PRODUCTION OF QUASI-MONOCHROMATIC POLARIZED BREMSSTRAHLUNG FROM A SINGLE CRYSTAL OF SILICON *

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After the pioneering work of Panofsky and Saxena (1), and Frisch and Olson (2), the group at Frascati has carried out a series of important studies on the interference effects in bremsstrahlung first predicted by Überall in 1956 (3). The fine structure (4) and the polarization (5) due to the interference have been measured when the incident angle of electrons with a row of atoms in crystal satisfies the following conditions [m (electron) = c = h = , is used through-out this paper):

$$\varphi_n = \frac{1}{n}\frac{a}{4\pi\sqrt{2}E_1}\frac{k}{E_2} \quad (\varphi_n \ll 1,\ n = \pm 1, \pm 2, ...) \qquad [1]$$

Here E_1, E_2 and k are energies of the primary, scattered electron, and of the emitted photon, respectively. The angle φ is referred to the [110] axis in a (001) plane of a diamond-like crystal having lattice constant a.

We have studied the interference effect in bremsstrahlung from a single crystal of silicon; a preliminary result has been reported and details of the present study will be published elsewhere (6). Our main purpose was to investigate the possibility of producing a quasi-monochromatic polarized γ-ray beam for nuclear experiments. The electron synchrotron in the Institute for Nuclear Study, University of Tokyo, was used at about 700 MeV.

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1. EXPERIMENTAL PROCEDURE

A silicon crystal of high purity was exposed to the internal beam of the 750 MeV electron synchrotron. The crystal was produced by a floating zone method. A flat specimen 1 mm × 8 mm × × 10 mm was cut with a face parallel to the (110) plane. Using an X-ray spectrometer the crystal was set in its holder with an accuracy of 0.15 mrad. It was then mounted in a remotely-controlled double goniometer placed in a straight section of the synchrotron. The electrons, spiralling in when the r.f. voltage was turned off, cut across one of its edges, approximately in the [110] direction. Before the experiments, the normal position of the crystal axes with respect to the electron beam where established with an accuracy of 1 mrad. The sensitivity of a rotation angle in the goniometer is lower than 0,1 mrad. A backlash of gear wheels ~ 0.1 mrad is eliminated by unidirectional measurements.

2. INTENSITY SPECTRA

The intensity spectra were measured using a pair spectrometer for two cases: as a function of photon energies produced (Fig. 1), and as a function of the incident angle of electrons with respect to the crystal axis (Fig. 2). For a fixed incident angle, the intensity peak is at

$$k_n = E_1 \frac{4\pi\sqrt{2}\, n\, \varphi\, E_1}{a + 4\pi\sqrt{2}\, n\, \varphi\, E_1} \quad (n = 1, 2, \ldots) \qquad [2]$$

corresponding to [1]. The measured intensities were normalized to that of a hard part of the radiation where the interference effect is negligible. The fine structure up to $n = 4 \sim 6$ was observed.

The cross section of bremstrahlung from a single crystal has been calculated by Überall (3) and Barbiellini and others (4). The result is

$$\frac{\partial\sigma}{\partial k} = \frac{\partial\sigma^c}{\partial k} + \frac{\partial\sigma^i}{\partial k} \qquad [3]$$

$$\frac{\partial\sigma^c}{\partial k} = N\frac{Z^2 e^6}{k}\left\{\left(1 + \frac{E_2^2}{E_1^2}\psi_1^c\right)(\delta) - \frac{2E_2}{3E_1}\psi_2^c(\delta)\right\} \qquad [4]$$

$$\frac{d\sigma^i}{\partial k} = N\frac{Z^2 e^6}{k}\left\{\left(1 + \frac{E_2^2}{E_1^2}\psi_1^i\right)(\delta,\varphi) - \frac{2E_2}{3E_1}\psi_2^i(\delta,\varphi)\right\} \qquad [5]$$

where $\delta = k/2E_1E_2$ is the kinematically allowed minimum momentum transfer, and N the number of atoms in the crystal. $\psi_{1,2}^c(\delta)$ depend on the δ's only, not on φ (3). The interfering part is given by

$$\psi_1^i(\delta,\varphi) = \frac{(2\pi)^2}{a^3}\sum_{\vec{q}=\vec{b}} \exp(-Aq^2)\,S(\vec{q})\cdot 4\delta\,\frac{q^2}{q_1^2\varphi^2}\,\frac{[1-F(\vec{q})]^2}{q^4} \qquad [6]$$

$$\psi_2^i(\delta,\varphi) = \frac{(2\pi)^2}{a^3}\sum_{\vec{q}=\vec{b}} \exp(-Aq^2)\,S(\vec{q})\cdot 24\,\delta^2\,\frac{q^2(q_1\varphi-\delta)}{q_1^4\varphi^4}\,\frac{[1-F(\vec{q})]^2}{q^4}, \qquad [7]$$

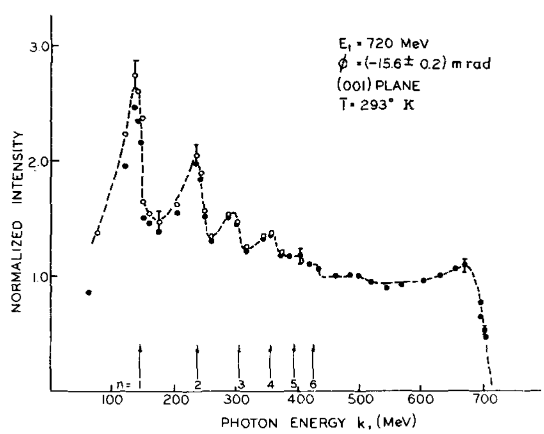

Fig. 1 - Intensity vs. photon energy.

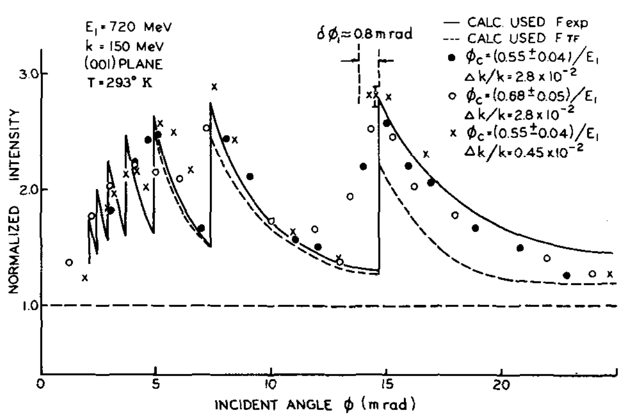

Fig. 2 - Intensity vs. incident angle of electron.

where $\vec{q}$ is the momentum transfer to atoms in the crystal (q_1 the component along the [001] axis), $S(\vec{q})$ is the structure factor, and $F(\vec{q})$ is the atomic form factor of the crystal. The summations are extended over $\vec{q}$'s, which are equal to a reciprocal lattice vector, $\vec{b}$, with a condition $q_1\varphi \geq \delta$. Assuming for silicon that $a = 5.43$ Å, Θ_D (Debye temperature) = 685°K; and A (Debye-Waller constant at room temperature) = 266, one obtains the theoretical normalized intensity in Fig. 2. It should be noted that the calculated values for a small momentum transfer are sensitive to the choice of the atomic form factor; good agreement is obtained if one uses the form factor determined by X-ray diffraction (7), but not if that of a Thomas-Fermi type is used. The correction due to the inelastic process by atomic electrons is to be less than a few percent of the calculated values.

3. POLARIZATION

The polarization has been measured at 105 MeV photon energy produced by 650 MeV electrons. The measuring method is similar to that of Barbiellini and others (5), i.e. pair spectroscopy employing narrow slit counters to observe the angular distribution of one branch of symmetric pairs (Fig. 3). The (001) plane of a silicon crystal is set in a horizontal plane, and the [110] axis is rotated through a small angle φ with respect to incident electrons. The photon beam passed through an evacuated tube is converted to electron-positron pairs in an Al converter of 7μ thickness. After the energy is analyzed, pair particles of 52.5 MeV are detected by counter telescopes S1 (S1') + S2 + S3 (vertical distribution) and S4 + S5 + S6 (total number). The scintillators S1 and S1' are slit counters having a vertical width of 4 mm each, and define the height of positrons; the distance between them is changed.

Numerical calculations on the measured asimmetry ratio and the polarization of photons will be reported elsewhere (6). Measurements where made for a few typical values of the incident angle φ, and normalized at $\varphi = 0$. Figure 5 shows the results with the theoretical curves obtained from the relation (5).

$$P \frac{\partial\sigma}{\partial k} = N \frac{Z^2 e^6}{k} \frac{2E_2}{E_1} \Psi_3^0(\delta, \varphi) \qquad [8]$$

where

$$\Psi_3^0(\delta, \varphi) = \frac{(2\pi)^2}{a^3} \sum_{\vec{q}=\vec{h}} \exp(-Aq^2)\, S(\vec{q})$$

$$4\,\delta^3 \frac{q_2^2 - q_3^2}{q^4 q_3^4} [1 - F(\vec{q})]^2 \,. \qquad [9]$$

A qualitative agreement is obtained between experiment and theory; the errors in measurements are only statistical ones. A negative polarization obtained for a small φ (~ 3 mrad) is reasonably related to the observed fine structure of $n = 3$ or 4 in the intensity spectra, while the previous measurement (5) gave almost zero polarizations for $\varphi \lesssim 6$ mrad.

4. DISCUSSION OF THE POSSIBILITY OF OBTAINING QUASI-MONOCHROMATIC γ RAYS

a. Coherent Path Length

To explain the interference effect in bremsstrahlung, several authors (9) have pointed out that an idea of the length of the essential interaction region is useful; the length is frequently called the "coherent path length" and is given by

$$l = \frac{1}{\delta} = \frac{2E_1 E_2}{k} \,. \qquad [10]$$

For analysis of the fine structure observed, another characteristic length will now be introduced.

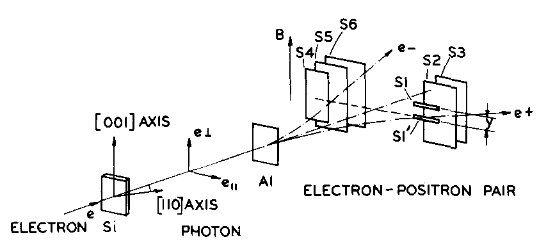

Fig. 3 - Schematic diagram of polarization measurement.

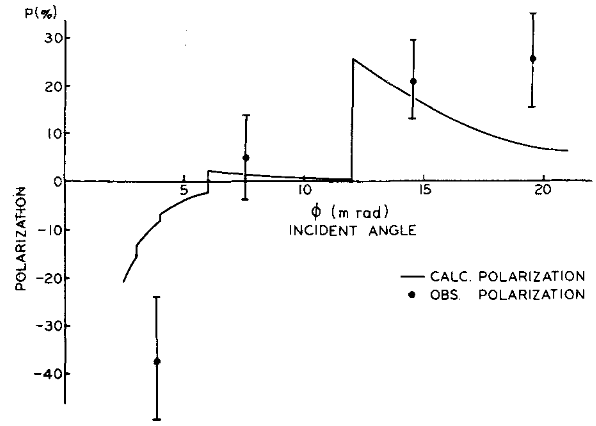

Fig. 4 - Polarization vs. incident angle of electron.

In a classical picture, the fine structure is explained as the interference which occurs when the electron incident at a small angle with a row of atoms runs across the next row after traveling the length, nl. In order that the fine structure can be clearly observed, the « coherent » interaction must continue in a region longer than nl. The new length of coherent interaction will probably be determined by the lattice defects in a crystal or the multiple scattering of electrons passing through the crystal. The coherent interaction is attributed to the recoil momentum transfer into the crystal "as a whole" as well as in the X-ray and electron diffraction, or the Mössbauer effect.

The new "effective coherent length" can be evaluated from the finite slope of a cut-off in the observed intensity spectra. In and ideal case, the interference effect should be cut off discontinuously at k_n or φ_n, as shown in the theoretical curve in Fig. 2. The finite slope observed comes partly from the experimental conditions; the finite resolution of the pair spectrometer, the angular divergence or the energy spread in the incident electron beam. However, its limit will be determined by the effective coherent length in a crystal discussed above. Using the value of $\delta\varphi_1$ in Fig. 2, one can obtain a lower limit of the number of rows coherently interacted thus

$$n_c > \left| \frac{k_1}{\delta k_1} \right| = \frac{E_1^2}{k_1 E_2} \frac{\varphi_1}{\delta\varphi_1} = 1.1 \times 10^2$$

and the corresponding effective coherent length

$$l_c = \frac{a}{\sqrt{2}\,\varphi_1} n_c \geq 2 \times 10^{-4}\,\text{cm} \,.$$

b. Effect of Photon Beam Collimation

Mozley pointed out (8) that if one selects a small angular interval of the coherent bremss-

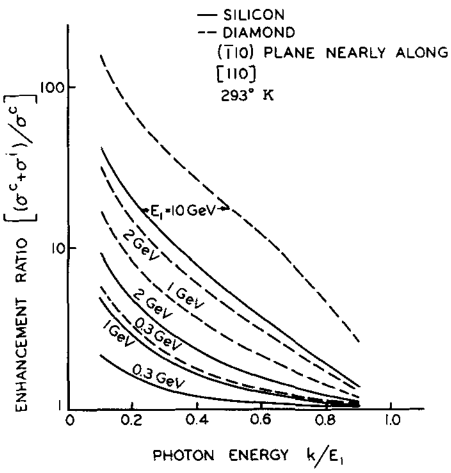

Fig. 5 - Enhancement ratio at the first peak calculated for silicon and diamond.

trahlung one should be able to change the fine structure observed into very narrow spikes and hence obtain essentially monochromatic bremsstrahlung. In the intensity vs. φ curves in Fig. 2, the width of the n^{th} spike $\Delta\varphi_n$ will be given by

$$\Delta\varphi_n \approx \varphi_n (\theta_c E_1)^2 \qquad [11]$$

where θ_c is the collimater angle.

We checked this effect in the present experimental condition; the normalized intensity was measured at $\varphi = (16.5 \pm 0.2)$ mrad for $\theta_c = 0.7 \sim \sim 0.1/E_1$ ($\varphi_1 \approx 14.7$ mrad and corresponding $\Delta\varphi_1 = = 0.15$ mrad for $\theta_c = 0.1/E_1$). No appreciable change could be observed in the measured intensity corresponding to the change in θ_c. This is attributed to the effect of angular divergence in the incident electron beam or to multiple scattering of electrons in the crystal.

c. Temperature Effect

As a possibility to reduce the continuous background in the spectra, low crystal temperatures may be preferable. A calculation shows that, by lowering the temperature to 77°K from 293°K, one can obtain about ten percent increase of the normalized interfering parts both for the intensity and the polarization.

d. Direction of Incident Beam and Comparison Between Silicon and Diamond

It has been suggested by Schiff (10), Barbiellini and others (4), that for a diamond-like crystal the [110] direction for the electron beam is to be preferred to either the [100] or [111] directions. Then two typical cases are possible when the electron lies on the (001) plane or on the (110) plane. From a phenomenological consideration and a numerical calculation, we can show that the intensity enhancement will be larger in the former case and the polarization in the latter.

For a comparison between silicon and diamond, the enhancement ratio and the polarization calculated at the first peak are shown in Fig. 5 and Fig. 6. The intensity enhancement in diamond

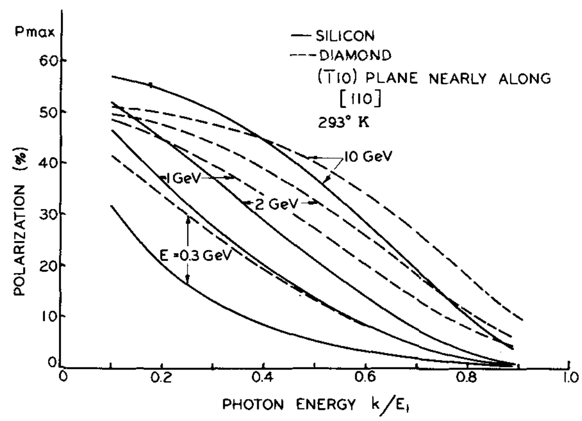

Fig. 6 - Calculated polarization for silicon and diamond.

is a few times stronger than that in silicon, while no essential difference is observed for the polarization between both crystals.

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OPERATIONAL EXPERIENCE WITH THE CPS FAST EJECTION SYSTEM

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(Presented by B. Kuiper)

1. EPICS AND POSSIBILITIES

Since its installation in the CPS early in 1963 the fast ejection system has been in operation for more than two years and it is appropriate to review the experience gained in this period, particularly in view of sharing the beam between several experiments.

After its first functioning in May 1963 the system was almost continuously in operation during the months June through September in conjunction with the CERN enhanced neutrino beam (1).

The additional facility provided at the first installation, i.e. single bunch ejection proved extremely useful, since it provides clean, short proton bursts of accurately known intensity. This was put to use during the above mentioned period for emulsion studies of the neutrino parent spectrum behind the magnetic horn (2, 3).

An experiment on small angle p-p scattering (4) was performed in the same period, using the extracted beam near the horn.

Though it was initially intended to use the entire proton beam for the neutrino experiment, the possibility was soon realized of taking small percentages from the beam for slow or rapid target bursts during the acceleration cycle before ejection. It proved thus possible to perform one or two additional experiments, yet eject practically the full beam intensity.

A start was made late in 1963 with the study of a second mode of partial ejection, i.e. to leave one, two or three proton bunches in the machine for internal targetting. This entirely electro-magnetic scheme would yield a much cleaner way of sharing. It permits experiments necessitating small fractions of the CPS beam to run in parallel with greater consumers using the fast ejection, such as the neutrino experiment. Successful tests early in 1964 proved the principles of the scheme. The development was pursued for making the equipment fully operational.

Beam sharing during the neutrino runs in 1964 was done by targetting before ejection. These neutrino runs proved efficient as is illustrated by Table I, containing statistics of one of the last periods.

Valuable experience was gained in summer 1964 ejecting the proton beam at an energy of 12 GeV. This was subsequently used for the design of the fast extracted beam for the precision g-2 experiment (5) planned for 1965. Also for use in the same experiment a start was made with the design of a device permitting the extraction of one to five proton bunches, leaving the remainder undisturbed in the PS.

In the meantime development of the radio frequency separators was nearing its completion. These are modulated by 8 μs pulses and need short particle bursts, preferably from an external target. The east site ejection being only scheduled for 1965, the first r.f. separated beam was set up with a short burst from an internal target. A sophisticated scheme (6) was developed in test sessions during autumn 1964, involving the fast ejection kicker magnet, the actual beam target and three dump targets for protection of the ejection equipment from secondary radiation. This scheme has successfully operated during January through April 1965, serving the r.f. separated K^- beam (7, 8) for the British national hydrogen bubble chamber. In tre course of that run two additional targets were operated, taking a rapid and a slow burst from the beam before