Experimental study of γ-rays emitted during axial and planar channeling of electrons in silicon

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An experimental study is reported of γ-rays emitted by 10-GeV electrons channeled along the $\langle 111 \rangle$ axis and over (110) planes in a silicon single crystal, 41 μm thick. The orientation dependence of the emission probability and of the radiative energy loss by electrons is investigated. It is shown that the maximum spectral density due to planar channeling exceeds the bremsstrahlung spectral density from an amorphous target by a factor of 28. The corresponding factor in the case of axial channeling is 70.

INTRODUCTION

The theoretically predicted properties of the electromagnetic radiation emitted by relativistic channeled particles have stimulated extensive experimental studies of this phenomenon.[1–9] The most interesting data, obtained by modern experimental techniques, are reported in Refs. 5–9.

In this paper, we present the result of a study of γ-rays emitted by electrons channeled in single-crystal silicon, 41 μm thick. Preliminary data, obtained from a small proportion of the statistical material, were published in a previous paper.[8]

The experimental setup in this investigation is described in detail in Ref. 10. The coordinates of the electrons transmitted by the apparatus were measured by a system of drift chambers. This enabled us to determine the angles of incidence of the particles on the crystal and the angles at which the electrons left the crystal to within 7 and 30 μradian, respectively.

The momentum of electrons transmitted by the crystal was determined from the deflection they experienced in an analyzing magnet. The electrons were identified by total absorption Cerenkov counters.

The γ–ray energies were measured by a scintillation detector based on a CsI (T1) phosphor surrounded by a lead shield and by anticoincidence counters. The root mean square error in the measured γ-ray energy was about 1% at 100 MeV. The aperture of the collimator placed in front of the detector enabled us to determine the angles of emission of the γ-rays (relative to the direction of the primary electron) to within ± 1.3 mradian. Background bremsstrahlung was reduced to 5×10^{-4} radiation lengths by using cleaning magnets, by minimizing the amount of material in the scintillation counters, and by evacuating the working part of the apparatus.

The 10-GeV/c electron beam[11] had an angular divergence of about 1 mradian. The momentum spread in the beam was about $\pm 1.3\%$ and the hadron impurity was less than 0.5%. The data were processed to select events satisfying the conditions for the identification of electrons by the total-absorption Cerenkov counters and the conservation of energy in each interaction event.

§1. RADIATION PRODUCED DURING THE MOTION OF ELECTRONS AT SMALL ANGLES TO THE CRYSTALLOGRAPHIC AXIS

The crystal was oriented so that the $\langle 111 \rangle$ axis lay along the electron beam.

Orientation dependence of emission probability

The probability of emission of a photon by an electron depends on the polar angle of incidence of the electron relative to the crystallographic axis and the azimuthal angle. Figure 1 shows the distribution of events in which electrons emit a γ-ray of between 10 and 600 MeV. This distribution clearly illustrates the effect of the $\langle 111 \rangle$ axis and the (110) planes on the γ-ray emission probability.

Figure 2 shows the number of recorded γ-rays as a function of the polar angle of incidence of electrons relative to the $\langle 111 \rangle$ axis of the crystal for different ranges of γ-ray energy. These distributions are shown in units of the crystal length, and each point is normalized to the number of electrons within the solid angle corresponding to the interval of polar angles of incidence. It is clear from the figure that the γ-ray yield is a maximum for channeled electrons ($\theta_{in} \leqslant 130\,\mu$radian). For "over-barrier" electrons ($\theta_{in} > 130\,\mu$radian), the γ-ray yield is much lower.

In the energy range $0.01 \leqslant E_\gamma \leqslant 3$ GeV, the maximum yield is about 30 γ-rays for each centimeter of the crystal. The effect of the crystal axis on the γ-ray yield remains significant for angles of incidence up to 400 μradian. The emission level remains constant at large angles and is largely determined by planar channeling of electrons. High-energy γ-rays ($2 \leqslant E_\gamma \leqslant 3$ GeV, Fig. 2) constitute an exception. For them, the emission probability is practically independent of the angle of incidence of the electron.

Comparison with data obtained for positrons of the

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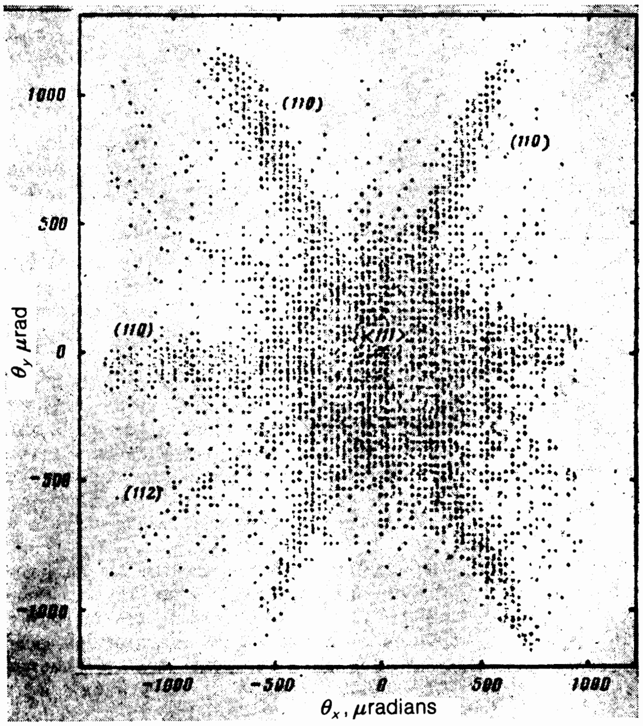

FIG. 1. Distribution of events accompanied by the emission of γ-rays with energies between 10 and 600 MeV for different angles of incidence of electrons on the crystal. θ_x and θ_y are the projections of the polar angle of incidence onto the abscissa and ordinate axes in a Cartesian coordinate frame.

same energy[9] shows that there are differences in the dynamics of electrons and positrons during axial channeling. Thus, the maximum γ-ray emission probability is reached for electron angles of incidence on the crystal close to zero (15–20 μradian, Fig. 2), whereas for positrons the maximum probability occurs at angles close to the critical value.[9] This is explained by the fact that, for near-zero angles of incidence, the electron can approach the axis in the region of high field gradients, whereas for positrons this occurs for angles of incidence close to the critical value.

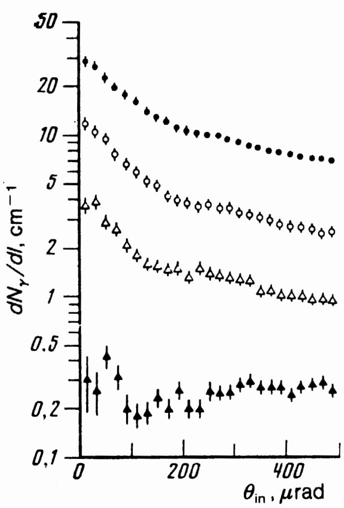

FIG. 2. Number of recorded γ-rays as a function of the polar angle of incidence of electrons on the crystal for different ranges of γ-ray energy E_γ (GeV): ●—0.01–3.0; ○—0.1–0.4; △—0.6–1.2; ▲—2.0–3.0.

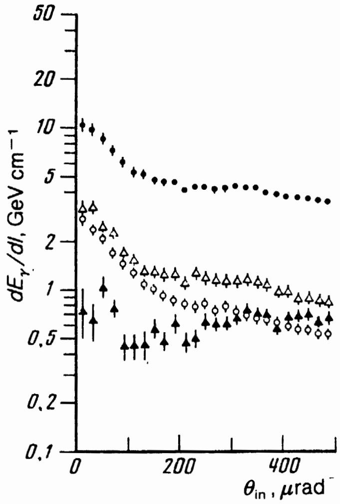

FIG. 3. Radiative energy loss by electrons as a function of the polar angle of incidence on the crystal for different γ-ray energy ranges. The energy intervals corresponding to the respective points are the same as in Fig. 2.

Radiative energy loss by electrons

Figure 3 shows the measured radiative energy loss by electrons as a function of the polar angle of incidence on the crystal. The curves were obtained under the same conditions as in Fig. 2.

We note that the maximum total radiative loss by elec-

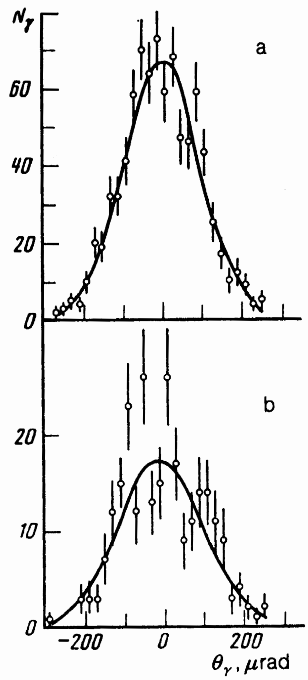

FIG. 4. Distribution of events in angle of escape of γ-rays from the crystal for electrons with polar angles of incidence less than 120 μrad relative to the ⟨111⟩ direction: $0.1 < E_\gamma < 0.5$ GeV (a) and $0.6 < E_\gamma < 1.1$ GeV (b).

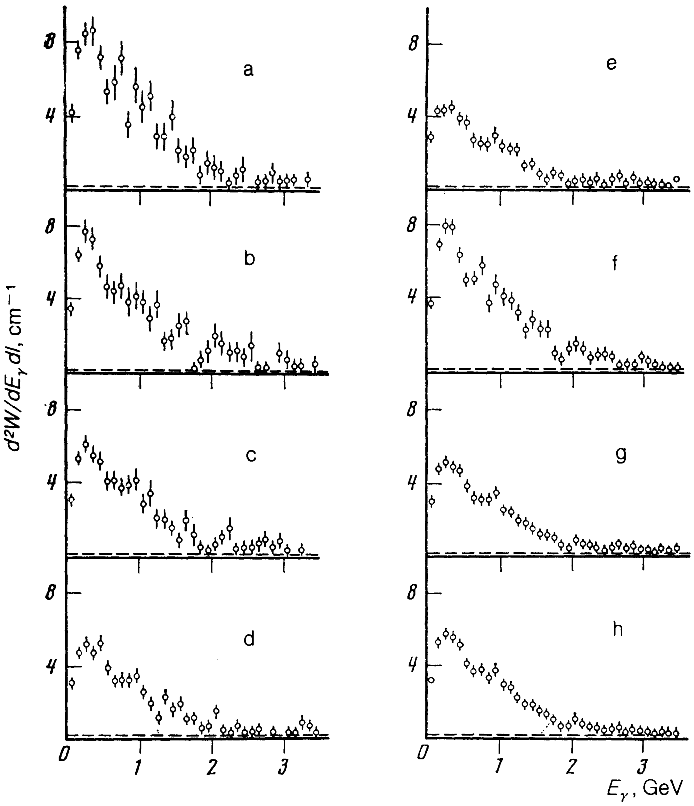

FIG. 5. Spectral density of emitted radiation as a function of the γ-ray energy for different angles of incidence θ_{in} (μrad) of electrons on the crystal: a—0–40; b—40–60; c—60–80; d—80–100; e—100–120; f—0–60; g—60–120; h—0–120.

trons can amount to about 10 GeV/cm. If we select events for which $0.1 \leqslant E \leqslant 0.4$ GeV, the maximum radiative loss amounts to about 2.8 GeV in each centimeter of the crystal in the case of channeled electrons. The energy lost by over-barrier electrons ($130 \leqslant \theta_{in} \leqslant 400$ μrad) is then about 600–900 MeV/cm.

Angular distribution of γ-rays

Figure 4 shows the distribution in angles of escape of the γ-rays from the crystal for electrons with polar angles of incidence $\theta_{in} \leqslant 120$ μradian relative to the $\langle 111 \rangle$ direction. We measured the vertical projection of the angle of emission of γ-rays onto the horizontal plane, obtained by reconstructing the point of conversion of the γ-ray into an electron-positron pair in the drift chamber with a built-in converter. The $\langle 111 \rangle$ direction was then in the horizontal plane. The solid curve shows the approximate representation of the experimental data by a Gaussian curve. For events with $0.1 \leqslant E_\gamma \leqslant 0.5$ GeV, the root mean square deviation σ is 105 ± 8 μradian, whereas for events with $0.6 \leqslant E_\gamma \leqslant 1.1$ GeV we found that $\sigma = 115 \pm 12$ μradian. It is clear from the figure that γ-rays emitted by axially channeled electrons are scattered into a cone with an angular aperture approximately equal to the critical angle for channeling, which is somewhat wider than the bremsstrahlung angle in an amorphous body of the same thickness.[12]

Spectral density of radiation

Figure 5 shows the spectral density of the emitted radiation as a function of γ-ray energy for electrons corresponding to different ranges of angles of incidence. These distributions were also normalized to the crystal thickness and the number of electrons in the corresponding range of angles of incidence. The broken lines represent the spectral density of bremsstrahlung from an aluminum target.

These data illustrate the dependence of the spectral density of emitted radiation on the angle of incidence of the electron on the crystal. Electrons with angles of incidence $\theta_{in} < 40$ μradian produce the strongest emission.

The spectral density maximum occurs at photon energy of about 250 MeV and exceeds the radiation density in an amorphous body by a factor of about 70. We note that, in the case of axial channeling of electrons, the spectral density

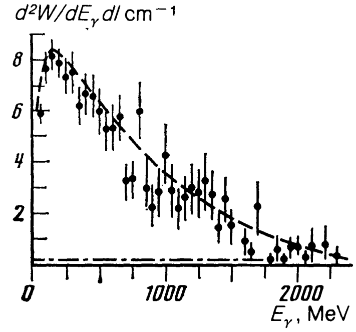

FIG. 6. Spectral density of emitted radiation for 10-GeV electrons.[8] Broken line—calculations.[17] Dot-dash line—radiation from an aluminum target of equivalent thickness. The specimen was Si$\langle 111 \rangle$, 41 μm thick, $\theta_{in} \leqslant 100$ μradian.

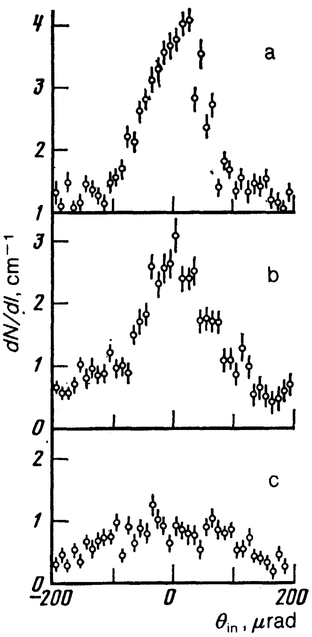

FIG. 7. Number of recorded γ-rays as a function of the angle of incidence of electrons on the crystal relative to the (110) plane for different ranges of the γ-ray energy E_γ (GeV): a—0.1; b—0.1–0.25; c—0.25–0.4.

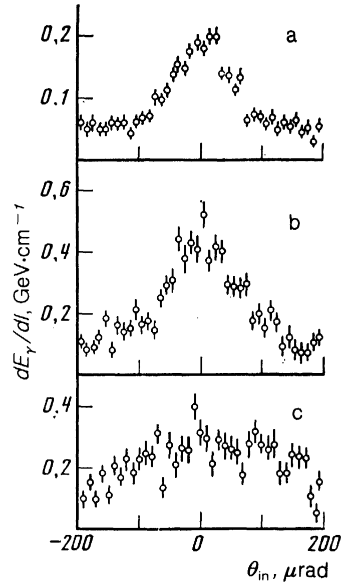

FIG. 8. Radiative energy loss by electrons as a function of the angle of incidence relative to the (110) plane for different ranges of the γ-ray energy E_γ (GeV): a—≤0.1; b—0.1–0.25; c—0.25–0.4.

distribution is wider (by a factor of about 3) and twice as high (at maximum) as the analogous distributions for positrons.[9]

The data obtained in the present paper are in qualitative agreement with the theoretical predictions developed in Refs. 13–17. The analytic methods developed in these papers for determining the spectral density of the emitted radiation are based on model descriptions and do not take into account certain features of the actual average potential of the crystal-

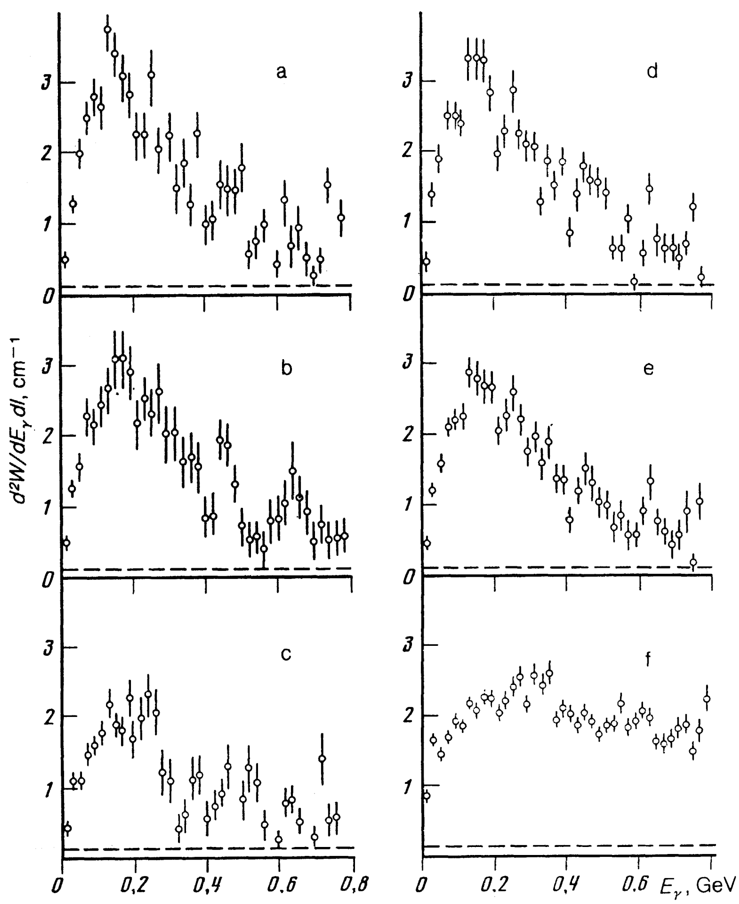

FIG. 9. Spectral density of emitted radiation as a function of the γ-ray energy for different ranges of the angle of incidence θ_{in} (μradian) of electrons on the crystal relative to the (110) plane: a—0–20; b—20–40; c—40–60; d—0–30; e—0–60; f—0–1000.

lographic axes, for example, its asymmetry. Still greater difficulties are encountered when the experimental conditions are taken into account. Data on the spectral density of radiation by 10 GeV electrons, obtained by modeling the trajectories in the real average potential of the crystal axes,[17] are in good agreement with experimental data (Fig. 6).

§2. RADIATION EMITTED BY ELECTRONS UNDERGOING PLANAR CHANNELING

There are practically no experimental data on the electromagnetic radiation emitted by ultrarelativistic electrons undergoing planar channeling. The problem was examined theoretically in Refs. 13, 18, 19, and 21. In the present paper, we present an experimental study of the radiation emitted by 10-GeV electrons moving in (110) planes.

The crystal was oriented so that the (110) plane was parallel to the direction of the beam. The misorientation relative to the $\langle 111 \rangle$ axis was 0.5°. The angles of incidence (escape) of electrons on the crystal were measured relative to the (110) plane. These angles were equal to zero when the (110) plane was parallel to the electorn velocity.

Orientation dependence and the radiative energy loss by electrons

Figure 7 shows the number of recorded γ-rays as a function of the electron angle of incidence on the crystal, relative to the (110) plane, for different ranges of the γ-ray energy. The length of the crystal is used as the unit of length and each point is normalized to the number of electrons in the corresponding interval of angles of incidence. It is clear from the figure that the orientation dependence of the photon yield is significant only for γ-ray energies below 250 MeV. The orientation effect is less well-defined at higher energies.

Figure 8 shows the measured radiation loss by electrons as a function of the angle of incidence on the crystal for the same γ-ray ranges as in Fig. 7. The distributions shown in Figs. 7 and 8 are similar. However, the number of γ-rays decreases with increasing γ-ray energy, whereas the energy lost by electrons is found to increase to some extent. Hence it follows that the average electron energy loss is almost constant in these γ-ray energy intervals, and amounts to 200 MeV/cm.

Comparison of the distributions given in Fig. 7 with the analogous data reported for positrons[20] shows that there is a difference between the dynamics of electrons and positrons undergoing planar channeling. For electrons, the distribution maximum occurs when the angle of incidence θ_{in} vanishes, whereas for positrons the distributions have two maxima which occur at angles of incidence close to the critical value for planar channeling (about 60 μradian at electron energy of 10 GeV).

Figure 9 shows the spectral density distribution of emitted radiation as a function of the γ-ray energy for different ranges of the angles of incidence of electrons on the crystal. The normalization used for these distributions is the same as for Fig. 7. (However, in Fig. 9f, the spectral density must be multiplied by 0.1, and the spectral density of bremsstrahlung from the amorphous target is 0.113 cm^{-1}.) The broken lines represent the bremsstrahlung spectral density due to an amorphous target of the same thickness. The strongest emission is produced by electrons with angles of incidence in the range $0 \leqslant \theta_{in} \leqslant 20$ μradian. In this case, the maximum spectral density occurs at γ-ray energy of 130 MeV. This radiation is 28 times strong as the bremsstrahlung radiation from the amorphous target. The data recorded at CERN for electrons undergoing planar channeling[7] show that the corresponding factor was 14. It has been pointed out[20] that this difference between our data and the CERN results is due to the poor angular resolution of the CERN installation.

The spectral density distribution (Fig. 9) is wider by a factor of about 3 than the analogous curves reported for positrons.[20] These differences are due to the different character of the interplanar potential for electrons and positrons.[13,19,21]

Angular distribution of γ-rays

Figure 10 shows the distribution in angles of escape of the γ-rays from the crystal for different intervals of the angle of incidence of electrons. We measured the vertical projection of the angle of escape of γ-rays relative to the (110) plane, arranged horizontally. The solid curves are the ap-

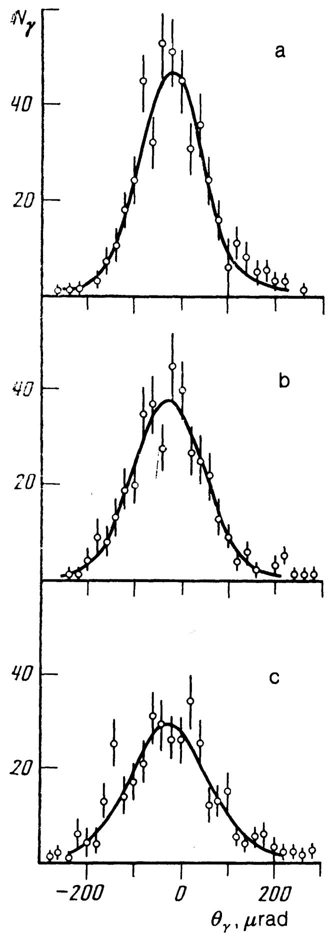

FIG. 10. Distribution of events over the angles of emission of γ-rays by the crystal for different ranges of the angles of incidence of electrons θ_{in} (μradian): a—<20; b—20–40; c—40–60.

proximate representations of the experimental data by Gaussian distributions.

The distributions of events corresponding to $\theta_{in} \leqslant 20$ μradian have the smallest width and, for them, the ms deviation σ was 75 ± 7 μradian. For $20 \leqslant \theta_{in} \leqslant 40$ μradian the deviation was $\sigma = 80 \pm 8$ μradian and, for $40 \leqslant \theta_{in} \leqslant 60$ μradian, the result was $\sigma = 86 \pm 8$ μradian.

CONCLUSION

Our experimental data refer to the radiation produced in the course of axial and planar channeling of 10 GeV electrons in a silicon single crystal 41 μm thick. We have presented the characteristics of the electromagnetic radiation for different angles of incidence of electrons on the crystal, and the data characterizing the radiative energy loss. The angular distributions of the emitted radiation are reported for the first time.

It is shown that the spectral density of the radiation emitted by electrons undergoing planar channeling exceeds the bremsstrahlung spectral density from an amorphous target by a factor of 28. In the case of axial channeling, the figure rises to 70. These data are in agreement with theoretical predictions.

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