diode.

(9) Front contact to the gold is made by a short length of silver-gold alloy galvanometer-suspension strip, cemented to the gold tab with a small drop of FSP 43. The paste should be sufficiently fluid to wet the gold but on no account should it be allowed to flow on to the uncoated silicon.

(10) The whole assembly is maintained at approximately 80° C for a few hours to set the conducting cement.

The device is then complete and ready for testing. The success rate of this method is very high and most of the differences in the performance of detectors are believed to be due to characteristics of the semi-conductor starting material. Thus a good detector can be satisfactorily reground and remade, while inferior detectors remain poor after reprocessing.

The procedure for germanium is identical to that described above for silicon except that (i) the etch may be used at room temperature and (ii) the method of making electrical connections is altered. Silver paste tends to fracture when cooled, so that it is better to make a solder connection, both to the base and to the gold layer, with indium (mp 155° C) as a solder.

II. Characteristics of surface-barrier detectors

Fig. 2 is a photograph of two silicon surface-barrier detectors which have been made as described above. It should be noted that the detectors are not enclosed in a mount, but are merely supported on the electrical connection at their rear surface. Fig. 3 is the spectrum of alpha-particles from an Am^{241} source as measured with such a counter;

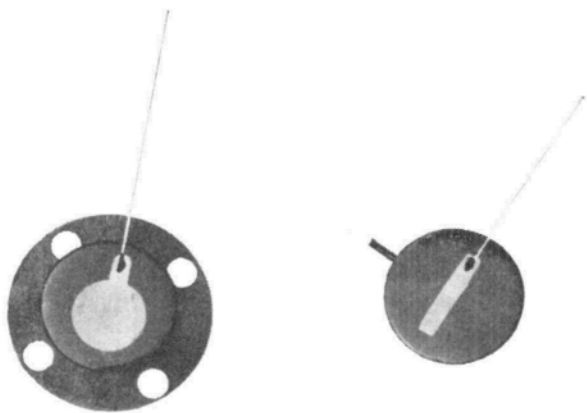


Fig. 2
Silicon surface-barrier charged-particle spectrometers

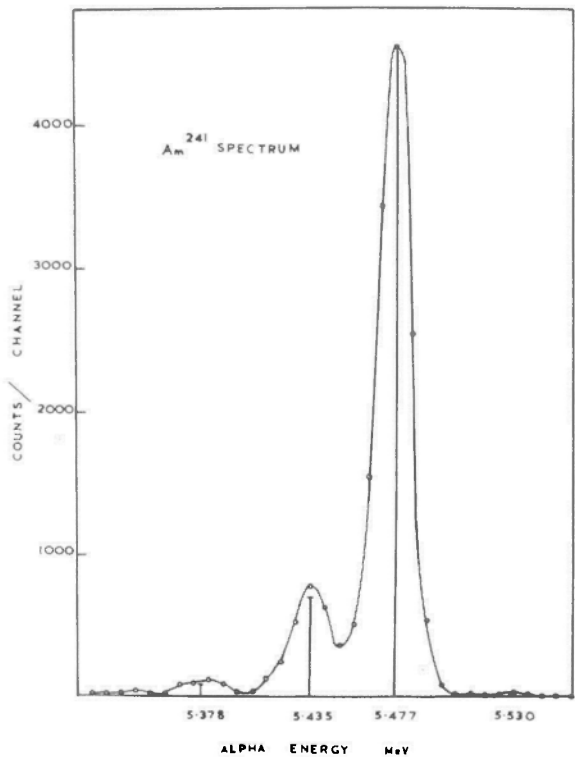


Fig. 3
Alpha-particle spectrum from an Am-241 source, as observed with a silicon surface-barrier detector

it can be seen that the four alpha groups are clearly resolved. The width at half maximum of one of the peaks is 16 keV, or 0.30% of the pulse height. The range of particle energies over which the counter gives a linear response increases as the bias voltage is raised. This is shown in Fig. 4; the particular detector has a linear response for proton energies up to 9 MeV when the bias is 150 V. We have achieved linearity for protons of 10 MeV energy; for these the resolution was 50 keV. Fig. 5 shows the spectrum obtained from a silicon detector in a study of the protons from the B(d, p) reaction. The multitude of particle groups is reminiscent of spectra obtained with a wide-range magnetic spectrograph, and indicates the future possibilities of these small surface-barrier detectors.

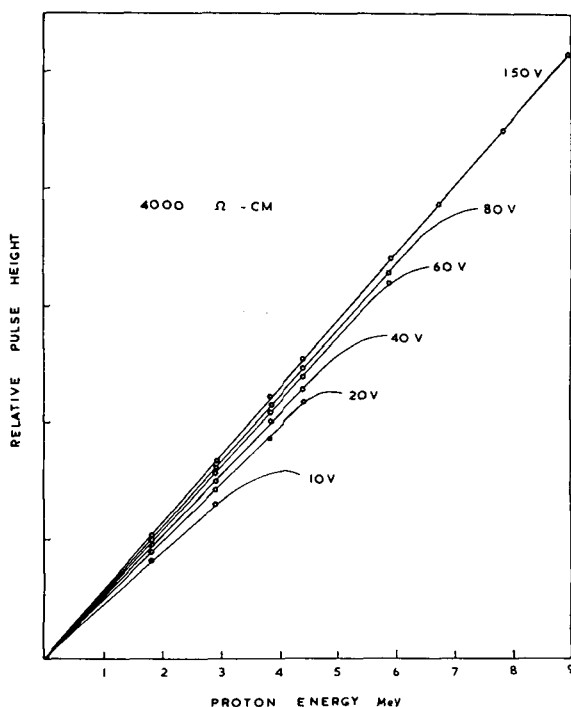


Fig. 4

Curves of pulse-height *vs.* proton energy, taken at various bias voltages with a silicon surface-barrier detector of 4000-Ω-cm resistivity. Each curve is labelled with the bias voltage at which it was taken

Not all detectors give performance figures such as those we have quoted, due to a variety of causes. Some silicon crystals contain structural defects so that the diode reverse current is high, giving poor signal-to-noise ratio. Parts of the crystal may contain regions where carriers recombine very readily, thus producing a lower signal; such crystals give an output which varies with the point of entry of the particle and hence poor resolution.

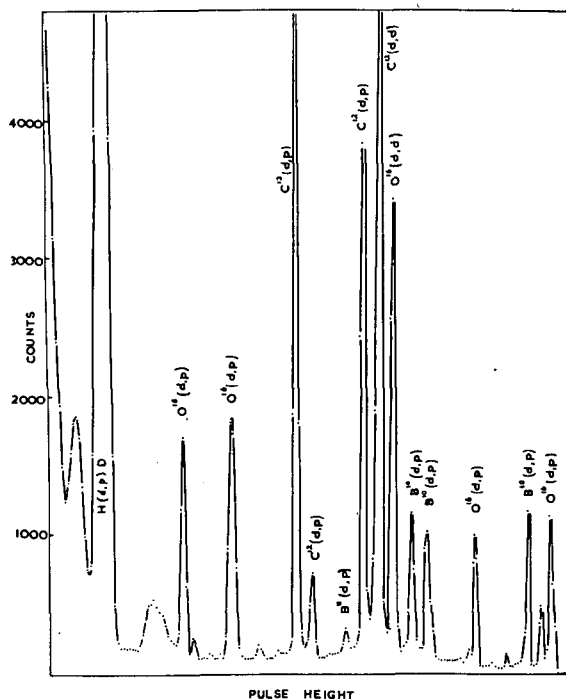


Fig. 5

Pulse-height spectrum from a silicon surface-barrier counter for particles emitted from a boron target bombarded with deuterons

III. Pulse amplification

A typical solid-state counter, with a capacity of about 20 pF, yields voltage pulses of about 2 mV per MeV; counters with large sensitive areas will have even lower voltage signals because of their increased capacity. Consequently a charge-sensitive amplifier with high gain and very low noise is desirable if the best performance is to be realized. For this purpose we are using an amplifier manufactured by Tennelec Instrument Co. of Oak Ridge, Tenn., United States of America.

In order to utilize the fast rise-time of the detectors, an amplifier of higher bandwidth is required, but the signal-to-noise ratio, and the stability of gain are then inferior. Thus with the AERE-type 2002A 200-Mc/s amplifier the noise level is around 0.5 mV. In many cases it is possible to use a combination of fast and slow amplification, so that fast coincidence measurements can be made simultaneously with a high-resolution pulse-height analysis. An example of such an arrangement is shown in Fig. 6.

IV. Proton-recoil neutron spectrometer

A recent application of the surface-barrier detector has been in use in a proton-recoil neutron spectrometer. The radiator is a thin layer of a hydrogenous material which is either evaporated on to the surface of the detector or is in the form of a self-

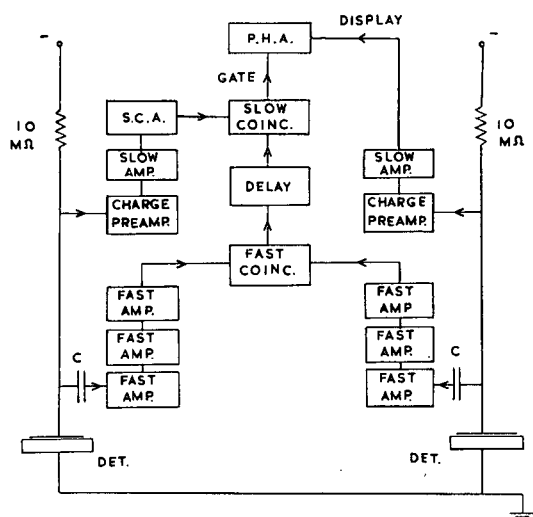


Fig. 6

Block diagram of an arrangement for making fast-coincidence measurements simultaneously with high-resolution pulse-height analysis

supporting film which is mounted just above the counter face. Such a detector works well at low neutron energies, as is demonstrated by the spectrum plotted in Fig. 7. This spectrum was taken at a neutron energy of 3.7 MeV. It is a typical proton-recoil

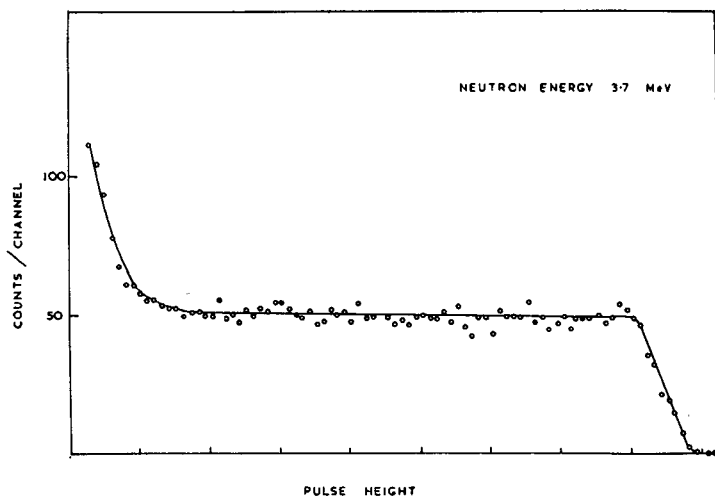


Fig. 7

Spectrum of recoil protons from a hydrogenous radiator bombarded with 3.7-MeV neutrons. The spectrum was taken with a single silicon surface-barrier detector

spectrum except for the rise at low pulse height which is a background due to hydrogen adsorbed in the walls of the counter housing. At higher energies, however, neutron interactions take place in the silicon, and the background becomes much larger and more complicated. In order to allow for this background, the counter shown in Fig. 8 has been constructed. Fig. 9 is a schematic drawing of the same counter. The counter consists of a disc of silicon, of diam. 2 cm, which has two separated gold semi-circles (marked "Au") evaporated on to it so that it is in reality two separate counters; "A" and "B" are the signal leads from these two detectors. The gold layers have the same shape and area so that the efficiencies of the two counters are the same. Over one of the gold semi circles, the left hand one on Fig. 9, a radiator ("R") in the form of a thin plastic film is supported on three small studs; this is shown as a shaded area. The



Fig. 8

Proton-recoil neutron spectrometer consisting of two semicircular surface-barrier detectors constructed side by side on the same silicon crystal, as described in the text

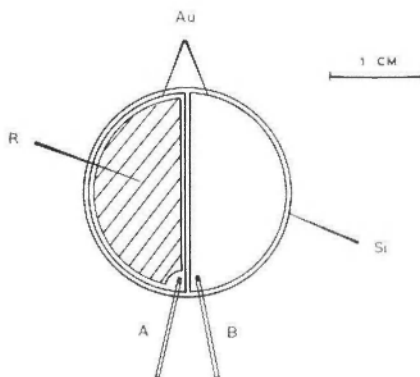


Fig. 9

Schematic diagram of the neutron spectrometer of Fig. 8. The two semicircular areas marked Au are the gold-covered sensitive areas of the two counters. R is the hydrogenous radiator, a plastic film which is suspended over the left-hand counter. A and B are the signal leads of the two counters

whole counter is enclosed in a pill-box like case. This case need not be evacuated—its purpose is simply to prevent contamination. When this detector is irradiated with neutrons, the left-hand counter will respond to the neutron induced background and to the recoil protons from the radiator, while the right-hand counter will respond to the background only. The two upper curves on Fig. 10 show the spectra obtained from such a counter pair when irradiated by neutrons of 6.86 MeV energy. The top curve, indicated by a solid line, is obtained from the counter covered by the radiator; the lower curve, shown by a broken line, comes from the uncovered counter and so corresponds to the background. A number of peaks can be seen in this background, all of which have been identified as due to neutron reactions with silicon; there is also a continuous background due to hydrogen adsorbed on the surface of the protective case, as has been mentioned previously. The lowest curve on the Figure shows the difference between the two upper spectra. It can be seen that the background has been almost completely eliminated, and that the resultant spectrum closely resembles a true proton-recoil spectrum.

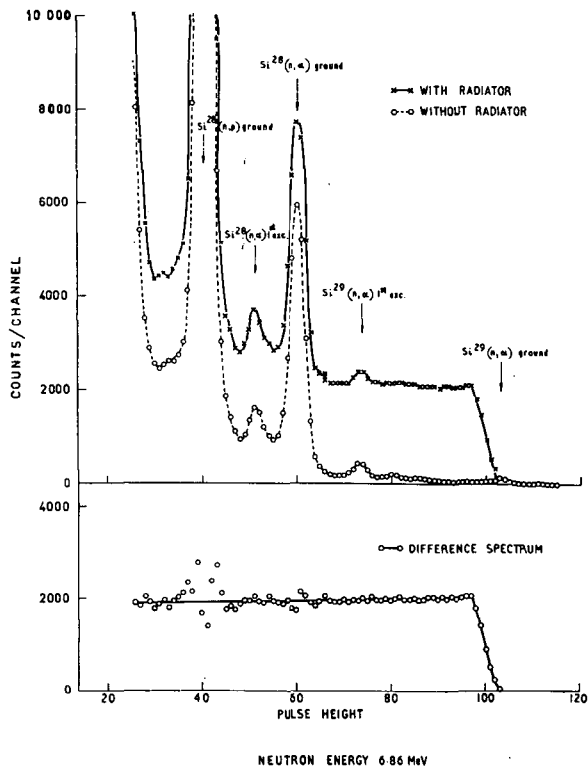


Fig. 10

Pulse-height spectra from the neutron spectrometer shown in Fig. 8, for a neutron energy of 6.86 MeV. The upper two curves are the spectra from, respectively, the side of the counter covered with a hydrogenous radiator (crosses) and the uncovered side (circles). The lower curve is the difference between the two upper curves, and is a true proton-recoil spectrum

This device is expected to compare very favourably with other fast neutron spectrometers. There is as yet little information as to the useful life of such a counter, but it is anticipated that radiation damage to the silicon will eventually affect the counter's resolution. However, the work of KLINGENSMITH [2] indicates that silicon detectors will tolerate 10^{12} — 10^{13} fast neutrons/cm².

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RECENT WORK ON INSTRUMENTATION FOR NUCLEAR PULSE-HEIGHT SPECTROSCOPY

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Abstract — Résumé — Аннотация — Resumen

Recent work on instrumentation for nuclear pulse-height spectroscopy. The invention of the semiconductor detector for charged nuclear particles has opened up new possibilities in the use of pulse-height spectroscopy techniques for studying nuclear reactions. The high intrinsic resolution of these detectors, both in time and energy measurements, has initiated some developmental work on the associated electronic circuits which will be described.

In the nuclear research work at the Nobel Institute a wide range of applications of semiconductor detectors is foreseen. The different experiments demand different types of detectors which generally have a limited life-time. In order to secure a sufficient supply of adequate units, the production of surface-barrier detectors has been started within the institute. A description of the detectors and the production techniques employed is given.

Travaux récents sur les instruments de mesure utilisés dans l'étude spectroscopique des impulsions nucléaires. L'utilisation des semi-conducteurs pour la détection des particules nucléaires chargées a ouvert de nouvelles possibilités d'application des techniques de spectroscopie des impulsions à l'étude des réactions nucléaires. Le fort pouvoir de résolution en temps et en énergie de ces détecteurs a permis d'apporter aux circuits électroniques connexes des perfectionnements que les auteurs décrivent.

Les travaux de recherche nucléaire entrepris à l'Institut Nobel permettent d'entrevoir un large champ d'application des détecteurs semi-conducteurs. Les différentes expériences exigent différents types de détecteurs, dont la vie est généralement assez brève. Afin de s'assurer une quantité suffisante de détecteurs appropriés, l'Institut a entrepris la production de détecteurs à barrière de surface. L'exposé donne la description de ces appareils et des méthodes de fabrication employées.

Новейшие достижения в приборах для спектроскопии ядерной амплитуды импульса Изобретение детектора на полупроводниках для заряженных ядерных частиц открыло новые возможности в использовании методов спектроскопии амплитуды импульса при изучении ядерных реакций. Высокая разрешающая способность этих детекторов как при измерениях времени, так и энергии положила начало дальнейшей работе по изучению связанных электронных схем, описание которых будет дано.

В исследовательской работе по ядерной энергии в Нобелевском институте предполагается широкое применение детекторов на полупроводниках. Для осуществления различных экспериментов требуются различные виды детекторов, которые в целом имеют короткий срок службы. Для того, чтобы обеспечить достаточное количество необходимых приборов, в институте приступили к производству детекторов с поверхностными барьерами. Дано описание детекторов и применяемых методов производства.

Trabajos recientes sobre el instrumental destinado a la espectroscopia de amplitud de impulsos. La invención del detector a base de semiconductores para partículas nucleares cargadas ha significado nuevas posibilidades en el uso de las técnicas de espectroscopia de la amplitud de impulsos que se aplican al estudio de las reacciones nucleares. El elevado poder intrínseco de resolución de estos detectores, tanto si se trata de medir tiempos como de medir energías, ha fomentado el estudio de los circuitos electrónicos respectivos, que se han de describir oportunamente.

En la labor de investigaciones nucleares llevada a cabo en el Instituto Nóbel se ha previsto una amplia serie de aplicaciones de los detectores a base de semiconductores. Los distintos experimentos exigen diferentes tipos de detectores cuya vida útil es generalmente limitada. A fin de asegurarse una provisión suficiente de estos elementos, se ha comenzado a producir en el Instituto los detectores de barrera superficial. La monografía incluirá una descripción de los detectores y de las técnicas de producción empleadas.

I. Introduction

The usefulness of the semiconductor detector for nuclear physics experiments is now well established. This is especially so for detecting charged particles heavier than electrons, for which the energy resolution is comparable with that of magnetic spectrometers. The devices also offer the additional advantage of making multi-channel measurements possible over a wide energy range at large solid angles. The applications lying nearest at hand are connected with the study of both alpha spectra from radioactive sources and nuclear reactions connected with particle accelerators.

The semiconductor detector is a very flexible device, not only in the sense that it can, by a proper choice of working conditions, be adapted to detect certain events and discriminate against others such as the selection of one type of particles from a mixed beam, but it can also be given physical dimensions that best fit into a certain experimental set-up and thus give optimum performance. This, on the other hand, implies that a laboratory using semiconductor detectors should also preferably have facilities for producing such detectors. Several reports on production techniques have been given [1]. This paper describes briefly the methods for manufacturing and testing the surface-barrier detectors adopted at this institute.

II. Construction techniques

The material used for the detectors is n-type silicon with a resistivity of 300 Ω cm and higher. After being cut to the proper size with a diamond saw, the detector elements are treated as follows:

- (1) Lapping with successively finer powder of Al_2O_3 or SiC down to 800 mesh. Very careful cleaning in water between successive steps in this process.
- (2) Careful cleaning in distilled water and boiling for five minutes in concentrated nitric acid.
- (3) Etching at 0° C for two minutes in modified CP-4 (2 vol. HNO_3 , 1 vol. HF, 1 vol. HAc, all concentrated). After this the element is transferred to a new bath of the same composition and is etched for another three minutes. The etching and the following cleaning are carried out in a well ventilated dry box. Extreme care is taken not to contaminate the hands with CP-4 as this can result in permanent damage due to the dissociation of the enzymes in the tissues.
- (4) Cleaning by successive dilution of the acid with de-ionized water or boiled distilled water. Air must not be admitted to the surface as long as acid is present.
- (5) Evaporation of 100 $\mu\text{g}/\text{cm}^2$ of gold on to the front surface. Before evaporation the gold is cleaned in concentrated HCl.
- (6) After this the elements are stored in dry air at room temperature for 3—5 days.

- (7) Additional gold is evaporated on to a limited area of the gold surface. Here the electrical connection is then made via a 0.1 mm Cu-wire fastened with JMC Thermo-Setting Silver Cement FSP 49.

The detector elements are mounted on holders as indicated in Fig. 1.

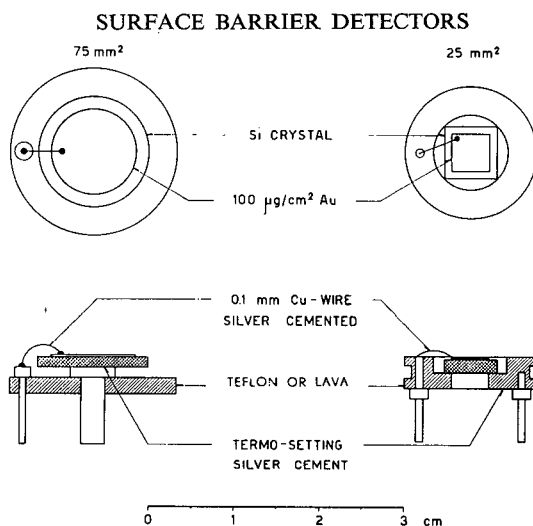


Fig. 1
Mounting of surface-barrier detectors

III. Test chamber and electronics

The detectors are tested in a vacuum chamber which is schematically shown in Fig. 2. This chamber can also be used in the routine measurements of alpha spectra from radioactive sources. No special precautions have hitherto been taken in order to avoid backscattering or the lowering of the background from the chamber walls.

The electronic equipment includes a charge-sensitive preamplifier [2]. The integrating and differentiating time-constants can be varied by means of switches which have been incorporated in the design in order to make possible the quick selection of the optimum values of these time-constants for a certain detector. The main amplifier and the biased post amplifier result from a design of FAIRSTEIN [3]. The bias voltage for the detector is also available from this unit. The pulse spectrum is analysed in a 100-channel pulse-height analyser of conventional design. A mercury-relay pulse generator feeds pulses into the input of the preamplifier. This arrangement has proved to be extremely useful for calibrating the energy scale of the spectrometer and also for determining the energy resolution and linearity of the system. The procedure in the resolution measurements is the following: the pulse-height distribution is recorded by the analyser for two different settings of the pulse generator with the peaks appearing symmetrically on both sides of an alpha peak of known energy. The shift in peak position and the full width at half maximum (FWHM) immediately gives the relative resolution in per cent and the resolution in kilo-electron-volt can be calculated from the known alpha energy.

ordinary capacitors. When the highest resolution with small detectors is desirable it is thus necessary to decrease the input capacity of the amplifier to a minimum and this suggests mounting the first tube of the cascode close to the detector, which should be possible [4].

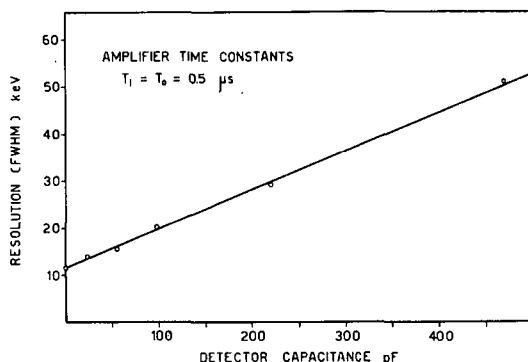


Fig. 4

Electronic resolution of alpha spectrometer measured by replacing the detector with various capacitances in the vacuum chamber

IV. Properties of the detectors manufactured

In Fig. 5 the reverse current of one of the detectors has been plotted as a function of bias voltage. The discontinuities in the current curve indicate three different sources of reverse current. The resolution curve shown in the same Figure was measured with $0.5 \mu\text{s}$ differentiating and integrating time-constants, which proved to give the best results for this particular detector. It gives the width (FWHM) expressed in kilo-electron-volts of a pulse-generator peak with the detector connected. The curve thus represents the resolution of an ideal source-detector combination with the exception that it has the capacitance

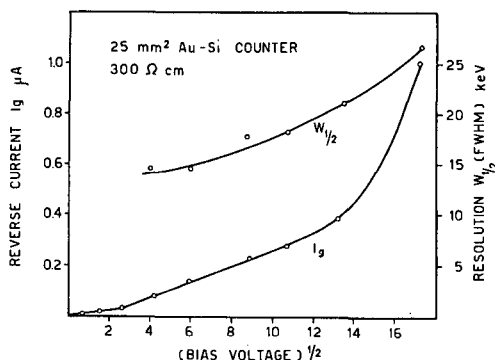


Fig. 5

Reverse current and resolution for a 25-mm² detector

and reverse current of the detector used. At lower biases, not shown in the Figure the resolution should become worse, due to an increasing detector capacitance as shown, in Fig. 4.

Figs. 6, 7 and 8 are examples of alpha spectra measured with one of the 25-mm² detectors. These measurements were made about four months after the detector had been manufactured. During this time the detector was stored in ordinary laboratory air and it was found that its performance gradually improved during that period. No method has so far been found which can accelerate this aging process.

Although the above examples indicate that a high energy resolution can be obtained with fairly easily manufactured surface-barrier detectors, the high resolution is not found for all units produced. It should be borne in mind, however, that very many experiments, especially on nuclear reactions, must be undertaken with a lower energy resolution, among other things because of time resolution considerations necessary at high counting rates.

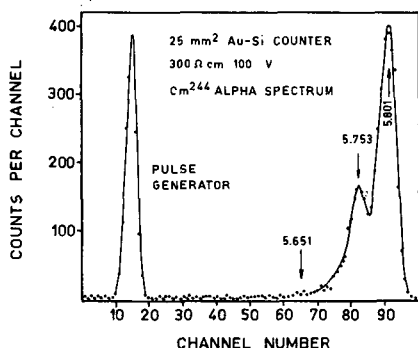


Fig. 6
Alpha spectrum of Cm²⁴⁴

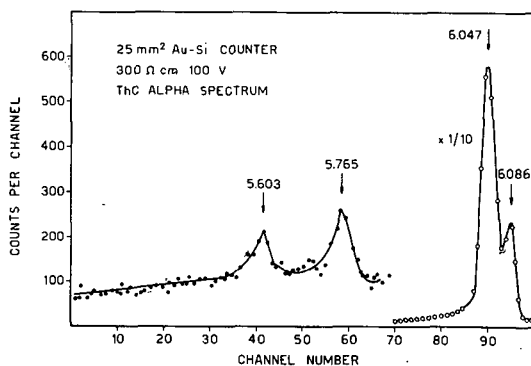


Fig. 7
Alpha spectrum of ThC

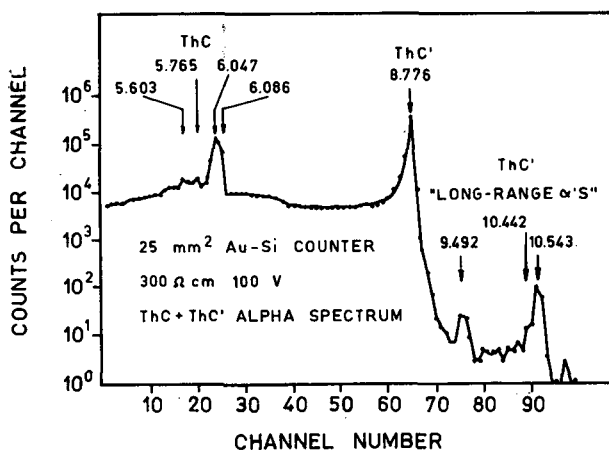


Fig. 8

Alpha spectrum of activities obtained by collecting recoils from RaTh source

ACKNOWLEDGEMENTS

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THE USE OF SEMICONDUCTOR COUNTERS FOR MEASURING THE DISTRIBUTION OF PILE-NEUTRON FLUX

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Abstract — Résumé — Аннотация — Resumen

The use of semiconductor counters for measuring the distribution of pile-neutron flux. Semiconductor counters for the detection of fast and slow neutrons and their use for measuring neutron-flux distribution in the RA reactor in Vinča are described.

Utilisation des semi-conducteurs pour mesurer la distribution du flux des neutrons dans les réacteurs. Description de compteurs à semi-conducteurs pour détecter les neutrons rapides et les neutrons lents et de leur utilisation pour mesurer la distribution du flux des neutrons dans le réacteur RA à Vinča.

Использование полупроводниковых счетчиков для измерения распределения нейтронных потоков в реакторе. Описываются полупроводниковые счетчики для обнаружения быстрых и медленных нейтронов и использование этих счетчиков для измерения распределения нейтронного потока в реакторе типа RA в Винче.

Uso de contadores a base de semiconductores para medir la distribución del flujo neutrónico en los reactores. Se describen contadores a base de semiconductores destinados a detectar neutrones lentos y rápidos y se explica la forma de utilizarlos en la medición de la distribución del flujo neutrónico en el Reactor RA de Vinča.

Summary

Semiconductor detectors are found to be suitable for neutron measurements in reactors with neutron fluxes up to 3×10^{13} n/cm²/s. At full reactor power (6.5 MW) the neutron-flux distribution was measured by placing the semiconductor detector at one end of a long evacuated tube and the target at the other end. Changes in the detector noise, the inverse resistance and the resolution under neutron and gamma irradiation were observed. A method of absolute measurement of the neutron flux was developed and the use of thinner detectors is suggested.

I. Introduction

Semiconductor detectors have been used for neutron counting through the detection of fission fragments [1] or through alpha particles from nuclear reaction in B¹⁰ [2] and Li⁶ [3]. Owing to their low sensitivity to gamma rays and neutrons, good resolution, small size and other properties, these detectors are especially suitable for measurements of pile-neutron fluxes. In order to study their applicability for this purpose and, in particular, their behaviour under strong neutron and gamma irradiation, a measurement was made of the neutron flux in the experimental channels of the 6.5-MW reactor in Vinča. In addition, we used a method of absolute measurement of the pile-neutron flux, based on the 4π coincident detection of fission fragments in two semiconductor counters.

This work is part of an experimental programme which involves the use of semiconductor counters for studying the ternary fission and angular correlation of neutrons and fission fragments.

II. Experimental technique and results

Junction-type silicon counters (supplied by RCA Victor Co., Montreal, Canada) with a sensitive area of 5 mm^2 were used for measuring the pile-neutron flux through the detection of fission fragments of natural uranium. A uranium layer, 0.1 mg/cm^2 thick and 2 mm in diam., was spread on a thin aluminium foil and placed 1 mm away from the counter surface. The counter was mounted on an aluminium tube 75 cm long, connected to a pre-amplifier. The counter and the pre-amplifier formed a rigid unit which could be placed in the desired position in a reactor channel. Differential constants of $5 \mu\text{s}$ were used in the pre-amplifier and the amplifier. Po^{210} and $\text{ThC} + \text{C}'$ alpha sources were used to calibrate the counters and to check their performance in the course of the experiments.

In the first series of measurements a detector without a uranium target was placed in the centre of the reactor core and the pulse spectrum was taken at various reactor power levels. It was found that the detector noise increased with reactor power and already at 100 W the peak noise amplitudes were the same size as those corresponding to the 3–4 MeV alpha particles. These high-noise pulses resulted from the piling up of smaller pulses caused by intense gamma and beta radiation. In view of such a high noise level, the use of n, alpha reactions for neutron detection in the presence of extremely strong gamma radiation does not seem easily realizable.

The next step was to measure the spectrum of fission fragments at various reactor power levels in order to determine the effect of irradiation on the counter characteristics. At low levels of power, around 100 W, the spectrum obtained had well-separated peaks due to heavy and light fission fragments, in spite of a relatively thick target and poor geometry. The fission pulses were also well above the low energy part of the spectrum. When the reactor power was increased to 10 kW, the positions of these peaks were not changed, but the noise level approached the peak of the heavier fragment. All these measurements were performed within a short period. Therefore, the effect of irradiation on the detector characteristics was not appreciable. When the counter was irradiated for a longer time, however, the pulse sizes decreased steadily and after several days of experiments the pulse size for Po^{210} alpha particles decreased twice. At the same time the inverse resistance of the detector changed from $200 \text{ M}\Omega$ to $4 \text{ M}\Omega$. The change of the inverse resistance under the prevailing gamma irradiation (at a zero reactor power level, or with a cadmium shield) was found to be reversible, but it was not the case after strong neutron irradiation. An analysis of the gamma-ray spectrum of the commercial detector showed the presence of the following radio-isotopes: Cu^{64} , Ni^{65} , Au^{198} , Si^{31} , and probably Mg^{27} . The first three came from the counter capsule and wire connections. In addition to these activities, there were short-life beta activities.

The distribution of the neutron flux along the central vertical channel was measured at a reactor power of 1 kW. The obtained results shown in Fig. 1 agree well with the measurements performed by using fission chambers. The reactor power was then varied and the neutron flux measured with the detector was placed in the centre of the core. A linear dependence of the number of counts per minute on the reactor power was obtained up to 3 kW (Fig. 2). The number of counts per minute started to increase

faster above this level than linearly because of the piling up of noise pulses. When the detector was placed at the edge of the core the linearity was observed up to 10 kW of reactor power.

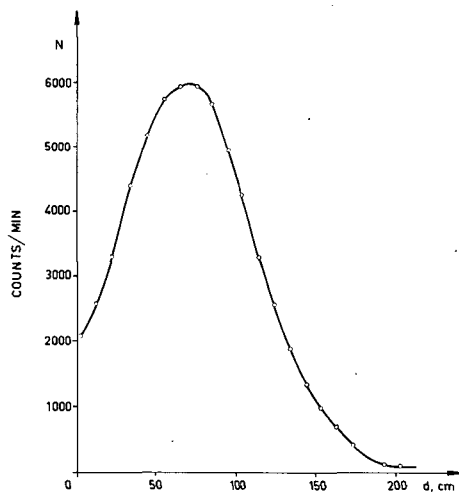


Fig. 1

The distribution of the neutron flux along the central vertical channel at a reactor power of 1 kW

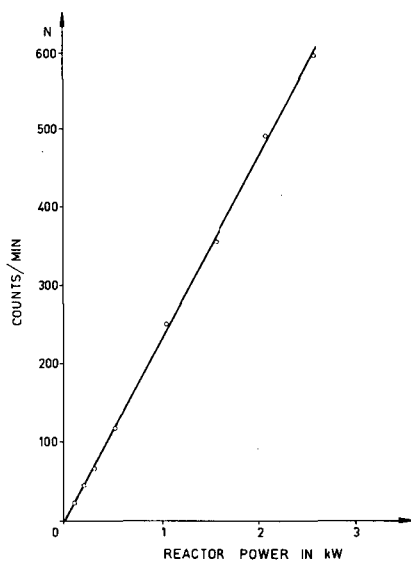


Fig. 2

The dependence of the counting rate on the reactor power

One way of measuring the neutron fluxes inside the core at much higher levels of operation, is by placing the target at one end of a long evacuated tube and the detector at the other end. Such measurements were performed at full reactor power (6.5 MW) by using a 6-m long tube of pure aluminium.* A 2% enriched-uranium target of 540 μg , spread on an aluminium foil with a 3-cm² surface area and a detector with a sensitive area of 20 mm², were used. The tube was evacuated to a pressure of 10^{-2} mm Hg. The geometrical efficiency for the detection was about 2×10^{-7} . The tube was inserted into a vertical channel of the reactor and the flux distribution was measured by moving the whole tube along the channel. The pulse spectrum from the detector showed well-resolved peaks due to fission fragments. The dependence of the neutron flux on the reactor power was also measured from 0.5 MW to 5.2 MW and was found to be linear. By using a target with a total quantity of 0.5 mg of U²³⁵ or Pu²³⁹ and the detector with a sensitive area of 2 cm² with the same arrangement, measurements can be performed from a reactor power of 1 kW to the full power of 10 MW. There seems to be no serious objections to using this method in reactors of much higher power. Thus, this method proves to be very suitable for neutron-flux measurements at high reactor powers [4]. The absolute measurement of the neutron flux, with reasonable accuracy, is also possible by using this method since the geometry can be well defined.

Another improvement is the use of very thin detectors (e.g. 100 μ thick), without any encapsulation, so that the detector be less sensitive to gamma rays and neutron activation. Such detectors have been made in this laboratory and measurements performed by using them are in progress.

Following these measurements, a 4π coincidence method of absolute measurement of the neutron flux was also developed. Two thin gold-silicon detectors with a sensitive area of 60 mm² were made of an N-type silicon by following the procedure developed

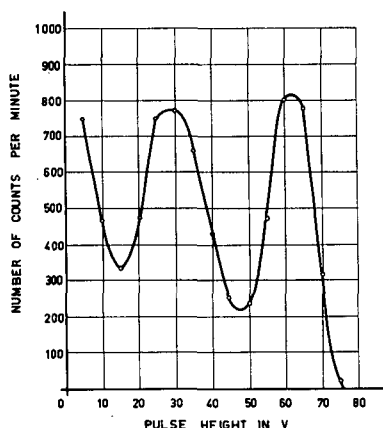


Fig. 3

The fission pulse spectrum obtained with the target in the centre of the core and with the counter 6 m away from the target. (The reactor power was 5.2 MW)

* Mr. Milan V. Kurepa also participated in this phase of the work.

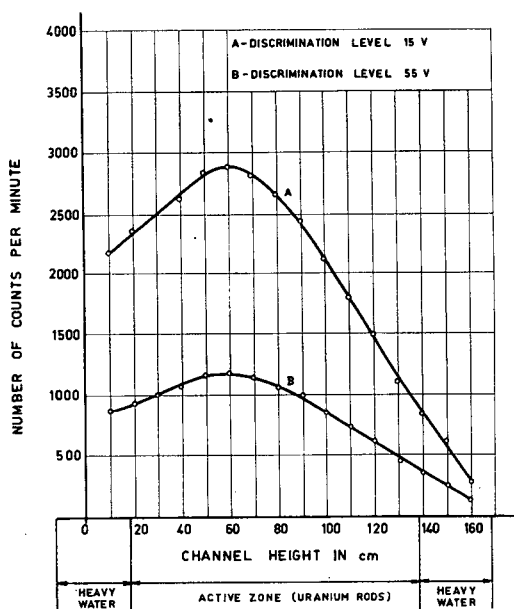


Fig. 4

The neutron flux distribution along the vertical channel obtained at the reactor power of 5.2 MW

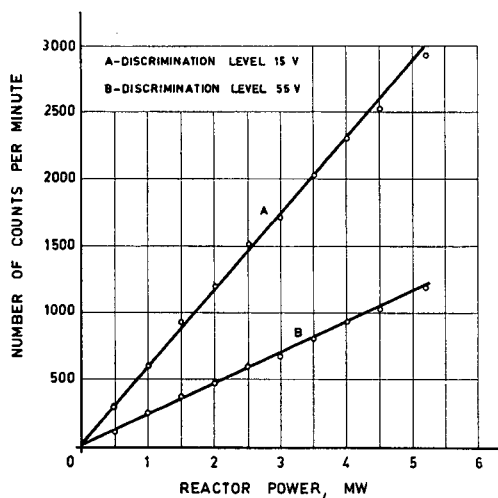


Fig. 5

Dependence of the counting rate on the reactor power. (The target was at the centre of the reactor core and the counter 6 m away from it).

at Harwell [5]. The gold layer was about $20 \mu\text{g}/\text{cm}^2$ thick, and a uranium layer $50 \mu\text{g}/\text{cm}^2$ thick and 5 mm in diam. was placed between the two counters. In this way the 4π geometry was realized. With this arrangement preliminary measurements of the neutron fluxes in the thermal column of the reactor were satisfactory, and further precise measurements and direct comparison with other methods of absolute measurement of the neutron flux are in progress.

III. Conclusion

Semiconductor detectors can be used successfully for neutron measurements in reactors with neutron fluxes up to $10^9 \text{ n}/\text{cm}^2/\text{s}$. Even higher fluxes can also be measured by placing the detector outside the reactor core at a certain distance from the target. Semiconductor detectors change their properties under heavy neutron and gamma irradiation and in this respect very thin detectors could be advantageous. Finally, the detection of neutrons through fission fragments is much easier than the detection through alpha particles from nuclear reactions.

ACKNOWLEDGEMENT

The authors are indebted to Dr. F. Boreli for giving us his results of measurements with fission chambers, Mr. A. Kukoč for gamma spectro-analysis and Mr. D. Tjapkin and Mr. A. Valčić for their kind help in providing and preparing silicon samples.

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DISCUSSION

E. M. Gunnensen (United Kingdom): I have a question to ask Mr. Montague. When using two electrically separated areas on one crystal, how close can these areas be before you get pick-up pulses going from one part to another?

J. M. Montague (United Kingdom): I am afraid I cannot give you a limit on that. On the counter you saw in the slide, the separation between the two gold areas was about 0.5 mm.

C. J. Borkowski (United States of America): I would like to suggest that this separation will depend on the ambient conditions in which the diode is located; the surface states will obviously not be the same in a high vacuum as they are in other ambients—wet London air for example. I think one has to qualify the statement by indicating the ambient in which the diode is to be found.

B. de Cosnac (France): I have a question for Mr. Ajdačić. I have never noticed that the piling up of gammas produced spurious pulses. Do you think that your spurious pulses could come from n, p reactions in the silicon?

V. Ajdacic (Yugoslavia): The neutron flux at the position of the silicon counter is very low, and we only obtain about 100 pulses per second from the n, α reaction. The fact that there are more pulses from the fission fragments than from alpha particles ensured good resolution; if we calculate the position of the first peak in the spectrum we see that it corresponds to an energy of about 40 MeV, but the spectrum from alpha particles—there are only 100 alpha particles per second—cannot give such a marked piling of pulses.

B. de Cosnac: I agree with you, but in that case it would seem impossible to get a correct pile spectrum using lithium and boron because everything would be spurious. The only detector which could be used would be a fission detector; as soon as you put a boron detector or a lithium detector in a reactor the counting would be swamped by the n, p reaction.

SEMICONDUCTOR COUNTER AND ITS APPLICATIONS FOR NEUTRON MEASUREMENT

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Abstract — Résumé — Аннотация — Resumen

Semiconductor counter and its applications for neutron measurement. Described in this report are the performance of a silicon surface-barrier semiconductor counter and its applications for radiation detection, especially neutron measurements.

The counter has been constructed, using a 1000- Ω cm n-type silicon with a vacuum-evaporated gold film electrode, which showed an energy resolution less than 1% for 5.3-MeV alpha rays.

The following are the main examples of its application:

(1) Portable-pencil, transistorized radiation monitors with a small count-rate-indicating meter and crystal earphone have been made.

(2) Alpha-ray spectrometers, which consist of a vacuum cell, low noise pre-amplifier, linear amplifier and a multi-channel pulse-height analyser, have been made. In the vacuum cell are a rotating disc, on which six alpha-ray sources can be mounted and a NaI(Tl) scintillator for low-energy gamma-ray/alpha-ray coincidence measurements.

(3) We have measured the precise spatial distribution of the JRR-1, a water-boiler type reactor, using the $B^{10}(n\alpha)$ and $Li^6(n\alpha)$ reactions.

Neutron induced threshold reactions, such as $U^{238}(nf)$ and $S^{32}(np)$ reaction, can be used for measuring the rough neutron energy distribution.

A fast neutron spectrometer can be constructed either by the use of the $Li^6(n\alpha)T$ reaction or by the recoil proton energy measurement.

By measuring $E_\alpha + E_T = E_n + Q$ in the $Li^6(n\alpha)T$ reaction, the value of E_n can be obtained. The actual method of the measurement, however, is by adding the two output pulse heights from a thin Li^6 foil or evaporated Li^6 , the Li^6 foil or evaporated Li^6 being sandwiched between two semiconductor counters.

The above recoil-proton energy measurement is for the proton energy, $E_p = E_n \cos^2 \theta$, which is recoiled from a polyethylene radiator.

Un compteur à semi-conducteur et son utilisation pour la mesure des neutrons. Le mémoire expose le comportement d'un compteur à barrière de surface au silicium et son utilisation pour la détection des rayonnements, notamment pour la mesure des neutrons.

Ce compteur comporte un monocristal de silicium de type n de 1000 Ω cm et une électrode revêtue d'une couche d'or par évaporation sous vide; dans le cas de particules alpha de 5,3 MeV la résolution en énergie s'est révélée inférieure à 1%.

Les principales applications du compteur faites par l'auteur sont les suivantes:

1. Construction de stylo-dosimètres transistorisés, munis d'un intégrateur de modèle réduit et d'un dispositif radiophonique à cristal.

2. Construction de spectromètres pour particules alpha, comprenant une cellule à vide, un préamplificateur à faible mouvement propre, un amplificateur linéaire et un analyseur d'amplitude des impulsions multicanaux. La cellule à vide contient un disque relatif sur lequel on peut monter six sources de particules alpha et un cristal de NaI(Tl) pour les mesures de coincidence gamma-alpha de faible énergie.

3. L'auteur a mesuré avec précision la distribution du flux neutronique dans le réacteur de recherche à eau bouillante JRR-1, en utilisant les réactions $^{10}B(n, \alpha)$ et $^6Li(n, \alpha)$.

Les réactions de seuil provoquées par les neutrons, telles que $^{238}U(n, f)$ et $^{32}S(n, p)$, peuvent servir à mesurer sommairement le spectre d'énergie des neutrons.

On peut construire un spectromètre pour neutrons rapides, dont le principe serait soit l'utilisation de la réaction ${}^6\text{Li}(n, \alpha)\text{E}$, soit la mesure de l'énergie des protons de recul.

Sachant que $E_\alpha + E_T = E_n + Q$ dans la réaction ${}^6\text{Li}(n, \alpha)\text{T}$, on peut calculer la valeur de E_n en mesurant E_α et E_T . La méthode de mesure effectivement utilisée consiste à additionner les deux amplitudes d'impulsion à la sortie d'une feuille mince de ${}^6\text{Li}$ ou de ${}^6\text{Li}$ évaporé, la feuille de ${}^6\text{Li}$ ou de ${}^6\text{Li}$ évaporé étant placée entre deux compteurs à semi-conducteur.

Les mesures ci-dessus de l'énergie des protons de recul sont valables pour l'énergie des protons de recul ($E_p = E_n \cos^2 \theta$) provenant d'un milieu radiatif de polyéthylène.

Полупроводниковый счетчик и его применение при нейтронных измерениях. В настоящем докладе излагаются результаты, полученные с кремниевым полупроводниковым счетчиком поверхностно-барьерного типа, а также его применения для радиационного детектирования и, в частности, для нейтронных измерений.

Этот счетчик был построен с использованием кремниевого электрода типа „п“ 1000-Ω см, покрытого распыленной в вакууме золотой пленкой. Разрешающая способность счетчика по энергии оказалась меньше, чем 1% для альфа-лучей в 5,3 мэв.

Главными примерами его применения могут служить:

1) Построенные на транзисторах переносные радиационные контрольно-измерительные приборы типа карандаша с малоразмерным указателем скорости счета и с кристаллическими наушниками.

2) Спектрометры, сконструированные для альфа-лучей и состоящие из вакуумной ячейки, предварительного усилителя малых шумов, линейного усилителя и многоканального анализатора амплитуды импульсов. В вакуумной ячейке помещается вращающийся диск, на котором могут быть смонтированы шесть источников альфа-лучей, и сцинтиллятор с кристаллом NaI(Tl) для измерения совпадений гамма- и альфа-лучей малой энергии.

3) На основании реакции $\text{B}^{10}(n\alpha)$ и $\text{Li}^6(n\alpha)$ нам удалось измерить точное пространственное распределение частиц в Японском исследовательском реакторе JRR-1 типа „водяной котел“.

Наведенные нейтронами пороговые реакции, как, например, $\text{U}^{238}(n, f)$ и $\text{S}^{32}(n, p)$ могут быть использованы для измерения приблизительного распределения энергии нейтронов.

Спектрометр для быстрых нейтронов может быть построен или с использованием реакции $\text{Li}^6(n, \alpha)\text{T}$ или путем измерения энергии протонов отдачи.

Путем измерения $E_\alpha + E_T = E_n + Q$ в реакции $\text{Li}^6(n, \alpha)\text{T}$ можно получить величины E_n . Однако фактическим методом измерения является сложение двух амплитуд выходящих импульсов, посылаемых тонкой фольгой Li^6 или нанесенным распылением слоем Li^6 , причем фольга Li^6 или нанесенный распылением слой Li^6 помещаются между двумя полупроводниковыми счетчиками.

Указываемые выше измерения энергии протонов отдачи предназначены для измерения энергии протонов $E_p = E_n \cos^2 \theta$, которые отдаются полиэтиленовым излучателем.

Contador semiconductor y su aplicación a medidas de neutrones. La memoria informa sobre las propiedades de un contador semiconductor de silicio del tipo de barrera superficial, y sobre sus aplicaciones en la detección de radiaciones, especialmente para medidas de neutrones.

El contador fue construido con silicio de tipo n, de 1000-Ω cm, y un electrodo recubierto de una capa de oro depositada por evaporación al vacío, obteniéndose un poder de resolución de energías inferior al 1 por ciento para rayos alfa de 5,3 MeV.

Los principales ejemplos de su aplicación son los siguientes:

1) Se han construido monitores portátiles de radiaciones, transistorizados, de tipo lapicero, con un pequeño indicador del ritmo de conteo y un auricular de cristal.

2) Espectrómetros de rayos alfa que consisten en una celda de vacío, un preamplificador de bajo ruido, un amplificador lineal y un analizador multicanal de amplitudes de impulso. La celda de vacío contiene un disco giratorio en el que se pueden montar seis fuentes de rayos alfa y un centelleador de NaI(Tl) para medida de coincidencias de rayos gamma y alfa de baja energía.

3) Empleando las reacciones $^{10}\text{B}(n, \alpha)$ y $^6\text{Li}(n, \alpha)$, el autor ha medido la distribución espacial precisa del flujo neutrónico del reactor JRR-1, de agua hirviendo.

Las reacciones umbral inducidas por neutrones como, por ejemplo, las reacciones $^{238}\text{U}(n, f)$ y $^{32}\text{S}(n, p)$, sirven para medir aproximadamente la distribución energética de los neutrones.

Si se utiliza la reacción $^6\text{Li}(n, \alpha)\text{T}$ o se mide la energía de retroceso de los protones se puede construir un espectrómetro para neutrones rápidos.

Midiendo las energías del litio y del tritio en la reacción $^6\text{Li}(n, \alpha)\text{T}$, se puede calcular E_n por la ecuación $E_\alpha + E_T = E_n + Q$. El método de medida consiste en sumar las dos amplitudes de los impulsos de salida procedentes de una hoja delgada de ^6Li o de una capa delgada de ^6Li aplicada por evaporación; tanto una como otra tienen adosado a cada lado un contador semiconductor.

La energía de retroceso del protón corresponde a $E_p = E_n \cos^2 \theta$, moviéndose en un radiador de polietileno.

Summary

The gold-silicon surface-barrier semiconductor detectors are constructed using 1000 $\Omega\text{-cm}$ n-type silicon. The applications are carried out on an alpha-particle spectrometer, portable pencil-type radiation monitor, neutron spectrometer (by measuring the sum of the energy of the products of $\text{Li}^6(n, \alpha)\text{T}$ reaction), B^{10} and Th^{232} coated-neutron detector, and the precise measurement of spatial neutron-flux distributions in a reactor has been done.

Also the radiation damage due to fast neutrons is shown.

I. Introduction

Recently, many reports [1] have been published on semiconductor detectors and the counters included are excellent, especially for good energy resolution, simplicity, fast rise-time for energy-charged particles, and are insensitive to neutrons and gamma-rays.

This report deals with the result of our work on semiconductor detectors and their applications to alpha-particle measurements and neutron measurements, which were started in January 1960.

II. Construction techniques of gold-silicon surface-barrier detectors

The gold-silicon surface-barrier detectors are constructed as follows; n-type silicon wafers, about 1 mm thick, are prepared and shaped with a diamond-impregnated saw and lapped with silicon carbide No. 600. These crystals are nickel-plated using the electroless nickel-plating method described in "Transistor Technology" [2]. An ohmic contact is made by soldering a copper wire to one side of the wafer. The ohmic contact and copper wire are covered by polystyrene dissolved in toluene. With the exception of this ohmic contact, the surfaces of the wafer are again lapped with silicon carbide No. 1200 and etched with CP-4 or CP-4A for about 10 min at ice-cold temperatures. After several washings with ion-exchanged water, the wafer is masked with a thin metal foil which has a square window to protect the edges against gold-evaporation, after which about 100 $\mu\text{g}/\text{cm}^2$ gold is evaporated in a vacuum-evaporator at a distance of 10 cm from a tungsten wire. Again the gold-evaporated surface is masked except for a small spot required for the electric-lead connection and thick gold is evaporated. Gold-evaporated crystals are mounted and the front contact to the gold is connected by using a silver-paste.

III. Electronics

The circuit used is shown in Fig. 1. The bias voltage of the crystal is supplied from a battery through a $1\text{ M}\Omega$ load resistor. A gain-of-34 pre-amplifier with a WE417A cascode input stage, an IDL-652 linear amplifier (the RC time-constant of which is adjustable), and an RCL-256 channel pulse-height analyser, are used. The input noise measured is about $10\text{ }\mu\text{V}$. Care has been taken not to increase the input capacitance.

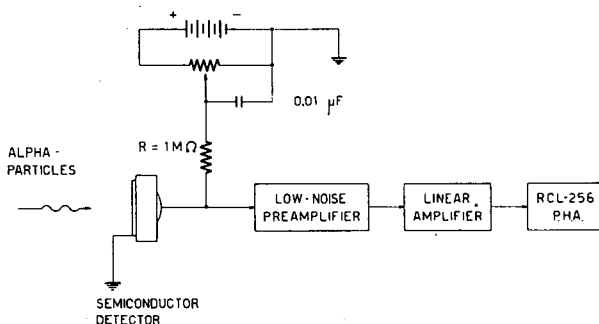


Fig. 1

Circuit diagram of a semiconductor detector

IV. Performances of gold-silicon surface-barrier detectors

$1000\text{ }\Omega\text{ cm}$ and $40\text{ }\Omega\text{ cm}$ nominal resistivity n-type silicon is used. The reverse current, pulse height, and percentage of the FWHM vs. the applied voltage of $5 \times 5\text{ mm}$ square are shown in Fig. 2. A 1% resolution is obtained for 5.3 MeV alpha-particles.

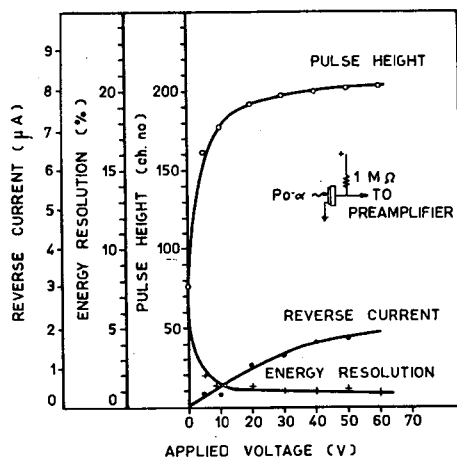


Fig. 2

Characteristics of a $1000\text{-}\Omega\text{ cm}$ silicon surface barrier-counter

The pulse-height linearity for alpha-rays is shown in Figs. 3, 4, and 5. The nominal 1000- Ω cm silicon detector shows its energy linearity for alpha-particles up to 20 MeV in an experiment of $O^{16}(d, \alpha)N^{14}$ reaction ($E_d = 15$ MeV). The 40- Ω cm silicon detector shows a linearity up to 8 MeV.

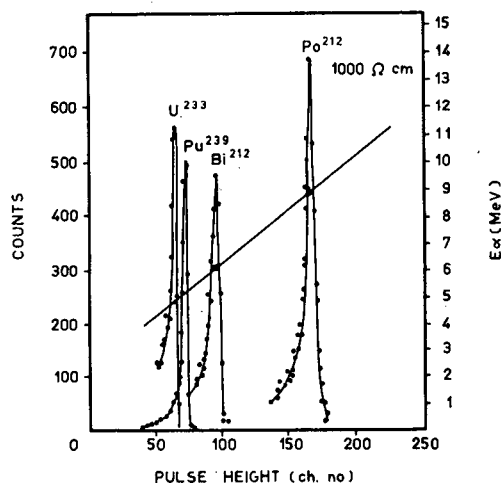


Fig. 3

Pulse-height distributions of a 1000- Ω cm detector for various alpha-particle sources

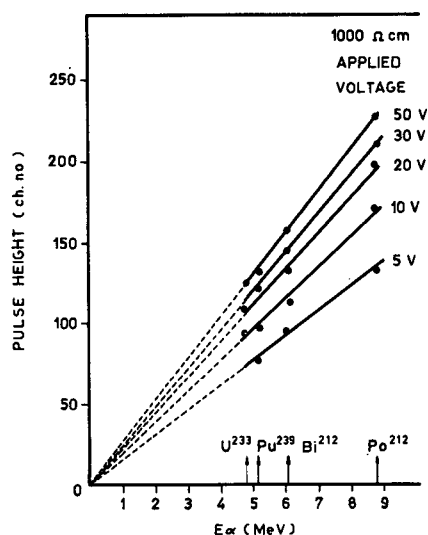


Fig. 4

Pulse-height linearity of a 1000- Ω cm detector

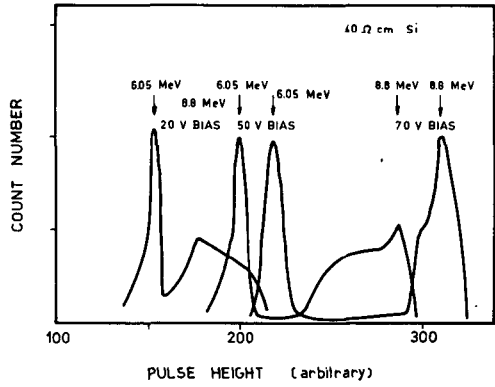


Fig. 5

Effect of the applied voltage to pulse-height distributions for alpha-particles

Fig. 6 shows an example of the $F^{19}(d, \alpha)O^{17}$ spectra of $E_d = 2$ MeV. We are planning to study the $(d, \alpha\gamma)$ and $(p, \alpha\gamma)$ nuclear reactions using semiconductor detectors.

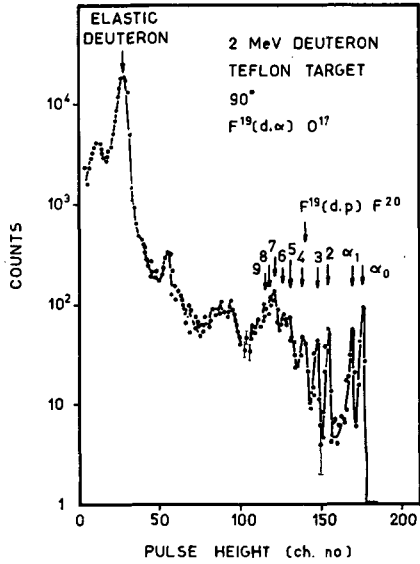


Fig. 6

Charged particles from deuteron bombardments of a teflon target

V. Alpha-particle spectrometer

A vacuum cell is constructed for alpha-particle energy measurements of transuranium elements. Six sources are mounted on a rotating disc, with the semiconductor detector for alpha-particle detection and the NaI(Tl) scintillation counter for gamma-ray

detection placed in the cell. In the precise alpha-particle analysis, it is necessary to keep as small as possible the background of alpha-particles which are due to contaminations and scatterings.

VI. Portable pencil-type, transistorized radiation-monitor

A portable pencil-type transistorized radiation-monitor with a small count-rate-indicating meter and a crystal earphone has been constructed. Fig. 7 shows a schematic circuit diagram of the radiation monitor.

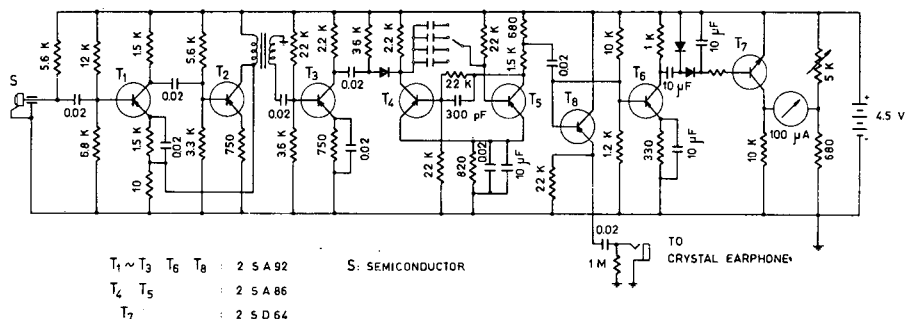


Fig. 7

A portable pencil-type transistorized radiation monitor

VII. Thermal-neutron detection using $B^{10}(n, \alpha) Li^7$ nuclear reaction

The thermal-neutron cross-section of $B^{10}(n, \alpha) Li^7$ reaction is about 4000b. B^{10} vacuum-evaporated semiconductor counters are used for the thermal-neutron detection. $B^{10}(n, \alpha)$

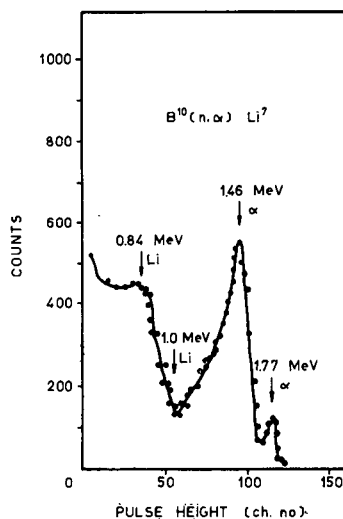


Fig. 8

Pulse-height distributions of a B^{10} -coated 1000- Ω cm detector for thermal neutrons

Li^7 reaction causes four energy groups of α and Li^7 . The obtained spectrum caused by reactor neutrons is shown in Fig. 8. The low-energy tail is due to the pile-up of intense gamma-rays, the B^{10} thickness and the area of B^{10} evaporation which is broader than a gold electrode. Care must be taken to see that B^{10} vacuum-evaporation does not destroy the thin gold surface of the counter.

Using the B^{10} evaporated counter, the precise measurement is made of the thermal-neutron spatial distributions in an experimental through-tube of a boiling-water nuclear reactor, JRR-1. Fig. 9 shows the effect of the control rods and reflector. Fig. 10 shows the cross-sectional thermal-neutron spatial distribution in the reactor hole.

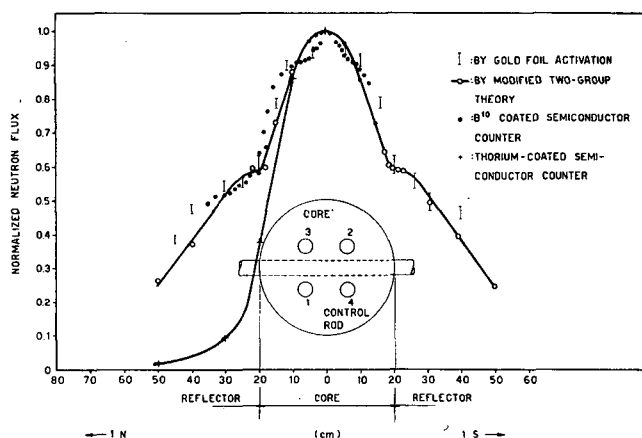


Fig. 9

Neutron-flux spatial distributions of the glory hole of JRR-1 (water-boiler-type) reactor

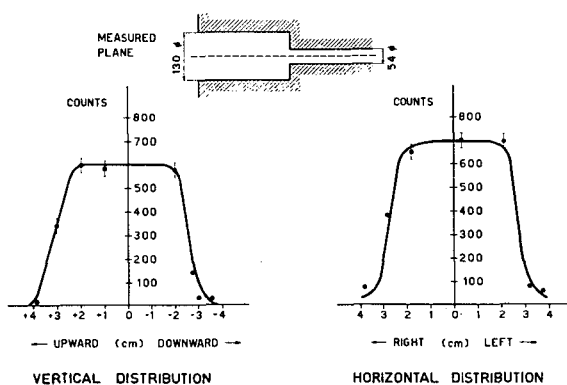


Fig. 10

Thermal neutron-flux spatial distributions of no. 2 hole of JRR-1 measured with a B^{10} -coated detector

VIII. Threshold detector using semiconductor detectors

Neutron-induced threshold reactions, such as (n, p) , (n, α) , (n, f) , can be used for a rough measurement of the distribution of neutron energy. Examples with relatively large cross-sections, suitable for a threshold detector are shown in Fig. 11. The use of $(n, \text{fission})$ reaction is suitable because of the large fission-fragment pulse-height, especially for the experiment which needs long input cables. Also large-area semiconductor detectors can be used.

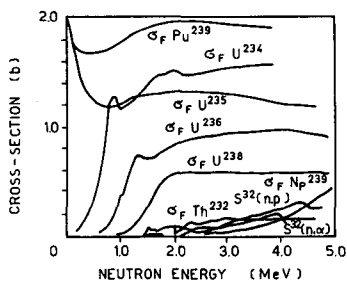


Fig. 11

Cross-sections of threshold reactions (BNL-325)

Thorium-evaporated semiconductor detectors are constructed. Fig. 12 shows the pulse-height of the fission fragments due to Th^{232} fast fission (neutron energy > 1.5 MeV).

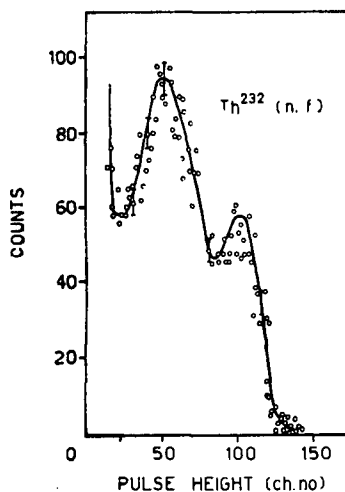


Fig. 12

Pulse heights of a Th^{232} -coated 1000- Ω cm semiconductor counter

Fig. 13 shows a spatial distribution of the fast neutrons with energy above 1.5 MeV in the reactor. The data of the $\text{Ni}^{58}(n, p)\text{Co}^{58}$, $\text{S}^{32}(n, p)\text{P}^{32}$, $\text{Al}^{27}(n, \alpha)\text{Na}^{24}$ foil-activation method [3] are compared.

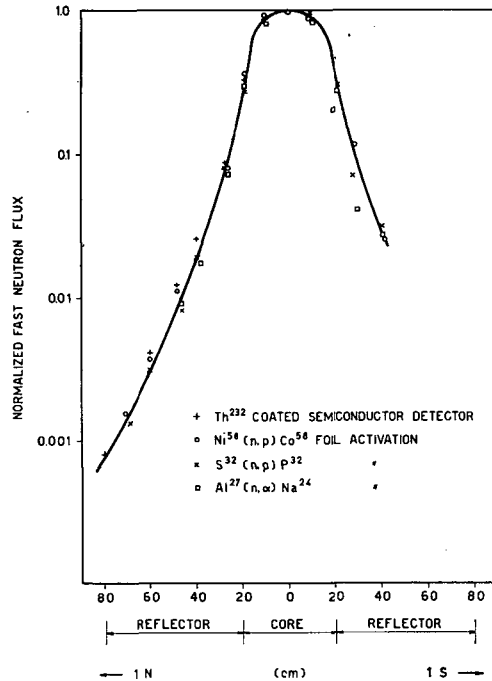


Fig. 13
Fast neutron-flux spatial distributions of the JRR-1 glory hole

IX. Precise measurement of the neutron-flux distribution in a reactor

Figs. 9, 10 and 13 show the spatial neutron-flux distribution in the reactor JRR-1 (boiling-water type, 50 kW, 10^{12} nv). In Fig. 9 are shown the data of the gold-foil activation method and the calculation by the modified two-group theory [4]. Compared with the gold activation method, the method by semiconductor detectors is very simple and time-saving. As a threshold detector a semiconductor is very useful for measuring the neutron-flux distribution of a low-power reactor.

X. Neutron spectrometer using the $\text{Li}^6(n, \alpha)\text{T}$ sum method

$\text{Li}^6(n, \alpha)\text{T}$ reaction has a large Q-value ($Q = 4.78$ MeV), and the sum of the energy of a alpha-particle and a triton is proportional to the neutron energy as shown in Fig. 14.

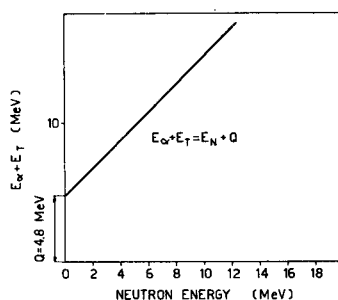


Fig. 14
 $\text{Li}^6(n, \alpha)\text{T}$ reaction

The circuit used is shown in Fig. 15. $\text{Li}_2^{6}\text{CO}_3$, $260 \mu\text{g}/\text{cm}^2$ thick, is evaporated on a semiconductor counter (A) while the other, (B), faces the counter (A). Both A and B counters are in a vacuum cell. Neutrons entered and alpha-particle-triton pairs are emitted and both counters detect two kinds of particles. The output of both counters is amplified by two low-noise pre-amplifiers, then added, and again amplified and analysed. The distance between the two counters must be as short as possible because of the counting efficiency. In our case, the geometry of each counter does not permit the distance to be shorter than 5 mm. 1000- Ω cm detectors show an energy linearity up to 20 MeV for alpha-particles, therefore 35-MeV fast neutrons can be measured. An experiment has been made for the thermal neutrons of the reactor. In this experiment the resolution for 5.3-MeV alpha-particles is 250 keV because a 3.5-m long RG-63/U input-cable is needed in the reactor. Fig. 16 shows the pulse-height distributions of Li^6 evaporated and non-evaporated detectors. Fig. 17 shows the total spectrum both with and without coincidence. The total peak shows a 280-keV resolution. The counting efficiency of our 0.1- cm^2 detector is 3.5×10^{-5} for thermal neutrons.

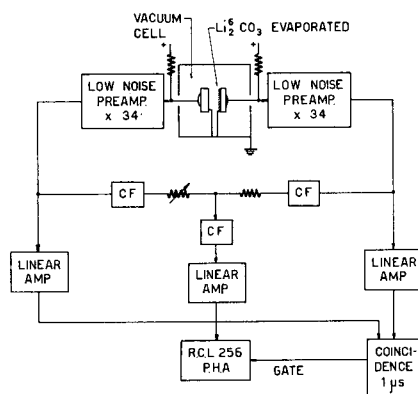


Fig. 15
Neutron spectrometer using a sandwiched- Li^6 target

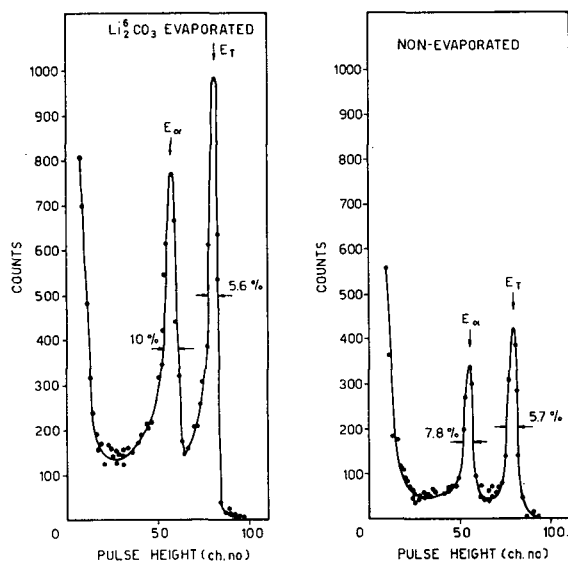


Fig. 16

Pulse heights of a Li^6 evaporated detector (A) and non-evaporated detector (B) for thermal neutrons

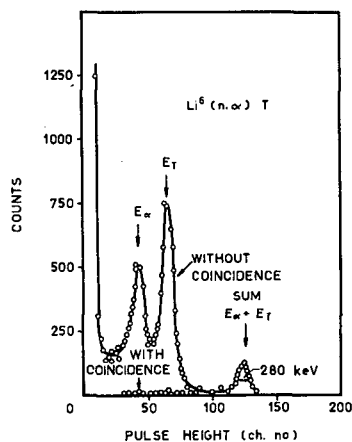


Fig. 17

Pulse heights of a Li^6 -sandwiched detector for thermal neutrons

With a 1-cm² detector, good geometry and Li^6F as a target, the counting efficiency may be increased to 10^{-3} /neutron. The experiment for fast neutrons has not yet been made.

XI. Radiation damage due to fast neutrons

Semiconductors are very structure-sensitive. Radiations produce defects in crystals. The p-n junction diodes of germanium, which were irradiated with $10^{12} \sim 10^{13}$ nvt, lose the rectification characteristics.

Fig. 18 shows the rectification characteristics of a gold-silicon surface-barrier detector before and after irradiation with about 10^{13} nvt fast neutrons. The reverse current increases and the forward current decreases. Fig. 19 shows a change in the pulse-height distribution of 5.3-MeV alpha-rays. Fig. 20 shows the changes of the pulse-height

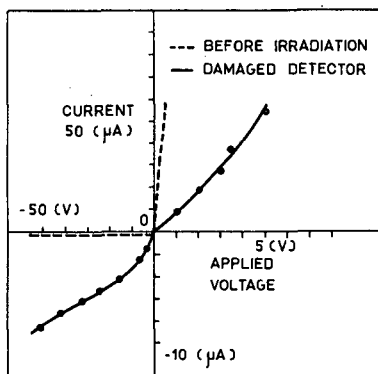


Fig. 18

Rectification characteristics of a neutron-irradiated detector

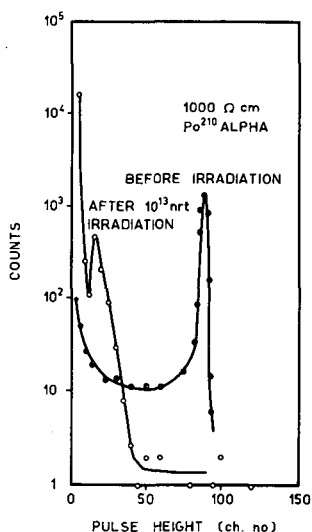


Fig. 19

Pulse heights of a damaged detector for Po^{210} alpha particles

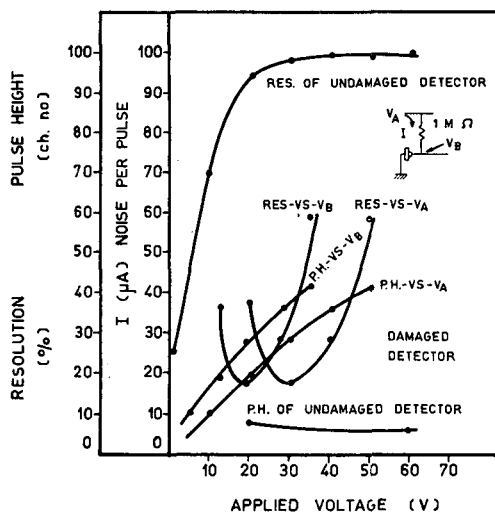


Fig. 20

Resolutions (Res) and pulse heights (P.H.) of a damaged and an undamaged detector

and energy resolution for 5.3-MeV alpha-rays vs the applied voltage. For the damaged counter the pulse-height decreases and the energy resolution becomes poorer. The pulse-height of the damaged counter largely depends on the applied voltage. These phenomena may be due to an extreme decrease of the minority carrier life-time. The “schubweg” of carriers becomes shorter than the depletion-layer thickness, and collection efficiency decreases.

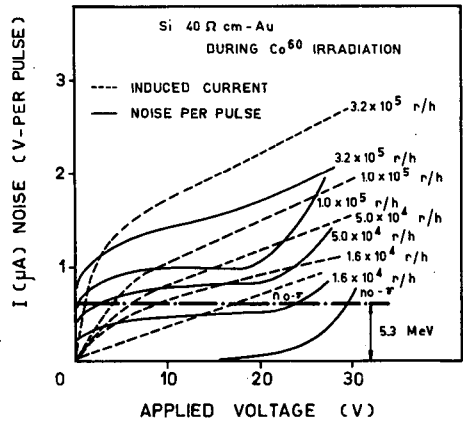


Fig. 21
Noise and induced current of a 40-Ω cm detector during Co⁶⁰ irradiation

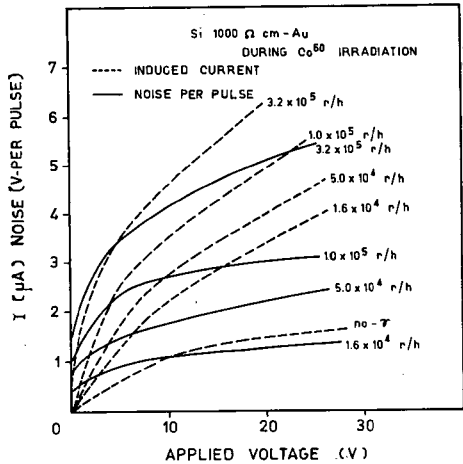


Fig. 22
Noise and induced current of a 1000-Ω cm detector during Co⁶⁰ irradiation

XII. Effect of intense gamma-rays

The noise and induced current of the semiconductor counter, which is moulded in Araldite, are measured under intense Co^{60} gamma-ray field. Figs. 21 and 22 show the effect at 10^4 r/h. Co^{60} gamma-rays cause the noises which have an equivalent pulse-height to that of 5.3 MeV alpha-rays. This is partly due to the pile-up of gamma-ray induced photoelectrons and may be partly due to the leakage of Araldite.

XIII. Conclusion

Gold-silicon surface-barrier detectors, which are constructed using 1000- Ω cm n-type silicon, show an energy resolution of 1% for 5.3-MeV alpha-particles and a pulse-height linearity up to 20-MeV alpha-particles.

The portable pencil-type radiation monitor and alpha-particle spectrometer are made.

After about 10^{13} nvt fast-neutron irradiation the pulse-height of 5.3-MeV alpha-particles decreases by about 1/5 and the resolution becomes very poor.

B^{10} and Li^6 -evaporated semiconductors are constructed and the spatial thermal neutron-flux distributions in a reactor are measured with precision. The Th^{232} -evaporated semiconductor is constructed for measuring fast-neutron fluxes with an energy larger than 1.5 MeV.

The fast-neutron spectrometer is constructed using the $\text{Li}^6(n, \alpha)\text{T}$ reaction. The evaporated Li_2CO_3 film is sandwiched between two semiconductor detectors and the sum of the energy of the products is analysed. A 280-keV resolution for the thermal neutrons is obtained.

ACKNOWLEDGEMENTS

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CHARACTERISTICS OF ION-DRIFTED P-I-N-JUNCTION PARTICLE DETECTORS

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Abstract — Résumé — Аннотация — Resumen

Characteristics of ion-drifted p-i-n-junction particle detectors. Ion-drift techniques have been used to produce p-i-n-junction particle detectors by drifting lithium in p-type silicon. Depletion widths up to and greater than 4 mm were obtained. Close agreement was found between calculated and measured drift rates. In these junctions the predominant contribution to the DC reverse current is due to thermally generated carriers in the depletion region. At elevated temperatures the influence of the space-charge of thermally generated carriers on the field can be seen from the room temperature capacitance-voltage relations. Although the response of the p-i-n junction to gamma rays is dominated by the Compton electron-energy distribution, photopeaks can be observed. The sensitivity to gamma rays follows a $1/r^2$ dependence. Typical energy resolutions were 1% and 4% for 17 MeV deuterons and 1800 keV electrons, respectively.

Caractéristiques des détecteurs de particules à jonction approfondie par dérive d'ions. Les techniques de dérive d'ions ont été utilisées pour produire des détecteurs de particules à jonction p-i-n approfondie par dérive de lithium dans du silicium. On a obtenu des largeurs d'appauvrissement allant jusqu'à 4 mm et même au-delà. On a constaté une bonne concordance entre les calculs et les mesures des taux de dérive. Dans ces jonctions, le facteur principal du courant continu de retour provient des porteuses produites thermiquement dans la zone d'appauvrissement. Pour des températures élevées, l'influence exercée par la charge d'espace des porteuses produites thermiquement sur le champ peut être observée à partir des relations capacité-tension pour la température ambiante. Bien que la réponse de la jonction p-i-n aux rayons gamma dépende de la distribution Compton de l'énergie des électrons, on peut observer des pics photo-électriques. La sensibilité aux rayons gamma a la forme d'une fonction $1/r^2$. Les résolutions d'énergie caractéristiques étaient de 1% pour les deutérons de 17 MeV et de 4% pour les électrons de 1800 keV.

Характеристики детекторов частиц дрейфующих ионов с переходом p-i-n. Был использован метод дрейфующих ионов для производства детекторов частиц с переходом p-i-n путем дрейфа лития в кремнии типа „р“. Была получена ширина обеднения вплоть до 4 мм и выше. Было обнаружено близкое соответствие между расчетными и измеренными скоростями дрейфа. В этих переходах обратный постоянный ток был в основном получен благодаря термически образованным носителям в зоне обеднения. При высоких температурах влияние пространственного заряда термически образованных носителей на поле можно наблюдать при комнатной температуре по соотношению мощности и напряжения. Хотя распределение энергии комптоновского электрона преобладает над ответной реакцией перехода p-i-n на гамма-лучи, можно наблюдать фотопики. Чувствительность к гамма-лучам составляет зависимость $1/r^2$. Типичными энергетическими разрешениями были 1% и 4% для дейтронов в 17 мэв и для электронов в 1800 кэв соответственно.

Características de los detectores de partículas con capa p-i-n de desplazamiento iónico. Los autores han empleado técnicas de desplazamiento iónico para preparar detectores de partículas con capa p-i-n. Para ello, desplazaron litio en silicio tipo p, obteniendo capas de detención de 4 mm y más de espesor. Las velocidades de desplazamiento calculadas concuerdan satisfactoriamente con las determinadas por vía experimental. La principal contribución a la corriente continua inversa en estas capas se debe a portadores generados térmicamente en la región de detención. A temperaturas elevadas, la influencia que ejerce sobre el campo la carga espacial

de los portadores generados térmicamente se refleja en las relaciones existentes entre la capacidad y la tensión a la temperatura ambiente. Se observan fotopicos a pesar de que la respuesta de la capa p-i-n a los rayos gamma dependa primordialmente de la distribución energética de los electrones de Compton. La sensibilidad a los rayos gamma varía en función de $1/r^2$. Para deuterones de 17 MeV y electrones de 1800 keV, los autores obtuvieron resoluciones energéticas de 1 y de 4 por ciento, respectivamente.

I. Introduction

The use of surface-barrier and p-n-junction detectors as charged-particle spectrometers established the fact that the sensitive volume of the devices is defined essentially by the width, W , of the region containing the high electric field (the depletion region) [1]. The pulse-height response of the junction detectors was found to be proportional to the energy lost by the charged particles in W .

In surface-barrier or shallow-diffused p-n junctions

$$W \propto (\rho V)^{1/2} \quad (1)$$

where ρ is the resistivity of the base material and V is the applied voltage. Due to the limitations imposed by the resistivity of silicon and the onset of excessive leakage currents at high applied voltages, the maximum width that has been obtained is less than 1 mm (equivalent to the range of a 10-MeV proton). Improved fabrication techniques, as the guard-ring structure [2], have not resulted in greatly increased depletion regions.

The concept of ion drift in a p-i-n structure, first discussed by PELL [3], afforded a means of significantly increasing W without the requirement of high-resistivity base material or high applied voltages. The use of ion-drift techniques in the Nuclear Electronics Laboratory, Hughes Aircraft Company, has resulted in p-i-n-junction detectors with sensitive volumes up to and greater than 4 mm thick [4–7]. Similar studies have been carried on at the University of California, Berkeley [8].

II. Ion drift techniques

Lithium introduced as a dopant in silicon has been found to act as a donor with an activation energy of 0.03 eV. Lithium diffuses interstitially and consequently has a diffusion constant a factor of 10^7 higher than that measured for impurities that diffuse by a vacancy mechanism (for example, boron and phosphorus) [9]. In the ion-drift process lithium is diffused into p-type silicon forming a p-n junction at a distance d below the surface. At this point the lithium concentration, N_{Li} , is equal to the acceptor concentration, N_A .

The lithium concentration after diffusion is given by

$$N_x = N_0 \operatorname{erfc} \frac{x}{2(D_T t)^{1/2}} \quad (2)$$

where N_0 is the surface concentration of lithium and D_T is the diffusion constant of lithium at the diffusion temperature, T (Fig. 1a). The electric field in the junction region exerts a force on the lithium ions moving them deeper into the p-type material [3] [11]. The velocity of the lithium ions at any point is given by

$$v_x = \mu_T E_x \quad (3)$$

where μ_T is the lithium mobility at temperature T . The velocity can be increased by either raising the temperature of the junction or by applying reverse bias, or a combination

of these two factors. As the lithium drifts, it tends to compensate the acceptor concentration as can be seen from Fig. 1b. If the lithium concentration were to "pile-up" at some point, X_1 , the field at $X > X_1$ would be greater than the field at $X < X_1$. In this example the field differential would remove the lithium excess at $X = X_1$. From similar arguments; it follows that during the drift process the lithium concentration will adjust itself to maintain a constant electric field (Fig. 1c). From the concept of a constant electric field, it follows that the growth of the intrinsic region, W , is governed by

$$\begin{aligned}\frac{dW}{dt} &= \mu_T E = \mu_T V/W \\ W_2^2 - W_1^2 &= 2\mu_T V(t_2 - t_1)\end{aligned}\quad (4)$$

It should be noted that, while $W(t)$ is not a function of resistivity, interactions of lithium with impurities and oxygen will lead to lower values of ion mobility. However, in silicon with an oxygen content of 10^{15} atoms/cm³ and with resistivity greater than $1 \Omega \text{ cm}$, these interactions will play a small role [12] [13]. A more detailed treatment of the increase in W has been given by PELL [3]. Fig. 2 shows W as a function of time with temperature as a parameter and a constant drift potential of 100 V.

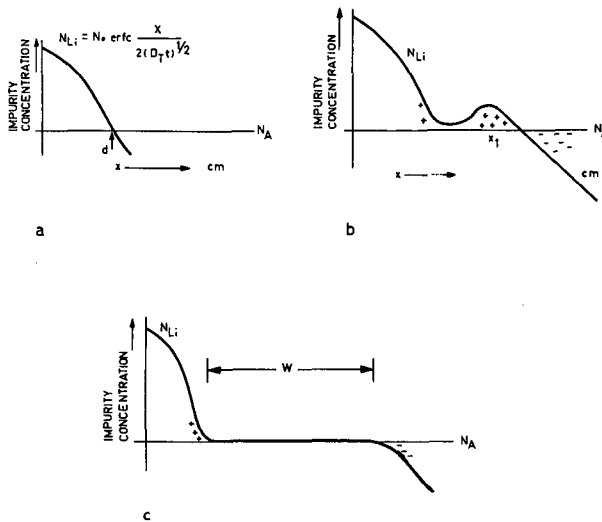


Fig. 1

The drift characteristics of diffused lithium in p-type silicon

- (a) Initial distribution of lithium following diffusion
- (b) Unstable distribution of lithium at X_1 . The excess at X_1 creates a non-uniform field
- (c) After drift, the compensated intrinsic region (W), is bounded on one side by heavily doped n-type silicon and on the other by the original p-type material

The current through the junction will be dominated by the space-charge generated component [14—16],

$$I = qGW = \frac{qn_i W}{2\tau_0} \quad (5)$$

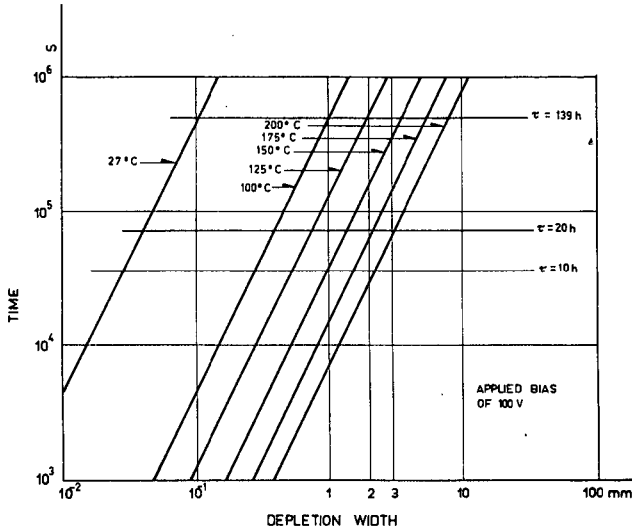


Fig. 2

The increase in the width of the depletion region with time as a function of temperature. Lithium mobility values were taken from Pell [3] [10]

where G , the generation rate has a maximum value given by $n_i/2\tau_0$ and n_i is the intrinsic number of carriers thermally generated. τ_0 is the effective carrier lifetime and is a measure of the density and capture cross-section of levels near the centre of the forbidden gap. Irrespective of the absolute value of G , the current should be proportional to W at any temperature.

The effect of the space-charge generated current at elevated temperatures is to distort the field. If recombination is neglected, the analysis of READ [15] shows that thermally generated carriers will produce hole and electron currents which are linear in X . This is illustrated in Fig. 3. The gradient, a , of the resultant space-charge due to the hole and electron concentrations will be given by

$$a = \frac{n_i}{\tau_0 \mu E} = \frac{n_i W}{\tau_0 \mu V} \quad (6)$$

where μ is the mobility of the mobile carriers. In this case it is assumed that electron and hole mobilities are equal. As a consequence of the initial field distortion, the lithium ions will be rearranged until the lithium distribution compensates the space-charge of the mobile carriers (Fig. 3). After the junction is cooled to room temperature, the space-charge due to the mobile carriers will be negligible; consequently, only the space-charge of the lithium-ion distribution will remain. The lithium distribution will, therefore, reflect the space-charge distribution of the mobile carriers at elevated temperatures. This distribution will be linear in X , in effect producing a linear-graded junction in which the capacitance follows a $V^{-1/3}$ dependence and the gradient, a , is

$$a = \frac{6.65 \times 10^7 C^3 V}{A^3} \quad (7)$$

where C is junction capacitance in pF, V the potential in volts across the junction and A the junction area [17]. The capacitance will not have this simple linear-graded relationship if diffusion from the lithium-rich region or recombination processes are not negligible.

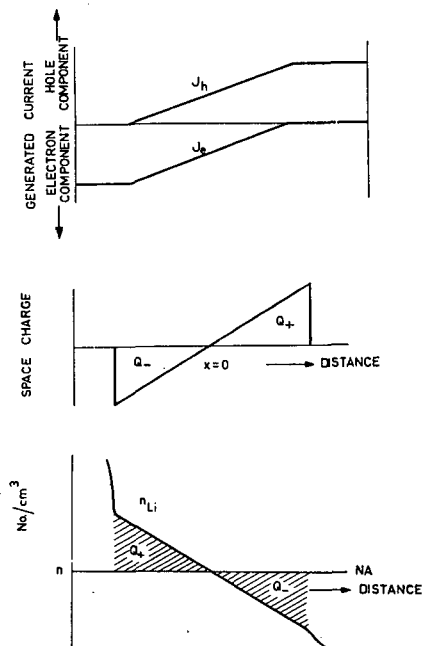


Fig. 3

The influence of space-charge generated current on lithium distribution in the drifted region. The spatial distribution of lithium compensates the space-charge distribution of the mobile carriers

III. Experimental procedure

In the fabrication of p-i-n-junction detectors, the basic techniques of PELL [3] are followed. Boron-doped p-type silicon with resistivities ranging from 0.1 to 1000 Ω cm are used. The silicon samples are ingot slices 1 to 6 mm deep, and with diam. between 1.5 and 2.5 cm and cut with faces perpendicular to the $\langle 111 \rangle$ direction. Larger sensitive volumes were obtained when ingots were cut with faces perpendicular to the $\langle 110 \rangle$ direction and active surfaces from 1 to 12 cm².

A suspension of lithium in oil [18] is applied to one face of the sample and dried in a nitrogen atmosphere at 200 to 250°C. The lithium is then diffused into the silicon at temperatures between 360° and 600°C for times ranging from 1 min to 1 h. Increased temperatures are required on low-resistivity samples (0.1 to 1.0 Ω cm) to maintain at least a factor of 10^3 between surface-lithium concentration [12] [13] [19] and acceptor concentration. Temperature measurements are made by a thermocouple positioned either in a silicon slice or a ceramic block.

The uniformity of the diffusion is routinely checked using a four-point probe-sheet resistivity measurement [20]. Some samples were then sectioned and stained [20] to verify the depth and the uniformity of diffusion.

Contact to the p-type surface is made by alloying Au-B, alloying aluminium, or by soldering to electroless Ni. Contact to the heavily doped n-region is made by Ag-paste, alloyed Au or by soldering to electroless Ni. The alloyed Au contacts have been found to short the junction after drift in the cases when the initial diffusion depth was less than 70 μ .

The slices are masked with Apiezon wax and etched with a 4-4-5 solution.* The differential etch-rate between the heavily lithium-doped n-type region and the p-type region also affords a qualitative indication of the diffusion depth.

The samples are then placed in a rapidly stirred silicon-200 fluid bath at temperatures between 120° and 250°C with reverse biases ranging from 10 to 300 V. At any bath temperature the maximum bias voltage is governed by the heat dissipation in the sample. For accurate temperature measurement, a thermocouple is mounted on the silicon sample being drifted.

Capacitance measurements are made at room temperature with a 100-kHz bridge capable of supplying DC bias voltage up to 100 V. The width of the drifted region is also measured by staining techniques and from the response of the unit to nuclear particles.

VI. Experimental results

(a) INITIAL DIFFUSION

The following data indicates the agreement between calculated and experimentally measured values:

	Junction Depth
	(μ)
1. Chemical Stain	
Calculated (360°C - 3 min)	75
Measured	78
2. Sheet Resistivity	
Calculated (360°C - 2 min)	56
Measured	58
3. Capacitance vs. V	
Calculated (360°C - 5 min - 1400 Ω cm)	131
Calculated Cap. = 480 pF Measured Cap. = 490 pF	

The initial capacitance measurements were compared with data given by LAWRENCE and WARNER [21], and close agreement could be obtained only when the effect of room-temperature drift was minimized by measuring the capacitance soon after diffusion.

Sheet-resistivity measurements yielded values between 1 and 40 Ω cm². The diffusion depths were calculated from correction factors published by BACKENSTOSS [22]. As a consequence of the high diffusion-constant of lithium into silicon, it was not possible to produce uniform diffusion layers of less than 50 μ . Further, these relatively "shallow" junctions exhibited non-uniform and high sheet resistivities following deep drifts. These

* 4 parts by volume (70%) HNO₃ to 4 parts (48%) HF to 5 parts glacial acetic acid.

effects are due to the removal of the lithium during drift (Fig. 1). The more stable devices had a value of $d \gtrsim 0.1$ mm.

(b) ION-DRIFT MEASUREMENTS

The increase in depletion width W was measured primarily by capacitance measurements

$$C = \frac{KA}{4\pi W} \quad (8)$$

where K is the dielectric constant of silicon. The comparison between measured and calculated values can be seen from the following data:

1. Capacitance	Drifted Width, mm
Calculated	1.42
Measured	1.4
2. Chemical Stain	
Calculated	1.40
Measured	1.35
3. Response to Protons (USC)	
Calculated	1.82
Linear Accelerator	$1.85 \pm 10\%$
Stain	1.80

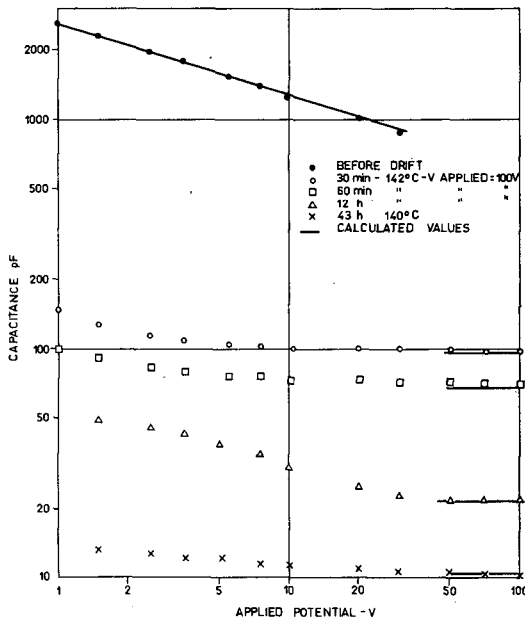


Fig. 4

The decrease in capacity of junction (area ≈ 3 cm²) with drift reflects the increase in depletion width. The calculated capacitance values for the drift times are indicated by the solid line

The variation of capacitance as a function of depletion-width is illustrated in Fig. 4. The drift measurements for float-zoned silicon with resistivity between 1 and 1000 Ω cm verifies the mobility values obtained by Pell. These well-behaved mobility values were only found when the field in the junction exceeded 500 V/cm. At lower field values, the influence of diffusion resulted in lower values of mobility as measured from the junction capacitance. When drifting material with $\rho > 300 \Omega$ cm, it is necessary to correct for the voltage-drop across the p-type material [10]. Preliminary measurements of the lithium mobility in 13 Ω cm silicon with an oxygen content of 9×10^{17} atoms/cm³ (determined from the 9- μ absorption band) confirmed the marked decrease in mobility expected in high-oxygen-content material [12]. Under conditions of high current and bias, the power dissipation in the diodes can rise to levels as high as 5 W, causing up to 10° temperature differential between diode and bath. In extreme cases, the units exhibited thermal runaway.

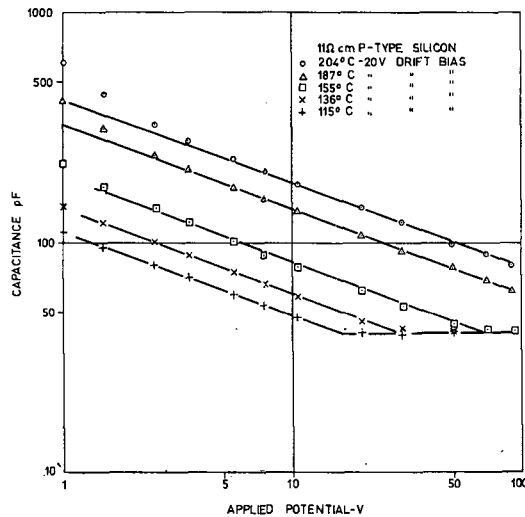


Fig. 5

Capacitance-voltage characteristics of a junction showing the effect of increased temperature on the lithium distribution

The influence of the thermally generated mobile carriers on the capacitance-voltage relationship is illustrated by Fig. 5. Following the procedure of READ [15], the influence of the mobile carriers can be calculated. The comparison of the calculated and measured values is indicated by Table I. In these calculations the only variable parameter is the effective lifetime τ_c , which varies from unit to unit and is in the range from 1 to 25 μ s.

The capacitance curves can be "flattened" by a high voltage drift at lower temperatures during which the field distortion by the holes and electrons is negligible. This flattening is illustrated by Fig. 6.

The current through the diodes is found to be primarily determined by space-charge generation in W . Equation (5) indicates that the product of $n_i W$ for any diode should be constant. This is shown in Table II.

TABLE I
INFLUENCE OF THERMALLY GENERATED MOBILE CARRIERS

Depletion Width (cm $\times 10^2$)	Temp. (°C)	Drift Potential (Volts)	Gradient	
			Calculated	Measured
4.5	177	20	3.5×10^{13}	3.6×10^{13}
4.5	133	20	5.2×10^{12}	5.3×10^{12}
7.1	133	50	3.3×10^{12}	3.2×10^{12}
7.1	204	20	1.4×10^{14}	1.4×10^{14}
7.1	187	20	6.8×10^{13}	7.3×10^{13}
7.5	136	20	4.2×10^{13}	3.9×10^{13}
11.0	117	20	3.5×10^{12}	3.0×10^{12}

TABLE II
DIODE CURRENT

Depletion Width (cm)	Temp. (°C)	n_i	I (ma)	$n_i W/I$ ($\times 10^{-11}$)
2.8×10^{-2}	24	1.3×10^{10}	2.1×10^{-3}	1.73
3×10^{-2}	192	4.2×10^{13}	12	1.0
3.5×10^{-2}	24	1.3×10^{10}	2.3×10^{-3}	1.95
4.4×10^{-2}	192	4.2×10^{13}	17	0.98
5.6×10^{-2}	24	1.3×10^{10}	4.6×10^{-3}	1.6
7.35×10^{-2}	198	4.7×10^{13}	37	0.96
1.33×10^{-1}	172	2.3×10^{13}	28	1.09
2.28×10^{-1}	24	1.3×10^{10}	15.5×10^{-3}	1.9
2.82×10^{-1}	124	3.5×10^{12}	13	1.03

The room-temperature values of $n_i W/I$ have been found to be consistently higher than those measured at elevated temperature. This is attributed to the temperature dependence of the effective lifetime. A typical current-voltage characteristic curve for a 10Ω cm junction is shown in Fig. 7 in which the increase in current with increasing W can be seen. The voltage dependence of the current at low biases follows the decrease in capacitance. The increase in current at high voltages is attributed to surface effects.

The variation in diode characteristics during room-temperature storage is indicated by Fig. 8. The increase in capacitance as a function of time is found to be a real effect. A study of this effect was made by observing the decrease in pulse height due to low-energy alpha-particles using a diode that had been drifted to the back contact. It was noted that the capacitance curves recovered to their initial values in a manner similar to the recovery seen in Fig. 6. An illustration of this effect is given by data in Fig. 8. From this fact and other evidence, it is inferred that the change in capacitance is associated with a rearrangement of the lithium ions caused by the "built-in" voltage of 1 V which appears across the diode at room temperature. It should be noted that the capacitance does not increase if the diode is held at applied bias voltages of the order of 50 to 100 V.

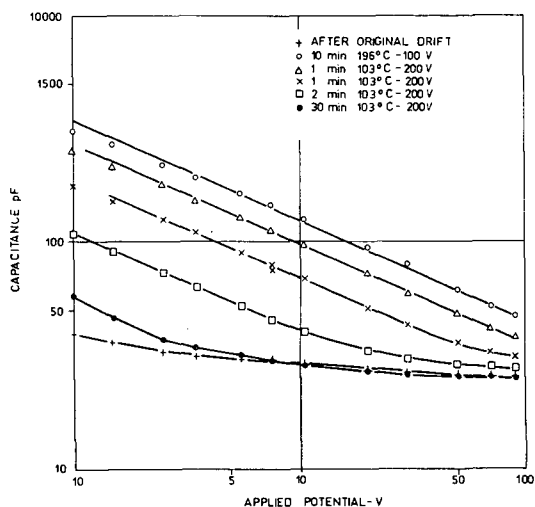


Fig. 6

Capacitance-voltage characteristics of a junction after low temperature drift followed by a short high-temperature drift and subsequent recovery after a series of low-temperature drifts

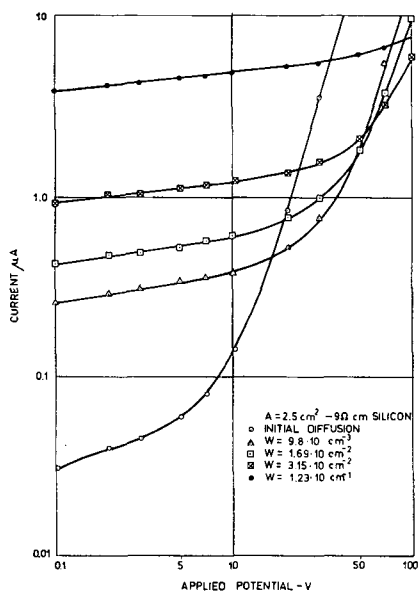


Fig. 7

Current-voltage characteristics of a junction plotted as a function of depletion width. The values of W were calculated from the junction capacitance measured at 100 V

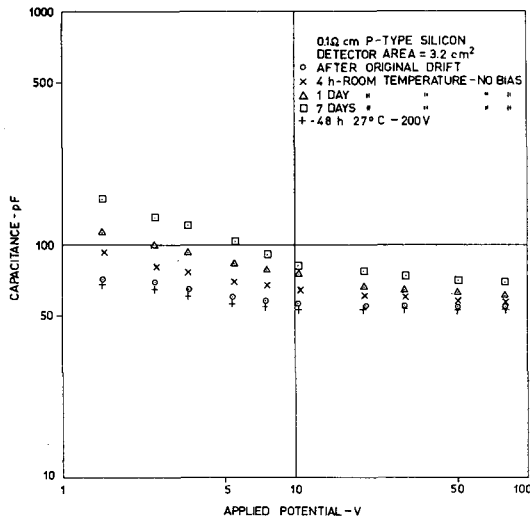


Fig. 8
Variation in capacitance-voltage characteristics with time

V. Response to nuclear particles

(a) GAMMA RAYS

The response of a 2-mm deep p-i-n-junction detector to the 662-keV mono-energetic γ -rays of the Cs^{137} decay products is illustrated by Fig. 9. It can be seen that the predominant mechanism contributing to the observed pulse-height distribution is Compton electrons. Similar spectra were observed with I^{131} , Cr^{51} and Co^{60} . Agreement was observed between the calculated and observed photopeak and Compton electron-energy distributions.

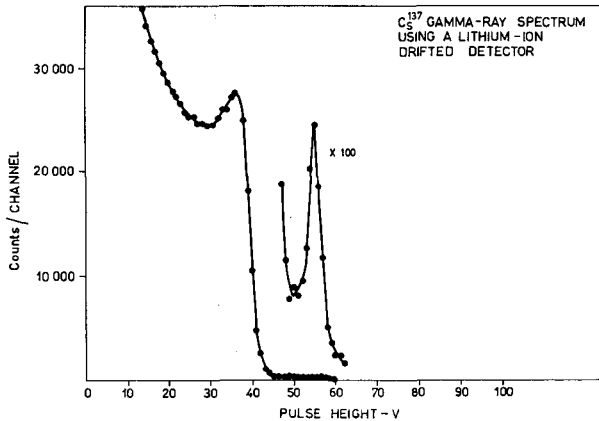


Fig. 9
Pulse-height distribution obtained with a p-i-n-junction detector ($A \approx 3 \text{ cm}^2$, $W = 2 \text{ mm}$) to the Cs^{137} gamma-ray spectrum

The $1/r^2$ dependence of the detector response shown by Fig. 10 indicates the detector is responding to the primary photon flux. The response of a 1.4-mm deep detector to various sources is given by the following Table III.

TABLE III
RESPONSE OF DETECTOR TO VARIOUS GAMMA RAY SOURCES

Isotope	cpm/mr/h/cm ² of detector area	cpm/ μ c/cm ²
Co ⁶⁰	280	310 (10 cm source to detector distance) 3.84×10^4 (2 cm source to detector distance)
Cs ¹³⁷	280	
I ¹³¹	850	
I ¹³¹ ($\beta + \gamma$)		
P ³²		

(b) ELECTRONS

The response of a 2-mm deep p-i-n-junction detector to mono-energetic electrons is shown by Fig. 11. As in the case of p-n junctions when the effective range of the electrons exceeds the width of the depletion region, there is a distribution peak at high channel numbers corresponding to electrons which lose all their energy in the sensitive volume due to multiple scattering and a broader peak at a lower channel number due to those electrons which escape before giving up all their energy.

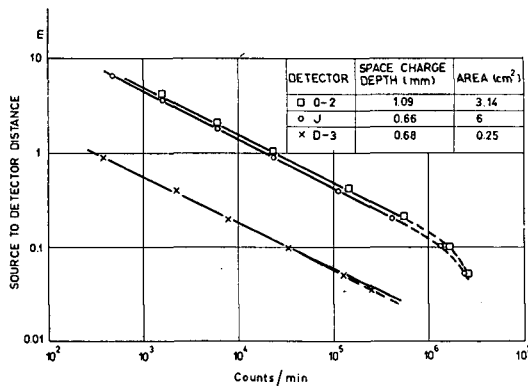


Fig. 10
Sensitivity of various p-i-n-junctions to the gamma rays of Co⁶⁰

The detector was placed at an exit slit of beta-ray spectrometer (Sr-Yr⁹⁰ source) and a comparison between the relative counting rate of a beta-sensitive proportional counter and the detector was made (Fig. 12). The difference in response of the detector from that of the proportional counter at high energy is due to the fact that the range of the electrons exceeds the depletion width.

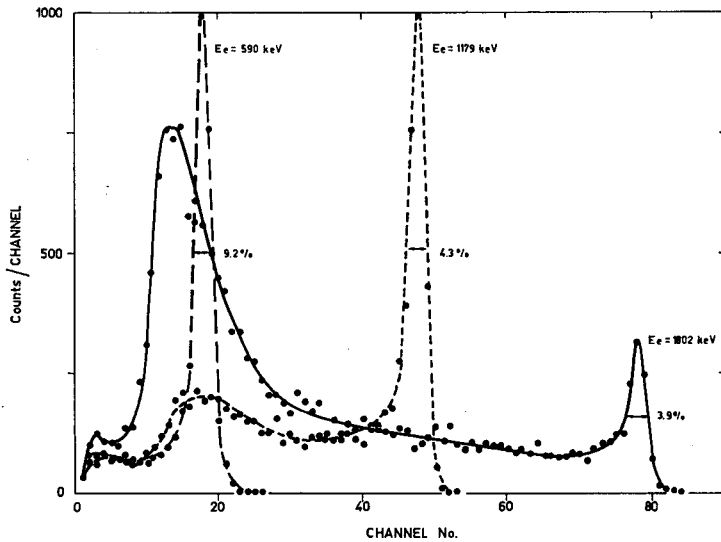


Fig. 11

Pulse-height distribution of the response of a junction ($W = 2$ mm) to mono-energetic electrons (data taken at Los Alamos Scientific Laboratory)

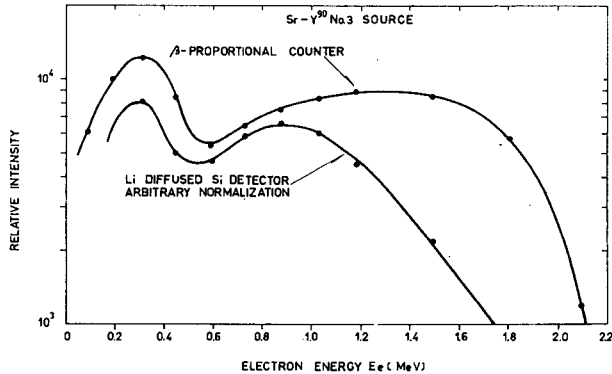


Fig. 12

Comparison of the intensity vs. energy of a p-i-n-junction detector and a β -sensitive proportional counter (data taken at Los Alamos Scientific Laboratory)

(c) HEAVY CHARGED PARTICLES

Charged particles from the Be^9 (He^3 , d) B^{10} reaction were allowed to impinge on a detector ($W = 2$ mm) through the heavily doped front surface. The pulse-height distribution obtained is shown by Fig. 13. The 17-MeV ground and excited states of the reaction are cleanly resolved. The response of a detector, $W \approx 4.5$ mm, to 28 MeV

protons is illustrated by Fig. 14. In both cases the width of the line is attributed to the effect of the lithium-rich “dead” layer [1] and the higher space-charge generated leakage current.

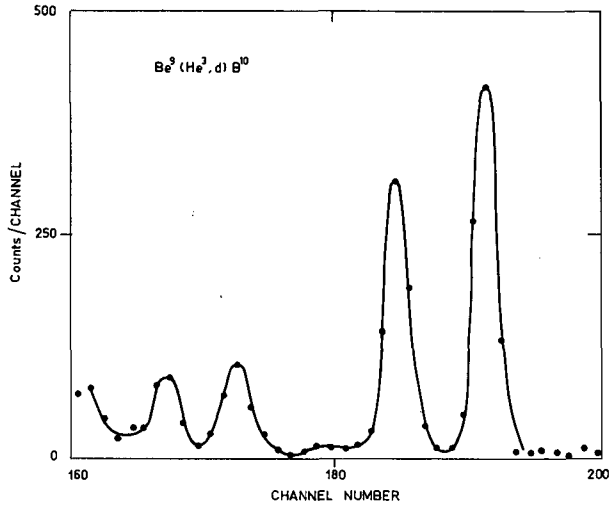


Fig. 13

Response of a p-i-n-junction detector to deuterons from the $\text{Be}^9 (\text{He}^3, d) \text{B}^{10}$ spectrum (data taken at Los Alamos Scientific Laboratory)

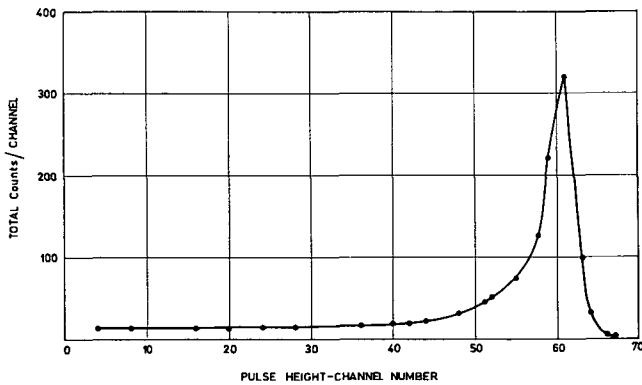


Fig. 14

Pulse-height distribution of p-i-n-junction detector ($W \simeq 4.5$ mm) to 28 MeV protons

An uncollimated Pb^{212} source (6 and 8.78 MeV alpha particles) was used to determine the response of a p-i-n detector ($W \simeq 1$ mm) drifted to the back contact (Fig. 15). The pulse-height distribution for particles in the front surface is clearly seen to be distorted by the “dead” layer. In this case the maximum value of pulse height is due

to particles incident on the etched sides. Comparing the distributions obtained by allowing particles to impinge alternately on both the front and back surfaces indicates that energy absorption at the back surface is negligible.

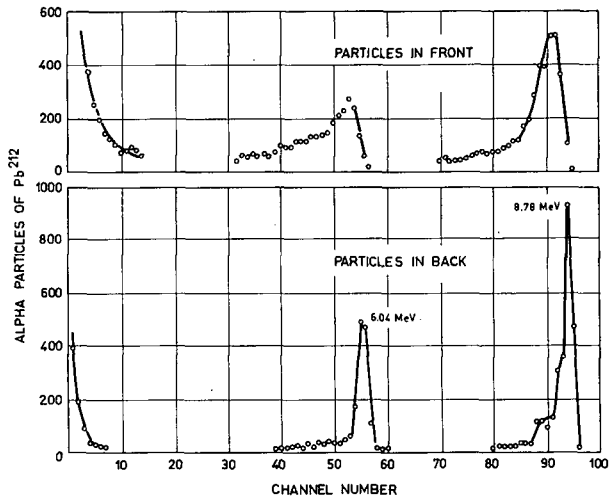


Fig. 15

Response of a p-i-n-junction detector drifted to the back contact to alpha particles (Pb^{212})

VI. Conclusions

The use of the ion-drift technique can provide p-i-n-junction detectors whose depletion depth and active areas are greater than those obtainable with p-n-junction detectors.

The data accumulated indicates the usefulness of these junctions in detecting deeply penetrating radiation and suggests the use of ion-drift techniques in high Z materials.

ACKNOWLEDGEMENTS

The authors are indebted to H. E. Wegner at Los Alamos Scientific Laboratory and Hans Bichsel at the University of Southern California for their encouragement and help in the evaluation of experimental devices. Discussions with H. Reiss at Atomics International and E. Pell at Haloid-Xerox were extremely helpful.

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DISCUSSION

C. J. Borkowski (United States of America): I want to ask whether the peak observed by Mr. Mayer for gamma rays was indeed a photoelectric peak, or was it a total Compton peak; was the barrier deep enough for the scattered gamma-ray to be re-absorbed?

J. W. Mayer (United States of America): From our experiments it is not possible to tell definitely whether the higher peak in the pulse-height distribution is due to Compton electron processes. However, analysis of the pulse-height response to the spectra of Cr^{51} , Cs^{137} , and Co^{60} * indicated that the high pulse-height peak corresponded to the gamma energy and the "shoulder" at lower pulse heights corresponded to the maximum energy transferred to an electron in a Compton scattering interaction.

R. J. Griffiths (United Kingdom): In Fig. 14 of your Paper you show what I believe to be a proton spectrum. Could you tell me what is the resolution of this spectrum and what was its limitation?

J. W. Mayer: Fig. 14 corresponds to the response of a 4.5 mm depletion region detector to 28 MeV protons. This work was done with the assistance of Dr. Hans Bichsel at the University of Southern California.

The relatively poor resolution was caused, partly by the high d.c. leakage currents (approximately 20 μa through the unit)—probably resulting from the thermally generated carriers in the wide depletion region—and partly by the poor experimental geometry, and beam instability at the SC unit. Since this measurement was designed to probe the depth of the drifted region, no effort was made to "clean-up" the geometry.

* BAILY, N. A., GRAINGER, R. J. and MAYER, J. W., *Rev. sci. Instr.* **32** (1961) 865.

ELECTRICAL LIMITATIONS TO ENERGY RESOLUTION IN SEMICONDUCTOR PARTICLE DETECTORS

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Abstract — Résumé — Аннотация — Resumen

Electrical limitations to energy resolution in semiconductor particle detectors. Based on the assumption that the noise contribution of a semiconductor detector is due solely to its bulk properties, equations are presented which indicate the theoretical limits of noise in detector-amplifier combinations. These equations show that an optimum amplifier time-constant and detector bias voltage exist for which condition the minimum noise is independent of the semiconductor resistivity. The optimum performance of a detector-amplifier system is shown to depend only upon detector area, input capacity (less detector capacity), semiconductor minority carrier lifetime and the transconductance of the amplifier input tube. A new detector structure which includes a guard-ring electrode as an integral part of the detector structure is described which has the effect of largely eliminating noise due to surface leakage. Experimental results for detector leakage and energy resolution which agree well with theory are presented. The theoretical limit of noise, expressed as full width at half maximum, is from 7 to 10 keV for 1-cm² p-type silicon detectors at 25°C.

Limitations électriques du pouvoir de résolution en énergie des détecteurs à semi-conducteurs. Partant de l'hypothèse que le bruit imputable au détecteur à semi-conducteur est dû exclusivement aux propriétés fondamentales du semi-conducteur, les auteurs établissent des équations donnant les limites théoriques du bruit dans les combinaisons détecteur-amplificateur. Ces équations montrent qu'il existe une constante de temps optimum de l'amplificateur et une tension de polarisation du détecteur, pour lesquelles le bruit minimum est indépendant de la résistivité du semi-conducteur. Les auteurs prouvent que l'optimum de fonctionnement d'un ensemble détecteur-amplificateur ne dépend que de la surface du détecteur, de la capacité à l'entrée (déduction faite de la capacité du détecteur), du porteur minoritaire du semi-conducteur, de la durée de vie et de la transconductance du tube d'entrée de l'amplificateur. Ils décrivent un modèle nouveau de détecteur qui comprend une électrode avec anneau de garde qui fait partie intégrante de l'instrument et qui a pour effet d'éliminer dans une large mesure le bruit dû aux fuites en surface. Le mémoire fournit des données expérimentales relatives aux fuites et au pouvoir de résolution en énergie qui concordent parfaitement avec la théorie. La limite théorique du bruit, exprimée en largeur totale à mi-hauteur du maximum, est de l'ordre de 7 à 10 keV pour les détecteurs au silicium type p de 1 cm², à une température de 25°C.

Электрические ограничения разрешающей способности по энергии в полупроводниковых детекторах частиц. Исходя из гипотезы, что производимый полупроводниковым детектором шум вызывается исключительно свойствами массы полупроводника, приводятся уравнения, дающие теоретические пределы шума при совмещении детекторов с усилителями. Из этих уравнений видно, что имеются оптимальная константа времени для усилителя и напряжение смещения для детектора; при соблюдении этих условий минимальный шум не зависит от удельного сопротивления полупроводника. Доказывается, что наилучшие результаты работы системы детектор-усилитель зависят только от площади детектирующей поверхности, входной емкости (за вычетом емкости самого детектора), срока жизни наименее многочисленного из носителей в полупроводнике и от крутизны входной электронной лампы усилителя. Описывается новая конструкция детектора с кольцевым оградительным электродом в качестве неотъемлемой части конструкции детектора, что в широкой мере устраняет шум, вызываемый поверхностной утечкой.

Сообщаются экспериментальные результаты определения утечки детектора и разрешающей способности по энергии, хорошо совпадающие с теоретическими данными. Теоретический предел шума, выраженного в виде полной ширины на половине максимума, лежит для кремниевых детекторов типа „р“ в интервале от 7 до 10 кэв на 1 кв. см при 25°С.

Limitaciones eléctricas en la resolución energética de detectores de partículas a base de semiconductores. Los autores parten de la suposición de que el ruido de fondo de un detector basado en un semiconductor se debe únicamente a este último, y presentan ecuaciones que indican los límites teóricos del ruido en las combinaciones detector-amplificador. Estas ecuaciones demuestran la existencia de valores óptimos en las constantes de tiempo del amplificador y en la polarización del detector, para los que el ruido mínimo es independiente de la resistividad del semiconductor. Los autores demuestran que el funcionamiento óptimo de un sistema detector-amplificador depende únicamente del área del detector, de la capacidad de entrada (menos la capacidad del detector), de la vida media de los portadores minoritarios del semiconductor, y de la transconductancia de la válvula de entrada del amplificador. La memoria describe la estructura de un nuevo detector que incluye como parte integral un electrodo de anillo de guarda cuyo efecto es eliminar en gran parte el ruido que ocasionan las fugas superficiales. Presentan los resultados obtenidos experimentalmente para las pérdidas en el detector y la resolución energética, que concuerdan satisfactoriamente con los valores teóricos. El límite teórico del ruido expresado como anchura del pico a la mitad de su amplitud está comprendido entre 7 y 10 keV para detectores de silicio del tipo p, de 1 cm² a 25°C.

The optimum signal-to-noise ratio obtainable from a semiconductor detector depends upon all the noise generators present in the detector and the amplifier with which it is viewed. For analytical purposes, it is convenient to treat the noise sources due to the amplifier and detector separately. Since a semiconductor junction may be looked upon as a solid ionization chamber, the general amplifier noise considerations will be the same as those developed for gaseous ionization chambers.

For noise calculations, ionization chambers may be regarded as very-high-impedance charge sources shunted by capacity. The junction detector acts in a similar way; the impedance is lower and the capacity greater than the ionization chamber and there is a significant leakage current. The only effect of these differences is to modify the optimum design parameters of the system for the particular detector. Formulae similar to those developed for ionization-chamber amplifiers [1] are presented in Table I. In these formulae, we assume that the pulse amplifier contains single integrating and differentiating circuits having equal time constants and that the detector collection time is very small compared with the amplifier time-constant.

In Table I, note that the contribution of the tube-flicker effect to total noise is independent of the actual value of the amplifier time-constant. Calculation also shows that it is small compared with the other terms in the practical case. Note that any other noise having a $1/f$ frequency dependence would also result in a noise component independent of the amplifier time-constant.

The remaining terms in Table I all demonstrate some dependence on the amplifier time-constant. The square of the tube-shot noise is inversely proportional to the amplifier time-constant, while the squares of the grid-current noise, detector-leakage-current noise, and resistance noise are all linearly proportional to the amplifier time-constant. Thus, there is an optimum amplifier time-constant at which the signal-to-noise ratio has its greatest value.

Fig. 1 presents curves calculated from Table I which illustrate the variation of mean-square noise with the various parameters in the equations. In the curves, we assume

TABLE I

NOISE CONTRIBUTIONS FROM VARIOUS SOURCES

Noise source	Input equivalent [noise] ² (coulombs ²)	Input equivalent a, b [noise] ² (keV ²)	Constants
Tube-shot noise	$4 \times 10^{-35} \frac{C^2}{g_m \tau}$	$2 \times 10^{-2} \frac{C^2}{g_m \tau}$	C : total input capacity (pF) g_m : tube mutual conductance (mA/V)
Tube flicker	$4 \times 10^{-37} C^2$	$2 \times 10^{-4} C^2$	τ : amplifier time constant (μ sec)
Grid current	$3.2 \times 10^{-34} i_g \tau$	$1.6 \times 10^{-1} i_g \tau$	i_g : tube grid current (m μ A)
Detector leakage	$3.2 \times 10^{-34} i_L \tau$	$1.6 \times 10^{-1} i_L \tau$	i_L : detector leakage (m μ A)
Input-resistance unit	$1.6 \times 10^{-32} \frac{\tau}{R}$	$8 \frac{\tau}{R}$	R : total input shunt (CR assumed $\gg \tau$)

a The third column gives equivalent energy absorbed from an incident particle, assuming 3.6 eV/hole electron pair (correct for silicon).

b Full width at half maximum of a resolution curve is approximated by taking the square root of the sum of contributions in column 3 and multiplying by 2.3.

a tube grid current of 2×10^{-9} A, a total shunt input resistance of 5 M Ω , and an input tube transconductance of 16 mA/V. For short amplifier time-constants, tube-shot noise is dominant, whereas detector-leakage-current noise is dominant for long amplifier time-constants.

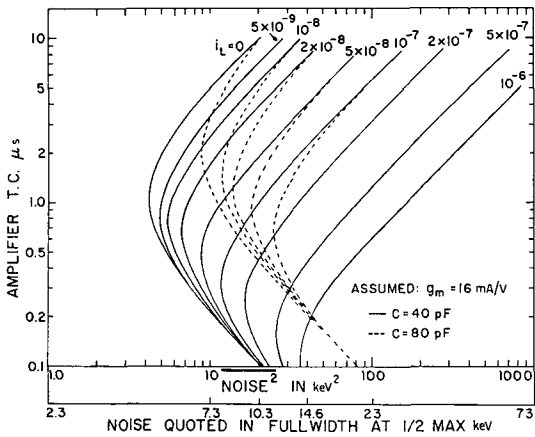


Fig. 1

Plot of noise variation vs. amplifier time constant

Using Table I, we can calculate the optimum amplifier time constant. Since tube-shot noise and detector-leakage-current noise are dominant, the remaining terms may be

neglected. Thus we have

$$\tau_{\text{opt.}} = \frac{0.35 C}{(g_m i_L)^{1/2}} \quad (1)$$

From this result, the optimum mean square noise is then given by

$$\langle (\text{noise})^2 \rangle = 0.11 C \left(\frac{i_L}{g_m} \right)^{1/2} \text{ keV}^2. \quad (2)$$

This equation gives very good agreement with the curves of Fig. 1, even though it includes only the contributions due to tube-shot noise and detector-leakage-current noise.

Table II presents formulae for calculating the depletion-layer width, capacity, and diffusion and generation currents for p-type silicon at 25°C. The formulae for calculating diffusion and generation currents assume that the trap and Fermi level coincide and thus are only proportional to the real currents [2]. However, the diffusion current is very small compared to the generation current in typical detectors and therefore will be ignored.

TABLE II
DETECTOR FORMULAE^a

Depletion-layer width	$W = 0.32 (\varrho V)^{1/2} \mu$
Detector capacity	$C_d = 3.3 \times 10^4 (\varrho V)^{-1/2} \text{ pF/cm}^2$
Generation current	$I_g = 38 \frac{(\varrho V)^{1/2}}{\tau_0} \text{ m}\mu\text{A/cm}^2$
Diffusion current	$I_d = 2.75 \frac{\varrho \cdot \ell}{\tau_0} \text{ m}\mu\text{A/cm}^2$
^a Here we define: W : depletion layer width ϱ : resistivity of bulk material (Ωcm) V : applied voltage C_d : detector capacity I_g : generation current τ_0 : minority carrier lifetime in bulk material (γs) I_d : diffusion current ℓ : thickness of material from which diffusion may occur (cm)	

From Eq. (2), which relates noise-to-detector characteristics, and the results of Table II, the mean-square noise at the optimum amplifier time constant is

$$\langle (\text{noise})^2 \rangle = \left(\frac{A}{\tau_0 g_m} \right)^{1/2} \left[0.7 C_{\text{in}} (\varrho V)^{1/4} + 2.2 \times 10^4 A (\varrho V)^{-1/4} \right] \text{ keV}^2, \quad (3)$$

where A is the detector area in cm^2 and C_{in} is the input capacity separate from the detector. Since the first term of Eq. (3) is proportional to $(\varrho V)^{1/4}$ and the second inversely proportional, an optimum voltage must exist from a signal-to-noise point of view. This voltage is given by

$$V_{\text{opt.}} = \frac{10^9 A^2}{e C_{\text{in}}^2} \text{ Volts.} \quad (4)$$

Inserting this result into Eq. (3), we have

$$\langle (\text{noise})^2 \rangle_{\text{opt.}} = 250 A \left(\frac{C_{\text{in}}}{\tau_0 g_m} \right)^{1/2} \text{ keV}^2. \quad (5)$$

When operated at the optimum time constant and voltage, Eq. (5) expresses the theoretical optimum signal-to-noise ratio for a p-type silicon detector at 25°C. For other conditions, the constant need only be modified. An important result of Eq. (5) is that e does not appear directly.

In order to realize practically the predicted theoretical behaviour, surface effects must be eliminated. We have found that simple junction detectors have much higher leakage currents than those predicted from the equations of Table II, and that this leakage current is neither constant nor reproducible. In order to decrease surface leakage as far as possible, the guard-ring structure shown in Fig. 2 was devised. The structure was formed by etching through a photo-resistant mask on phosphorus-diffused p-type silicon wafers. This broke the n-type skin on the front face into two areas—a central area used as the detector, and a surrounding guard-ring area. The space between the guard ring and detector should be as small as is practicable; it is 2 mil in the work described here.

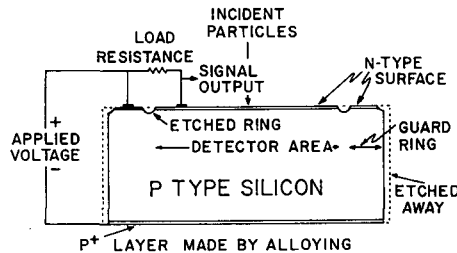


Fig. 2
Guard-ring detector

The semiconductor guard ring resembles the conventional insulator guard ring in geometry; however, its principal role seems to be to limit the growth of surface-inversion layers that can inject charge into the bulk material. A typical plot of detector leakage current is shown in Fig. 3 and the capacity in Fig. 4, for a 1-cm-diam. detector. Both curves show the square-root law predicted by the equations of Table II. Measurements of the noise of a detector-amplifier system, made by using the detector of Figs. 3 and 4, are shown in Fig. 5. The curve shown in Fig. 5 agrees very well with that predicted from Fig. 1, which indicates that the equations given in Table I accurately represent all noise sources and that no additional significant noise source is present.

Fig. 3 shows a leakage current that is poorer than average, while a better-than-average result is shown in Fig. 6. The lifetimes shown on Figs. 3 and 6 are calculated from the equations of Table II and serve only as a qualitative indication of the trapping

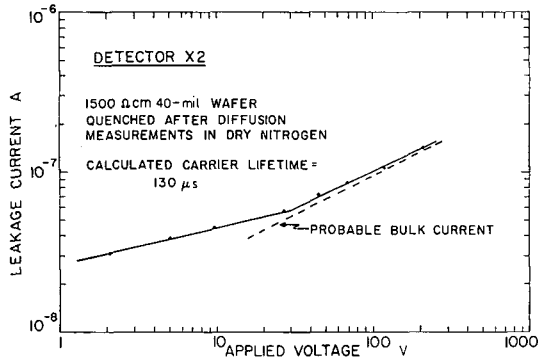


Fig. 3
Typical relationship of leakage current to voltage

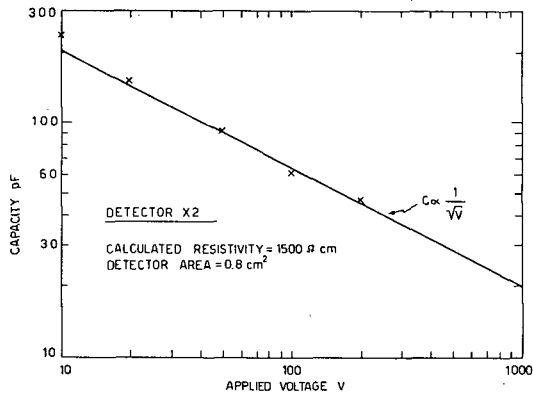


Fig. 4
Typical relationship of voltage to capacity

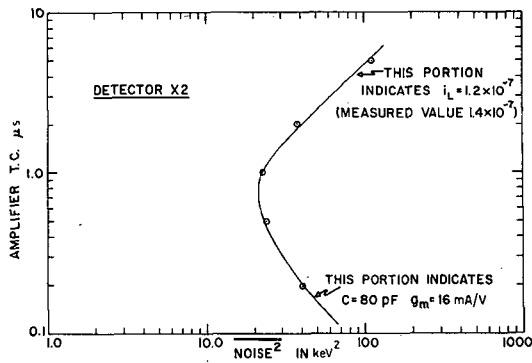


Fig. 5
Typical plot of noise variation vs. amplifier time constant

levels. The interelectrode impedance for a slightly inverted surface, i.e., lightly n-type, is shown in Fig. 7. For p-type surfaces, the impedance is high at all voltages.

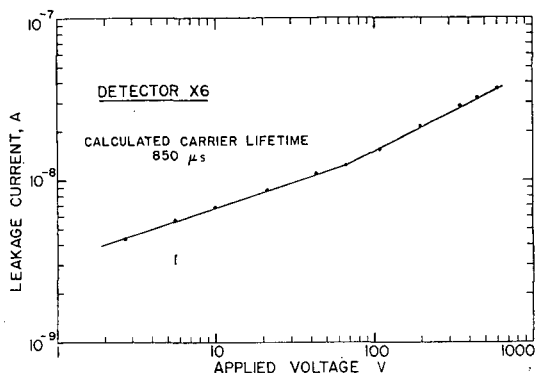


Fig. 6

Curve showing less than average leakage current

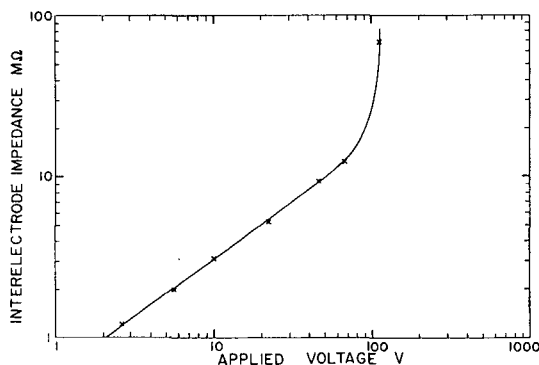


Fig. 7

Interelectrode impedance characteristic (n-type surface)

The main purpose here has been to evaluate electrical noise in a detector-amplifier system. It has been shown that, if surface problems are eliminated, there is reasonable agreement between the theory using measured values of detector leakage and that of practical noise measurements. However, other limits to the particle energy resolution of practical detectors may exist.

In general, our energy-resolution experiments using β -particles indicate that the limit to β -particle resolution is electrical noise. It appears that the equations derived in this paper may be used to determine the energy resolution.

We consistently achieve an energy resolution of 10 to 13 keV (full width at half maximum) using conversion electrons from a Hg^{203} source and a 1-cm-diam. detector.

On the other hand, the measured resolution figures for α particles are much larger than can be accounted for by electrical noise. The best resolution for 6-MeV α particles has been about 20 keV and, in many cases, much worse resolutions are observed. Many detectors show an auxiliary upper peak; the reason for this is not clear. However, it does seem that the poor resolution of α particles is not, in general, due to unresolved multiple peaks.

A more basic understanding of the charge-collection process will be required before the ultimate in resolution of heavily ionizing particles is achieved.

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- [2] SAH, C. T., NOYCE, R. N. and SHOCKLEY, W., "Carrier Generation and Recombination in p-n Junctions", *Proc. IRE* 45 (1957) 1228.

DISCUSSION

E. Gatti (Italy): I would like to make a few comments on the paper of Mr. Hansen. I have made similar measurements on RCA silicon semiconductor detectors in my lab., and investigated signal-to-noise ratio as a function of the time constants of an RC-RG amplifier. I injected artificial charge pulses into the semiconductor, with the back voltage on, and I found the minimum as Mr. Hansen has shown, but I also found evidence of the presence of a current with spectrum $1/f$, that is $1/f^3$ as voltage on the first tube. I then made theoretical calculations just to show how much this current noise should affect the resolution of the semiconductor detector. The calculations show that the current associated with $1/f$ noise does not adversely affect the resolution if a clipping time constant of about 20 μ s is added to the amplifier.

W. L. Hansen (United States of America): Was this detector in which you observed $1/f$ noise a simple diode? Was this a surface effect?

E. Gatti: Yes, probably it was a surface effect. It was leakage current having an excess spectrum of current noise.

W. L. Hansen: I believe that these equations which we have just presented indicate that a $1/f$ noise of whatever magnitude will simply add directly to the noise present; there is no frequency dependence.

E. Gatti: You mean $1/f$ as the flicker noise of a tube, but I mean $1/f$ current noise, which integrates over the input capacitance and makes $1/f^3$ noise.

ПОЛУПРОВОДНИКОВЫЕ СПЕКТРОМЕТРЫ ЗАРЯЖЕННЫХ ЧАСТИЦ

Л. А. Зубрицкий, А. И. Попов, П. В. Сорокин и В. Ф. Самойлов
СССР

Abstract — Résumé — Аннотация — Resumen

Semiconducting spectrometers for charged particles. The paper presents a method of making germanium and silicon spectrometers, describes their design and gives various properties. Germanium spectrometers with an area of $5 \times 5 \text{ mm}^2$ at the temperature of liquid nitrogen have a resolution of not less than 0.5% for alpha particles of Po^{210} at voltages up to 30 V. Silicon spectrometers with an area of $4 \times 4 \text{ mm}^2$ have a resolution of 2.5% at the temperature of liquid nitrogen at voltages from 50 to 180 V. At room temperature the silicon spectrometer has a resolution of 3% at voltages up to 10 V.

Spectromètres à semi-conducteurs pour particules chargées. Les auteurs décrivent une méthode permettant de construire des spectromètres à jonctions en germanium et silicium, la structure de ces spectromètres et certaines de leurs caractéristiques. Les spectromètres à jonctions en germanium d'une superficie de $5 \times 5 \text{ mm}^2$ ont, à la température de l'azote liquide, un pouvoir de résolution minimum de 0,5% pour les particules α de ^{210}Po , pour une tension maximum de 30 V. En ce qui concerne les spectromètres à jonctions en silicium, d'une superficie de $4 \times 4 \text{ mm}^2$, le pouvoir de résolution est de 2,5% à la température de l'azote liquide et pour des tensions de 50 à 180 V. A la température ambiante et une tension inférieure à 10 V, ce pouvoir de résolution est de 3%.

Полупроводниковые спектрометры заряженных частиц. Описывается метод изготовления германиевых и кремниевых спектрометров, их конструкция и некоторые свойства. Германиевые спектрометры с площадью $5 \times 5 \text{ мм}^2$ при температуре жидкого азота имеют разрешение для α -частиц Po^{210} не менее 0,5% при напряжении до 30 вольт. Кремниевые с площадью $4 \times 4 \text{ мм}^2$ имеют разрешение 2,5% при температуре жидкого азота и напряжении от 50 до 180 вольт. При комнатной температуре кремниевый спектрометр имеет разрешение 3% при напряжении до 10 вольт.

Espectrómetros de semiconductores para partículas cargadas. Los autores describen un método de construcción de espectrómetros de germanio y de silicio, facilitan datos relativos a su diseño y exponen algunas de sus propiedades. A la temperatura del nitrógeno líquido, los espectrómetros de germanio con una superficie de $5 \times 5 \text{ mm}^2$ tienen un poder de resolución de 0,5 por ciento, como mínimo, para partículas alfa de ^{210}Po a tensiones inferiores a 30 V. A la misma temperatura, los espectrómetros de silicio con una superficie de $4 \times 4 \text{ mm}^2$ tienen un poder de resolución de 2,5 por ciento a tensiones comprendidas entre 50 y 180 V. A la temperatura ambiente el poder de resolución del espectrómetro de silicio es de 3 por ciento a tensiones inferiores a 10 V.

1. Введение

За последние 1,5—2 года в периодической печати появился ряд сообщений [1]—[7] об использовании полупроводниковых приборов в качестве спектрометров заряженных частиц. Такие спектрометры обладают качествами, во многих отношениях превосходящими сцинтилляционные спектрометры и ионизационные камеры. Чувствительным элементом полупроводникового спектрометра является область пространственного заряда, находящегося под обратным напряжением, перехода, образованного или контактом металла с полупроводником, или границей раздела p и n полупроводников. Ширина области пространственного заряда определяется по формуле:

$$D_0 = \sqrt{\frac{\varepsilon(\varphi_0 + V) \rho \mu}{2\pi}} \cdot 10^{-6} \text{ см} \quad (1)$$

где ε — диэлектрическая проницаемость полупроводника,

φ_0 — контактная разность потенциалов,

V — напряжение на переходе,

ρ — удельное сопротивление полупроводника, зависящее от концентрации примесей,

μ — подвижность основных носителей тока.

При прохождении слоя пространственного заряда р-п перехода частица расходует часть своей кинетической энергии на образование электронно-дырочных пар. Благодаря наличию в области пространственного заряда сильного электрического поля носители, образованные на пути движения частицы, с большой скоростью переносятся к границе перехода, вызывая увеличение тока в цепи источника питания, подающего смещение на р-п переход. Это вызывает появление импульса на р-п переходе, если в цепь питания включено достаточно большое сопротивление нагрузки.

В качестве спектрометров р-п переходы могут быть использованы лишь в том случае, если пробег частицы не выходит за пределы области пространственного заряда, т.е. в случае, когда все генерированные частицей носители тока находятся в сильном электрическом поле и выводятся из объема полупроводника с большой скоростью. Это обеспечивает крутой фронт импульса и отсутствие рекомбинационных потерь, генерированных носителей в объеме полупроводника. В этом случае практически все генерированные частицей неосновные носители достигают границы перехода, и амплитуда импульса будет пропорциональна энергии частицы:

$$V_{\text{имп}} = \frac{E}{\varepsilon_0 C_{\text{бх}}} \quad (2)$$

E — энергия частицы,

ε_0 — энергия образования электронно-дырочной пары в полупроводнике (для кремния $\varepsilon_0 = 3,6$ эв, для германия 2,9 эв),

$C_{\text{бх}}$ — входная емкость, состоящая из емкости перехода и монтажа.

Такие детекторы могут быть эффективно использованы в качестве спектрометров тяжелых частиц — протонов, α -частиц, тяжелых частиц, осколков деления ядер, так как ширина области пространственного заряда р-п перехода, полученная обычными методами с наиболее чистыми материалами, не может быть больше 1 мм. Исследования показали [1] [3] [6], что энергия образования пар, а следовательно, и величина импульса не зависят от сорта ионизирующей частицы.

Полупроводниковые спектрометры обладают хорошими временными характеристиками, так как благодаря сильным электрическим полям в области пространственного заряда 10^4 — 10^5 в/см время сбора носителей тока очень мало и достигает значений $5 \cdot 10^{-10}$ — $5 \cdot 10^{-9}$ сек.

Нами был изготовлен ряд полупроводниковых спектрометров на основе германия и кремния и исследованы некоторые их свойства. Спектроскопические свойства детекторов изучались с помощью α -частиц Po^{210} . Импульсы напряжения, полученные на детекторе, усиливались линейным усилителем с экспандером и анализировались с помощью 100 канального анализатора импульсов АИ-100.

2. Германиевые спектрометры

Германиевые спектрометры изготавливались на основе электронного германия с удельным сопротивлением 40—45 ом/см. Поверхностно-барьерный р-п переход создавался напылением золота на поверхность германия. Для изготовления полупроводниковых спектрометров германий разрезался на пластинки $5 \times 5 \times 1$ мм. Пластины травились в растворе СР-4 до получения зеркальной поверхности, промывались, сушились и припаивались оловом с небольшой присадкой сурьмы к коваровым кристаллодержателям. Одновременно с припайкой пластинки к кристаллодержателю в верхнюю поверхность впаивался кусочек индия, которым создавался вплавной р-п переход диаметром около 0,3 мм. После припайки пластинки травилась в кипящей H_2O_2 в течение 0,5—1 мин, промывались дважды дистиллированной водой и сушились. Края пластинки покрывались защитным слоем лака БФ-2, ограничивающим область р-п перехода и предохраняющим золотой слой от замыкания с кристаллодержателем. После этого пластинки помещали в вакуум, где проводилась очистка поверхности германия ионной бомбардировкой и напыление слоя золота толщиной около $500 \text{ \AA}$. Вплавной индиевый переход дает надежный контакт с золотой пленкой и позволяет осуществить ее подключение к внешней схеме. Конструкция полупроводникового прибора схематически изображена на рис. 1. Золото-германиевые спектрометры исследовались при температуре жидкого азота.

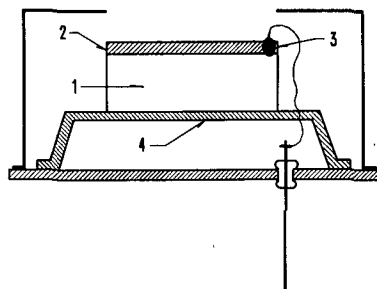


Рис. 1

Конструкция полупроводникового спектрометра

1. пластина германия $5 \times 5 \times 1$ мм,
2. пленка золота $500 \text{ \AA}$,
3. вплавной индиевый контакт,
4. коваровый кристаллодержатель.

Вольтамперная характеристика спектрометра изображена на рис. 2. Сравнивая вольтамперную характеристику нашего спектрометра с характеристикой описанной в работе [3], следует сказать, что изготовленный нами спектрометр имеет более качественный переход. Это позволяет подавать на переход значительно большее смещение и сформировать слой объемного заряда в 4 раза больший.

На рис. 3 представлена зависимость амплитуды импульса от напряжения на переходе. Быстрый рост амплитуды при напряжении от 0 до 5 вольт связан как с уменьшением емкости перехода, так и со значительным улучшением сбора

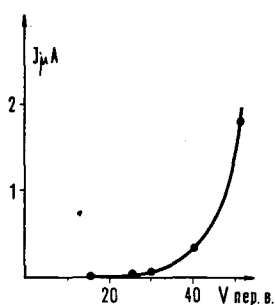


Рис. 2

Вольтамперная характеристика золотогерманиевого спектрометра

носителей тока. Свыше 5 вольт рост импульса связан, в основном, с уменьшением емкости перехода.

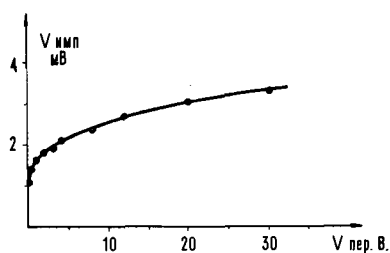


Рис. 3

Зависимость амплитуды импульса от напряжения смещения на р-п переходе золотогерманиевого спектрометра

На рис. 4 представлена зависимость разрешения $\frac{\Delta E}{E}$ от напряжения на переходе. С увеличением напряжения от 0 до 5 вольт разрешение резко улучшается в связи с улучшением сбора носителей тока. При малом напряжении на переходе ширина

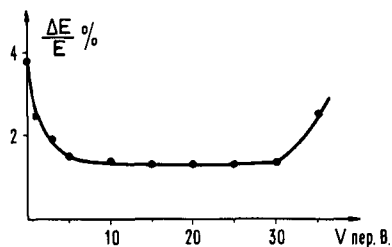


Рис. 4

Зависимость разрешения от напряжения на р-п переходе золотогерманиевого спектрометра

слоя объемного заряда получается меньше пробега α -частицы в германии, и сбор носителей осуществляется, в основном, за счет диффузионного движения. При этом значительная часть носителей может рекомбинировать. В таких условиях флуктуация числа нерекombинированных носителей больше, а разрешение хуже, чем при полном сборе носителей. Свыше 30 вольт разрешение ухудшается за счет появления шумов, связанных с увеличением тока, текущего через переход.

Следует отметить, что полученное нами разрешение 1,25% не является собственным разрешением спектрометра, а определяется уровнем шумов усилителя. На рис. 5 показан спектр импульсов от α -частиц и импульсного генератора. Видно, что относительная ширина обоих пиков одинакова. По-видимому, разрешение нашего спектрометра не хуже 0,5%, так как при собственном разрешении спектрометра 0,5% относительная ширина линии от α -частиц была бы 1,35%, что было бы легко обнаружено.

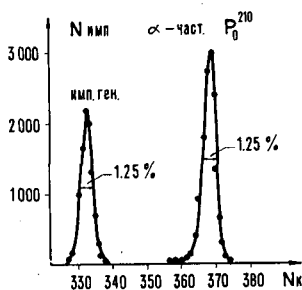


Рис. 5

Спектры α -частиц Po^{210} и импульсов от импульсного генератора

3. Кремниевые спектрометры

Кремниевые спектрометры изготовлялись нами несколько иначе, чем германиевые. В качестве материала использовался электронный кремний с удельным сопротивлением 100 ом/см. Монокристалл кремния разрезался на пластинки $4 \times 4 \times 1$ мм. Пластинки подвергались травлению смесью азотной и плавиковой кислоты. Переход р-п создавался напылением бора в вакууме на нагретые до 1200°C пластинки кремния и последующей диффузией бора в кремний на глубину ≤ 1 микрон. После проведения диффузии лишний „р“ слой стравливался, пластинка промывалась и припаивалась сплавом золота с 2% добавкой сурьмы к танталовому кристаллодержателю. Одновременно с припаиванием производилась подпайка алюминиевого контакта к „р“ слою. Конструктивно кремниевый прибор аналогичен германиевому с той разницей, что слой золота заменен тонким диффузионным слоем р-кремния. Кремниевые спектрометры были исследованы при комнатной температуре и при температуре жидкого азота.

Зависимость разрешения от напряжения на р-п переходе при комнатной температуре показана на рис. 6. Видно, что такой спектрометр обладает разрешением 3% при напряжении от 5 до 10 вольт. Свыше 10 вольт разрешение ухудшается за счет увеличения шумов. При температуре жидкого азота были определены зависимости амплитуды импульса (рис. 7) и зависимость разрешения от напряжения на переходе (рис. 8). При изменении напряжения от 50 до 180 вольт раз-

решение не изменяется и равно 2,5%. Ток через переход до напряжения 200 вольт меньше 0,01 μ A. При напряжении более 200 вольт наблюдается резкое увеличение тока. После снятия напряжения спектрометр восстанавливает свои свойства.

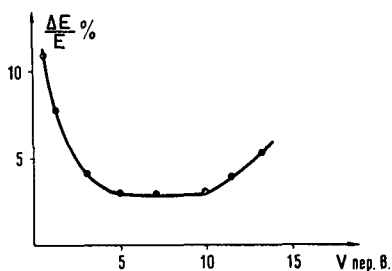


Рис. 6

Зависимость разрешения $\frac{\Delta E}{E}$ от напряжения на р-п переходе кремниевого спектрометра при комнатной температуре

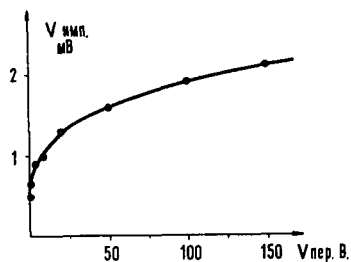


Рис. 7

Зависимость амплитуды импульса от напряжения на р-п переходе кремниевого спектрометра при температуре жидкого азота

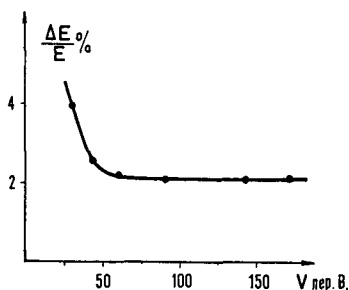


Рис. 8

Зависимость разрешения $\frac{\Delta E}{E}$ от напряжения на р-п переходе кремниевого спектрометра при температуре жидкого азота

Для кремниевых спектрометров была определена эффективная ширина чувствительного слоя. Для определения эффективной ширины чувствительной зоны мы регистрировали кремниевым спектрометром, охлажденным до температуры жидкого азота протоны, упруго рассеянные толстой бериллиевой мишенью. Максимальная энергия рассеянных протонов была равна 2,2 Мэв. Спектры импульсов при различных напряжениях на переходе представлены на рис. 9. При напряжении на переходе 5 вольт протоны с большими энергиями в эффективном слое теряют только часть энергии и на спектре импульсов имеется пик, соответствующий энергии, потерянной в эффективном слое. При напряжении на переходе 30 вольт пик пропадает. Это соответствует тому, что толщина чувствительного слоя становится равной пробегу протонов. Отсюда следует, что эффективная толщина

чувствительного слоя детектора при напряжении 30 вольт составляет 55 микрон. Ширина слоя пространственного заряда, вычисленная по формуле (1), составляет 27 микрон. Таким образом оказывается, что эффективная ширина чувствительного слоя больше пространственного заряда р-п перехода на 28 микрон. Это объясняется тем [3], что значительная часть генерированных частицей носителей тока за пределами пространственного заряда диффундирует в область пространственного заряда и участвует в образовании импульса.

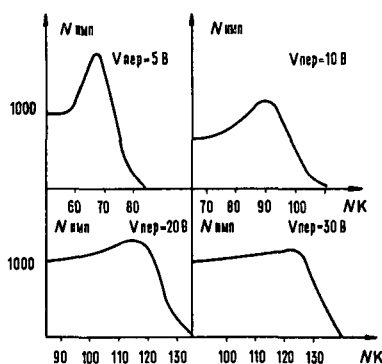


Рис. 9

Спектры импульсов от протонов, рассеянных бериллиевой мишенью при разных напряжениях на р-п переходе кремниевого спектрометра

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END OF VOL. I

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