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THIRTY-YEAR WORK WITH LEAD-GLASS CHERENKOV γ-SPECTROMETERS AT DUBNA

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An understanding of the structure, production laws and interactions of elementary particles is inseparably linked to the development of experimental methods.

Putting big accelerators into operation and the complexity of experimental problems arising from this fact have required development of new detectors.

Detectors using Cherenkov radiation in different media have become one of the effective methods which were widely adopted in high energy experimental physics. Among them are Cherenkov total adsorption lead-glass γ-spectrometers used for γ-quantum and electron detection.

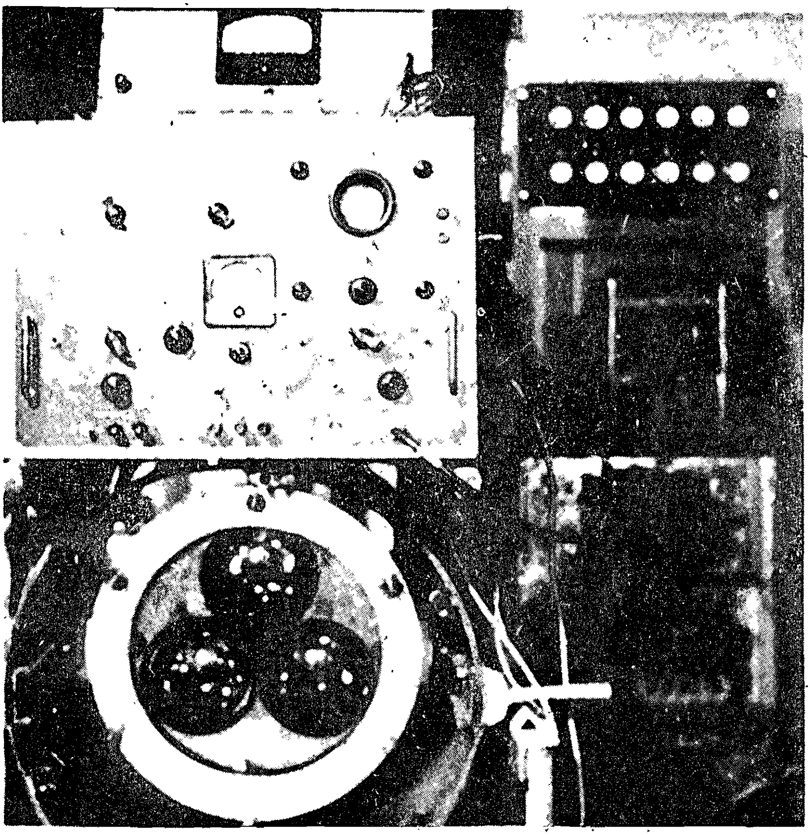


Fig.1. A general view of the Cherenkov lead-glass γ-spectrometer (1954). The glass is 36 cm in diameter and 30 cm deep. The radiation length is 1.76 cm. The energy resolution for 200 MeV electrons is 40% (HWHM).

One of the first Cherenkov γ-spectrometers was proposed and constructed at JINR in 1954-55 and intended for the detection of antiprotons and antineutrons at the 10 GeV proton synchrotron [1] (Fig.1).

To increase the energy resolution of lead-glass γ-spectrometers which is to a great extent dependent on the optical transparency of a radiator, in 1955-56 new lead-glasses were made from extra pure materials. This allowed the energy resolution of lead-glass γ-spectrometers to be considerably increased. In 1957-59 one of these counters was used in measurements of the Panofsky ratio [2] (Fig.2).

At the end of the fifties a great deal of information on the interaction cross sections of charged hadrons was obtained by a number of laboratories. The situation was less favourable for the production cross sections of neutrons with nucleons and nuclei for which there were practically no experimental data above 1.4 GeV. This circumstance was naturally limited by checking a variety of theoretical models which predict the behaviour of nucleon cross sections at high energies. The lack of experimental data for neutron cross sections was related to the fact that existing neutron detectors based on measuring the energy of recoil protons by means of absorbers could be used only over an energy range of less than 1 GeV. As energy increases above 1 GeV, the proton paths become many times larger than the mean nuclear free path in an absorber, and this results in a dramatic decrease of detector efficiency. In order to measure the neutron cross sections for GeV energies, a device based on other principles of energy measurement should be used. For high energy neutron cross section measurements in 1958 we proposed a lead-glass Cherenkov counter several nuclear free paths in thickness, i.e., a hadronic total absorption detector (Fig.3). This detector was used for neutron cross section measurements with protons, neutrons and nuclei over an energy range of 2-10 GeV [3].

The construction of Cherenkov counters having a high energy resolution made it possible to measure for the first time the charge exchange scattering cross section of π^--mesons on hydrogen over an energy range of 2 GeV [4]. A study of the charge exchange reaction $\pi^- p \to \pi^0 n$ (1) is of great interest for checking the principles of field theory and also theoretical models in which particle interactions for high energies are interpreted as an exchange of virtual particles.

Using kinematical features of the reaction (1) at high energies, in 1962 it was pointed to the possibility of measuring the charge exchange cross section using a characteristic maximum in the γ-quanta spectrum arising from the absorption of practically monoenergetic π^0-mesons in a lead-glass counter. A 18x18x30 cm^3 lead-glass counter was constructed for these measurements [5]. A study of the γ-spectrometer on a monoener-

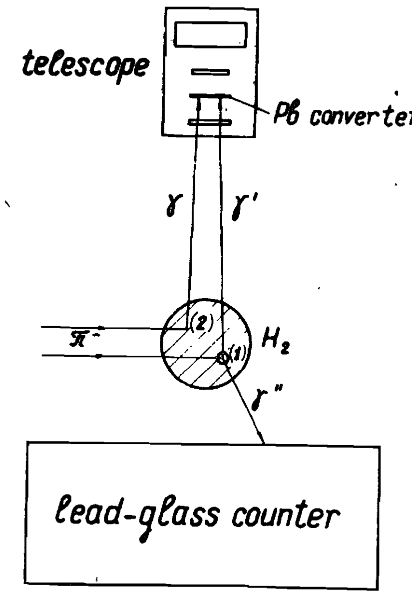
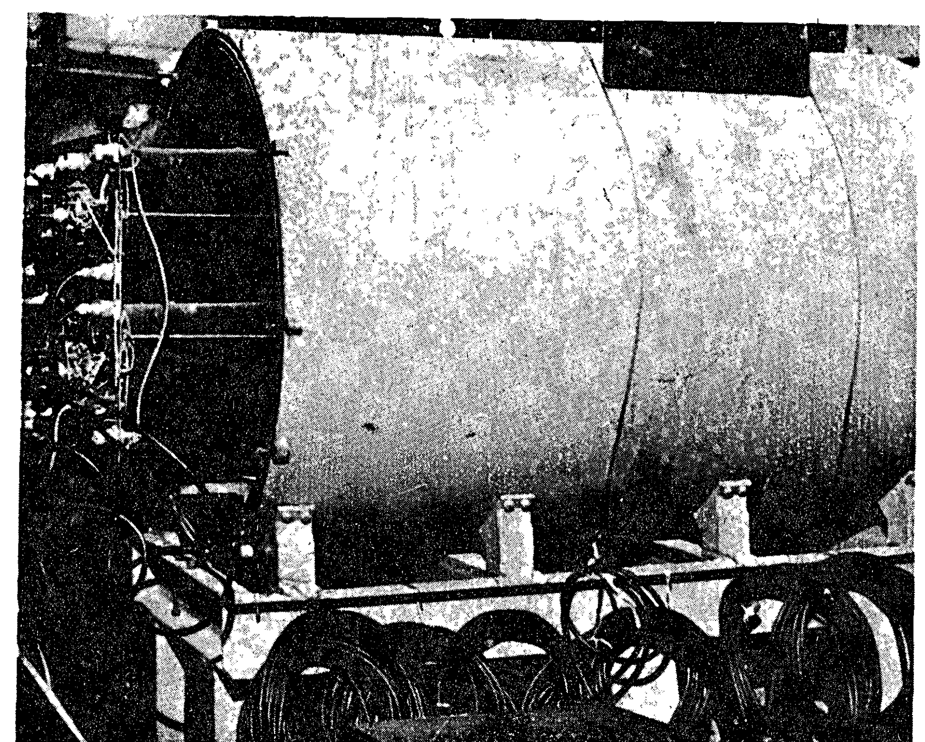


Fig. 2. A schematic diagram of the experimental set-up for measuring the Panofsky ratio. The radiator is 50x50x20 cm^3 in size. The radiation length is 2.5 cm.

Fig. 3. The Cherenkov lead-glass calorimeter (1957) used to measure the interaction cross sections between 2-10 GeV neutrons and protons, neutrons and nuclei. The Pb glass size is 50x50x50 cm^3. The radiation length is 2.5 cm. The energy resolution for 1 GeV electrons is 14% (HWHM).



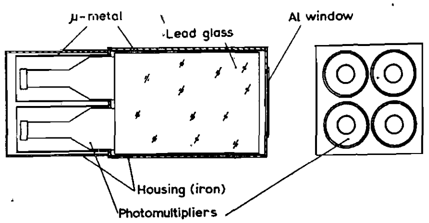


Fig.4. A schematic diagram of the Cherenkov lead-glass spectrometer. The radiator dimensions are 18x18x30 cm³. The radiation length is 2.5 cm. The energy resolution, R *for 4 GeV electrons is 5% (HWHM).*

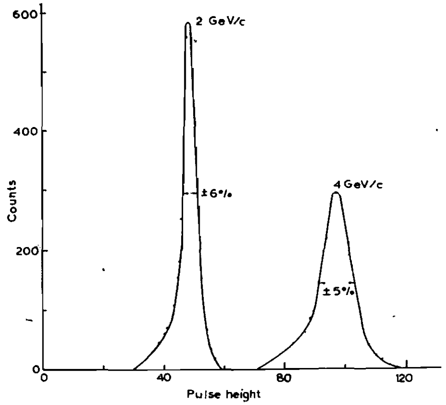


Fig.5. The amplitude spectra for 2 and 4 GeV electrons. The energy resolution is shown on the curves.

getic electron beam demonstrated a surprising result: over an energy range of 2-4 GeV the counter resolution was practically constant and very high (about 5%) (Figs. 4 and 5). The obtained data suggested that relatively small (7.2x7.2x12 rad. lengths) counters could be used for the spectrometry of γ-quanta with an energy of several GeV at a high energy resolution. These results opened up possibilities of constructing multichannel lead-glass hodoscopes.

A qualitatively new method /6/ proposed in 1964 permitted one to measure the effective mass of electromagnetic particles by means of spark chambers and lead-glass counters.

The operation principle of a γ-mass-spectrometer is very simple and based on the possibility of measuring simultaneously the direction and energy of electrons and γ-quanta. A high accuracy in measuring the energy and the possibility of identifying the nature of the electromagnetic particles in lead-glass are important when very rare processes are under study. The development of this method and the construction of a high-efficiency detector, i.e., a two-arm Cherenkov mass-spectrometer /7/, made it possible to carry out a series of complicated experiments to prove the existence of rare electromagnetic decays of ρ° and ϕ-mesons into electron-positron pairs and to measure their partial widths /8/.

The partial widths "vector meson-lepton pair" is directly related to the transition constants "photon-vector meson" that are of fundamental importance in the vector dominance model and its numerous applications. This mass-spectrometer allowed one to observe the structure in the differential cross section of the reaction $\pi^- p \to \eta^{\circ} n$ at $-t < 0.1$ $(GeV/c)^2$ /9/, to establish the

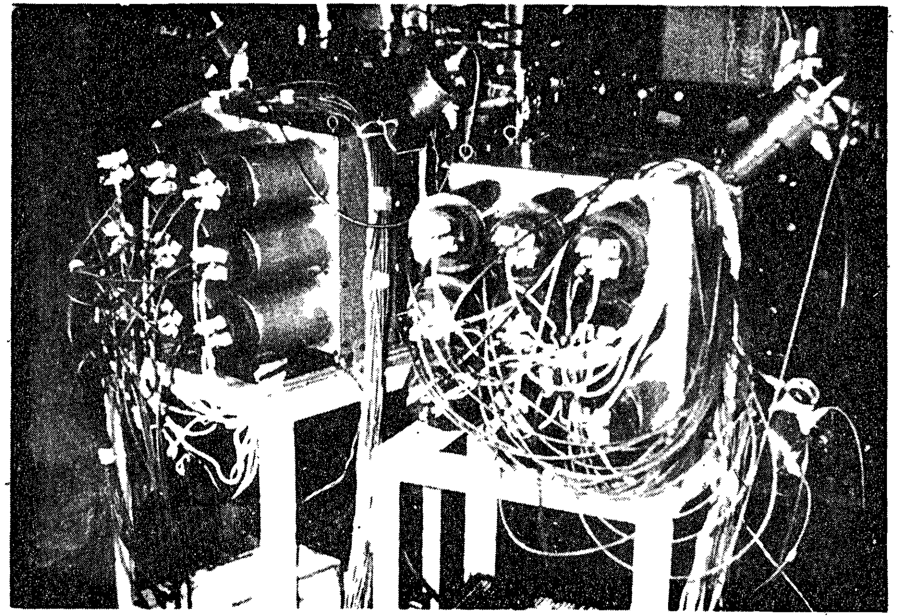
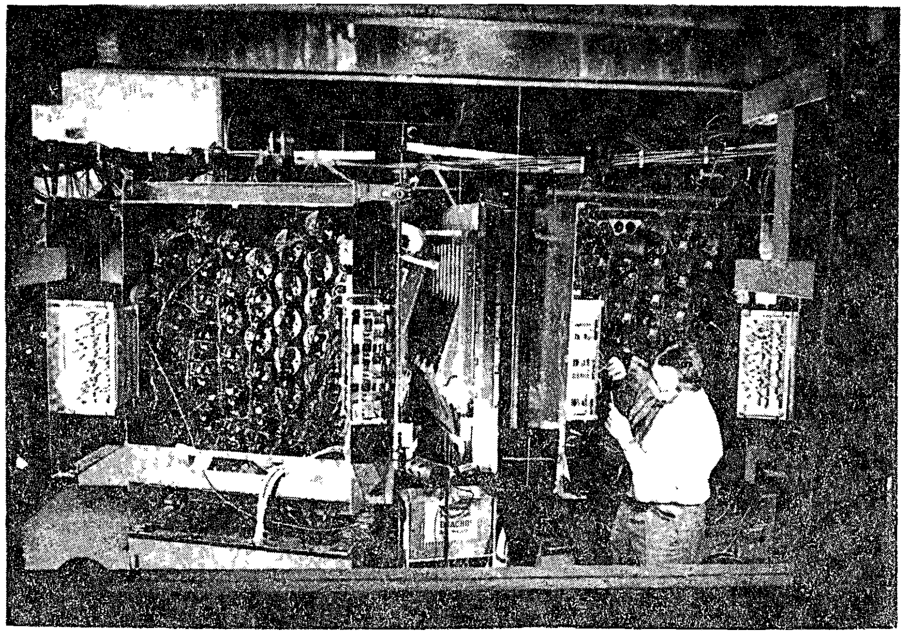


Fig.6. The two-arm lead-glass γ-mass-spectrometer. The radiator is 50x50x30 cm³ in size. The radiation length is 2.5 cm. The energy resolution for 4 GeV electrons is 5% (HWHM).

existence of η' (958)-meson decays into two γ-quanta and to measure their relative probability /10/.

To search for heavy vector mesons, in 1967 we proposed a multichannel Cherenkov lead-glass mass-spectrometer which can be considered as a second generation of mass spectrometers. The new set-up (Fig.7a,b) consists of 90 lead-glass modules /11/. The use of new optical high-transparency glasses, photomultipliers with high sensitivity, new technical aids and materials made it possible to increase significantly the energy resolution R of lead-glass counters. For example, for electrons with an energy of 4 GeV R = 2.3% (HWHM).

The set-up includes: 1. beam detectors composed of scintillation counters and proportional chambers; 2. γ-quantum detectors composed of 32 wire spark chambers with magnetostrictive information readout. The total number of wires is 64000. The wire chambers are separated into two identical arms of 16 chambers. The chambers are grouped in four: in order to remove ambiguities in the correlation of sparks between different planes, two of them turn through an angle of 17°. Copper converters 1.2 rad lengths in thickness are placed between the groups of chambers, and their



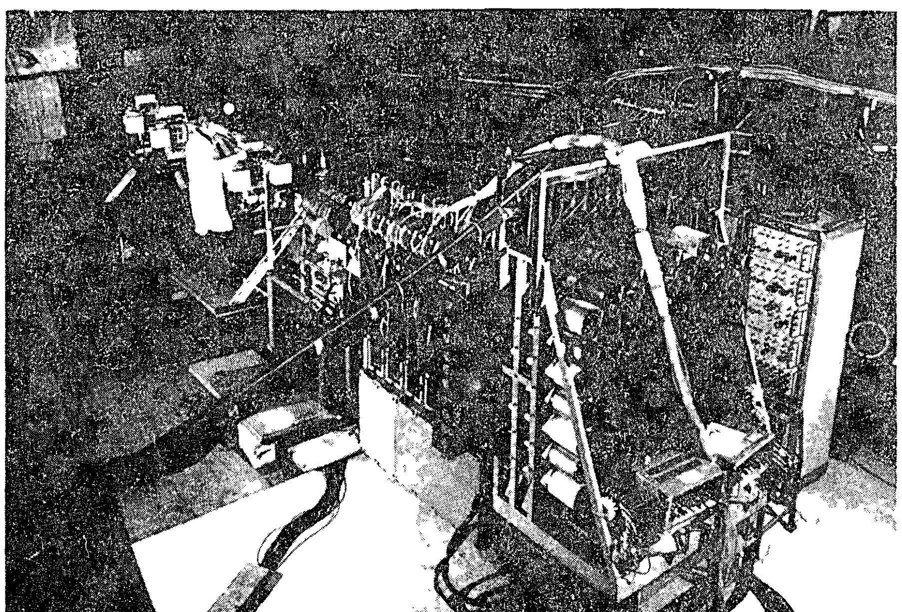


Fig.7. The hodoscopic Cherenkov γ-mass-spectrometer. The hexagonal module is 35 cm deep. The radiation length is 2.5 cm. The energy resolution for 4 GeV electrons is 2.3% (HWHM).

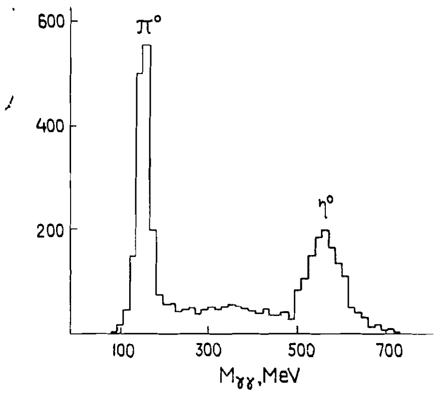


Fig.8. The effective mass spectrum for 2γ events measured by means of the hodoscopic Cherenkov γ-mass-spectrometer.

thickness is a compromise between detection efficiency and angular resolution. The direction of γ-quanta is measured by a group of 4 chambers positioned directly after the converter in which γ-conversion occured. The first group of 4 chambers from a target is used for γ-quantum identification.

Four identical scintillation fodoscopes, each consisting of 10 elements 100 cm long and 10 cm wide, oriented in the horizontal and vertical planes, are placed between the wire chambers and Cherenkov γ-spectrometers.

The lead-glass counters for γ-ray energy measurements consist of 90 hexagonal prisms 14 radiation lengths deep, each viewed by a 17 cm phototube. The counters are grouped in 45 in each of the two arms. The set-up operates on-line with a computer. The effective mass distribution of 2γ events measured by the γ-mass-spectrometer is presented in Fig.8.

A series of experiments has been performed using the multichannel γ-mass-spectrometer. Among them the following experiments should be noted:

1. The measurement of the differential cross sections of the reaction $\pi^- p \rightarrow \eta^\circ n$ from 3 to 5 GeV in the region of momentum transfers from 0 to 0.3 $(GeV/c)^2$. In the differential cross sections an appreciable minimum was observed in the forward direction (having confirmed the data obtained previously /9/) indicating a significant role of the amplitude with changing helicity /13/.

2. The measurement of the differential cross sections of η-meson production by π^-'s on different nuclei which allowed one to measure the interaction cross section between η-mesons and nucleons for a momentum of 3.3 GeV/c /14/.

3. The study of cumulative π°-meson production at an angle of 180° in the reaction $\pi^- C \rightarrow \pi^\circ(180^\circ) X$ for 3.8 GeV/c. Experimentally the value of $\langle Q \rangle$ was found to be 0.16 ± 0.01 ($\langle Q \rangle$ is the average number of nucleons in the cumulative volume). This fact was an independent support of a striking universality of the parameter $\langle Q \rangle$ describing the quark-parton structure functions of nuclei /15/.

Increasing the number of spectrometric channels, using filmless readout chambers instead of optical spark chambers and computers, the possibilities of the method of Cherenkov gamma-mass-spectrometers were considerably extended. However, these advantages could not get rid of a variety of grave difficulties. In fact, in order to detect γ -quanta by means of spark chambers, it is necessary to use converters the total thickness of which is limited by the requirement for high energy resolution. For 10 GeV γ-quanta this thickness is not larger than one radiation length [16]. In this case the conversion efficiency of the mass-spectrometer is proportional to $\epsilon_k \sim (0.5)^n$, where n is the number of γ-quanta. Large errors in measuring decay angles of γ -quanta which are due to bremsstrahlung of conversion pairs and multiple scattering are another consequence of using converters. It should be emphasized that spark chambers in similar devices have large longitudinal dimensions and a dead time of the order of milliseconds which has an essential influence on the geometric efficiency and fast operation of the mass-spectrometer.

Due to these disadvantages, the problem of construction of γ -mass-spectrometers without spark chambers is of great interest. This problem is complicated because the coordinate of particles should be measured with an accuracy comparable to that achieved by means of modern chamber technique.

In 1972 we proposed one of the solutions of this problem - a cell structure γ -spectrometer consisting of a large number of independent spectrometer-modules of small transverse dimensions [17].

The first question which should be answered can be formulated as follows: what transverse dimensions must the module of the γ -spectrometer have in order to measure the γ-quantum coordinates with an accuracy of ~ 1 mm? The character of the transverse electromagnetic shower development for electrons with an energy of 1 GeV shows that the radius of the shower is weakly dependent on energy and is equal approximately to $1X_m$, where X_m is a Moliere unit. If the transverse dimensions of the spectrometer module satisfy the condition $D_m/D_s < 1(1)$, where D_m and D_s are respectively the module and electromagnetic shower diameters, the shower energy is distributed in the module group. The analysis of the energy distribution between the modules in the group permits the γ-quantum coordinate to be localized by measuring the shower center of gravity. However, a detailed consideration of the problem indicates that in addition to (1) it is necessary to fulfil the second condition: the energy resolution of the spectrometer and hence of each module must be sufficiently high so that the energy difference in a module may exceed measurement errors due to small shifts of the shower axis. The Monte-Carlo method was used for qualitative estimates. This method

made it possible to determine errors in measuring the γ-quantum coordinates $(\Delta X, \Delta Y)$ in the spectrometer versus

1) the module size "D_m";
2) the coordinates "X,Y" of the γ-quantum entry point to the spectrometer;
3) the γ-quantum incident angle "θ" (angle between the γ-quantum direction and the module axis);
4) the energy resolution "$\Delta E/E$" of the γ-spectrometer.

The Monte-Carlo results have shown that the γ-quantum coordinates and direction can be measured with an accuracy of $\Delta X = \Delta Y = \pm 0.5$ mm and $\Delta\theta = \pm 0.5°$, respectively, for the module 1.2 rad. units in diameter if $\Delta E/E = 2.5\%$.

These ideas forming the basis of γ-mass-spectrometers of the third generation have been realized in a series of experimental developments both in USSR and abroad [18].

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