

# Angular distributions of gamma radiation of 900-MeV electrons channeled in diamond and silicon

Yu. N. Adishchev, P. S. Anan'in, S. A. Vorob'ev, V. N. Zabaev, B. N. Kalinin, V. V. Kaplin, A. P. Potylitsyn, V. K. Tomchakov, and E. I. Rozum

*Scientific Research Institute of Nuclear Physics, S. M. Kirov Tomsk Polytechnic Institute*

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The angular distributions of strong  $\gamma$  radiation from 900-MeV electrons channeled in the diamond and silicon crystals were measured for the first time. The rotation of the particle beam by a bent crystal relative to the original direction, which was predicted by E. N. Tsyganov, was observed by using sharp directivity of the radiation.

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Recently, the strong electromagnetic radiation produced as a result of channeling of ultrarelativistic electrons in crystals has attracted a great deal of attention. According to Refs. 1–3, this new physical effect of electromagnetic radiation from the optical region to the gamma rays is due to radiative transitions between the energy levels (bands) of the transverse motion of fast electrons. The theoretical model,<sup>[4]</sup> which is similar to a wiggler, can give some characteristics of this radiation, although it does not reflect the essence of the physical process which is generally a purely quantum effect. Subsequently, this was taken into account.<sup>[5]</sup> In this paper we measured for the first time the angular distributions of  $\gamma$  radiation of 900-MeV electrons transmitted through diamond and silicon single crystals in the axial channeling mode. These results are needed to produce on the basis of the channeling effect a new source of powerful  $\gamma$  radiation for experimental nuclear physics and radiation technology.

The measurements were made in the internal electron beam of the Tomsk synchrotron for a 0.35-mm-thick diamond single crystal and 0.4-mm-thick silicon single crystal. The beam divergence in the target was about  $2 \times 2 \text{ mm}^2$ . The crystallographic axes  $\langle 110 \rangle$  for diamond and  $\langle 111 \rangle$  for silicon were matched with the direction of the electron beam according to the maximum of the total energy flux of  $\gamma$  radiation.<sup>[6]</sup> The crystal was oriented in two mutually perpendicular planes with an accuracy of 0.05 mrad. In the experiment we measured the two-dimensional distribution of the points of entry of the  $\gamma$  rays ( $x, y$ ) into the spark chamber (SC) located in the  $\gamma$ -ray beam. A single-gap SC with a  $160 \times 160 \times 20\text{-mm}^3$  working volume had wire electrodes with a winding pitch of 1.5 mm and a memory time of 3.5 msec. The information was collected by an optical method. To convert the  $\gamma$  rays to  $e^+e^-$  pairs, we used a 1-mm lead converter which was placed close to the SC electrode. The  $\gamma$  rays produced as a result of emission during channeling were separated from the ordinary bremsstrahlung photons by using a NaI(Tl) spectrometer located directly behind the SC. A  $200 \times 200\text{-mm}^2$  NaI(Tl) single crystal was used to record the total energy of the  $e^+e^-$  pair which almost coincides with the energy of the photon that produced this pair. To actuate the SC a signal was fed from the spectrometer to the differential discriminator, whose "window" was selected according to the investigated energy range. The energy resolu-

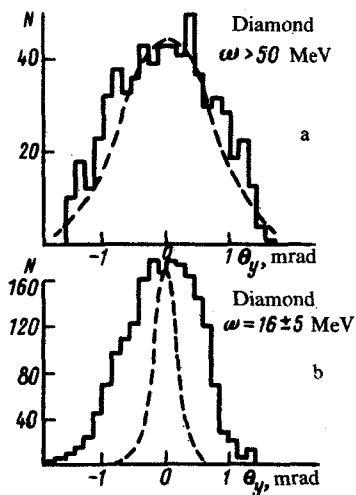


FIG. 1. Angular distributions of  $\gamma$  radiation of electrons in a  $\langle 110 \rangle$  diamond crystal with an energy  $\omega > 50$  MeV (a) and  $\omega = 16 \pm 5$  MeV (b). The dashed lines represent the results of calculations. The diamond is 0.35 mm thick.

tion of the spectrometer was  $\leq 10\%$  and the linear region was up to 130 MeV. The measurements were performed at an electron flux of  $10^4$ – $10^5$  particles/cycle. A scintillation counter was placed in front of the SC in order to suppress triggering by background particles.

The measurements showed that for axial channeling of 900-MeV electrons the intensity spectrum for a diamond has a maximum with phonon energies near  $\omega_0 = 16$  MeV, and for silicon  $\omega_0 = 12$  MeV. For  $\gamma$ -ray energies  $\omega > 50$  MeV the spectrum approaches the Schiff spectrum for bremsstrahlung. Therefore, the angular distributions were measured separately for the  $\gamma$  rays from the region of the spectrum peak and  $\omega > 50$  MeV.

Figure 1 shows histograms for the angular distributions in a diamond single crystal. In the experiment we measured the projected exit angles of  $\gamma$  rays  $\theta_x$  and  $\theta_y$  in the horizontal and vertical planes. It can be seen that the distribution of the high-energy  $\gamma$  rays is much broader than that of the  $\gamma$  rays with energy  $\omega = 16 \pm 5$  MeV, whose radiation is primarily due to electron channeling. The distribution in the horizontal plane is identical to that shown here.

The dashed line in Fig. 1a represents the result of calculation of the angular distribution of the  $\gamma$  rays of the 900-MeV bremsstrahlung electrons with an initial divergence of 0.3 mrad, which were transmitted through a target with a thickness of  $2.8 \times 10^{-3}$  rad. unit length.<sup>17)</sup> A good agreement between the calculated and experimental results confirms that the high-energy part of the  $\gamma$ -ray spectrum is due to ordinary bremsstrahlung. The dashed line in Fig. 1b represents the angular distribution of the  $\gamma$  rays, which was obtained within the framework of a simple quasi-wiggler model in the dipole approximation. A noticeable discrepancy with the experimental data can be partially eliminated by taking into account the nondipolarity of the radiation due to a certain relativity of the transverse motion of the channeling electrons, since  $k_D = \gamma\psi_c = 0.69$  (where  $\psi_c = 0.38$  mrad is the channeling angle and  $\gamma$  is a relativistic factor). For example, for a spiral wiggler<sup>(8)</sup> the harmonics in the radiation

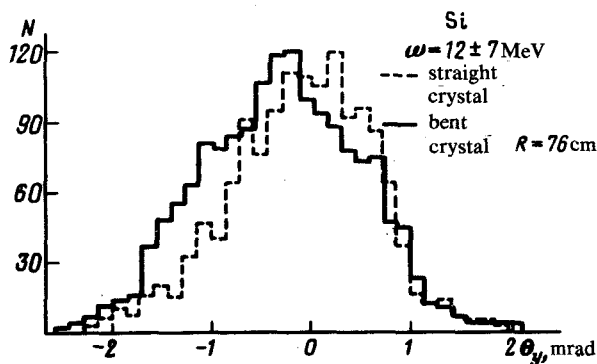


FIG. 2. Angular distributions of  $\gamma$  radiation of electrons in a  $\langle 111 \rangle$  silicon crystal with an energy  $\omega = 12 \pm 7$  MeV. The silicon is 0.4 mm thick. The broken line represents the straight crystal and the solid line represents the bent crystal with a radius of curvature  $R = 76$  cm.

higher than the first harmonic for a dipolarity criterion  $k_D = 0.72$  amount to 40% of the total radiation intensity and broaden by 60% the angular distribution along the half-width, since their maximum contribution at  $\theta > 0.5 \gamma^{-1} = 0.27$  mrad. We should note that the electrons moving in the above-the-barrier mode,<sup>[1,9]</sup> for which the angular distribution of the electron beam incident on the crystal is essential, can contribute significantly to the radiation picture for channeling. By recording relatively soft photons of the channeling part of the radiation, we can conceivably obtain a broader angular distribution, since the soft photons correspond to large exit angles. The broken line in Figs. 2 and 3 represents histograms of the angular distributions for silicon, from which it follows that the angular distribution of the high-energy  $\gamma$  rays is much broader than that of the  $\gamma$  rays emitted by channeling electrons.

We used the directional effect of radiation in channeling to observe a new physical effect—rotation of a relativistic-electron beam by a bent crystal, which was predicted for positive particles by É. N. Tsyganov.<sup>[10]</sup> In the case of axial channeling of electrons in a bent crystal, the electrons follow the bent atomic chains,<sup>[11]</sup> but since they can radiate photons in any part of the trajectory, the angular distribution of  $\gamma$  radiation is “smeared out” in the direction of the beam rotation. In addition, the

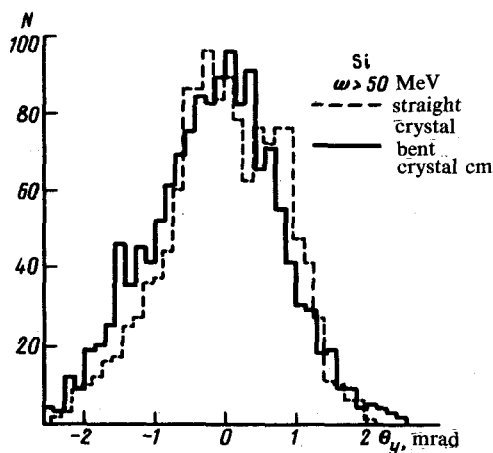


FIG. 3. Angular distributions of  $\gamma$  radiation of electrons in a  $\langle 111 \rangle$  silicon crystal with energy  $\omega > 50$  MeV. The silicon is 0.4 mm thick. The broken line represents the straight crystal and the solid line represents the bent crystal with a radius of curvature  $R = 76$  cm.

motion of electrons in a bent crystal is strongly influenced by dechanneling,<sup>[12]</sup> which also leads to smearing of the angular distribution of radiation. Thus, the angular distribution of radiation is the criterion for the beam rotation. The silicon plate (whose  $\langle 111 \rangle$  crystallographic axis made an angle of  $37^\circ$  to the normal of the crystal plane) was bent with a special device placed directly in the goniometer. The bending radius  $R = 76$  cm corresponded to the maximum rotation angle of the electron beam  $\theta_b \approx 0.5$  mrad. Figure 2 shows a histogram of the angular distribution of  $\gamma$  rays  $\omega = 12 \pm 7$  MeV, which corresponds to a bent crystal. As expected, there is a smearing of the angular distribution—the left slope of the distribution is broadened by about 0.3 mrad, which indicates that a fraction of the electrons are entrained by the bent lattice, and hence the channeled beam rotates relative to the initial direction. A similar histogram for the high-energy photons is shown in Fig. 3. No significant broadening is observed (which is attributable to the large contribution for the radiation of the dechanneled electrons); however, the center of the distribution is shifted by 0.15 mrad, which also indicates a rotation of the beam. The observed rotation effect can be used for guiding beams of charged particles. In addition, because of the narrow directivity of radiation during channeling, it is possible to focus and guide the  $\gamma$  radiation by controlling the motion of the particle beam by a deformed crystal shaped like a “crystal lens.”

In conclusion, we note that a charged particle moving in the averaged field of the crystalline planes or chains is capable of radiating electromagnetic quanta and other elementary particles. For example, if the intensity of the crystal field is about  $\mathcal{E} = 2m_0^3 c^3 / e\hbar\gamma$ , then at a distance  $\hbar/mc$  it will do work on the relativistic particle  $2m_0 c^2$ . At an average intensity of the field that guides the motion of the channeled particles  $\langle \epsilon \rangle = Ze^2/4 = (50\text{--}100)\text{V}/\text{\AA}$ , for example, the electrons may produce electron-positron pairs at an energy  $E_{\text{gr}} \sim 2m_0^3 c^5 \langle \epsilon \rangle^{-1} / e\hbar \sim 1$  GeV. The narrow directivity of the angular distributions of the yield is also characteristic for such particles, which is of practical interest. It is possible to effectively guide the beams of produced particles by elastically bending the crystal target. At sufficiently high energy of channeling electrons  $E > 5\text{--}10$  GeV, these effects can be observed experimentally.

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