Observation of anomalies in the spectrum and angular distribution of the γ-ray emission by ultrarelativistic electrons in thick crystals

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A new method has made it possible to measure the true spectrum and angular distribution of the γ-ray emission by high-energy electrons in thick crystals for the first time. Anomalies have been observed in the angular distribution of the hard γ emission during passage of an electron beam along a crystallographic axis through a silicon crystal.

1. The interaction of ultrarelativistic electrons with thick crystals oriented with a crystallographic axis along the beam direction is accompanied by a multiple production of γ rays, which are detected as a single γ ray with the total energy by the conventional detection methods.[1-3] The result is a serious distortion of the true emission spectrum. This distortion in turn hinders an analysis of the mechanisms by which the radiation is generated in oriented crystals.

In the present letter we are reporting a new measurement method and the first use of this method. This new method makes it possible to measure the true spectrum and angular distribution of intense fluxes of γ rays over a wide γ-ray energy range (0.1–600 MeV), without the distortion of the spectrum due to the multiple production of γ rays. The method is based on a Compton scattering of the emitted γ rays and a subsequent measurement of the energy of the γ rays scattered through a certain angle by a total-absorption spectrometer.

We are reporting the first results here. They indicate the presence of an anomaly (a dip along the direction of the crystallographic axis) in the angular distribution of the hard ($\omega \gtrsim 50$ MeV) γ rays. For the softer γ rays, there is a clearly expressed peak in the angular distribution of the emission. The width of this distribution is essentially independent of the energy of the emitted γ ray. A theoretical analysis of the results has shown that these structural features in the angular distribution of the emission stem from a coherent effect in the emission by above-barrier electrons at atomic chains in the crystal.

2. The measurements were carried out at the LU-2000 accelerator of Kharkov Physicotechnical Institute. Figure 1 shows the layout of the experimental apparatus used in measuring the spectrum and angular distribution of the emission. The γ rays scattered toward the measurement channel by the scattering target (6) are detected by a total-absorption scintillation spectrometer (14), which was described in Ref. 4. The beryllium scattering target is positioned by remote control along the axis of the measurement channel within an angular error of $\pm 2\times 10^{-6}$ rad for measurement of the

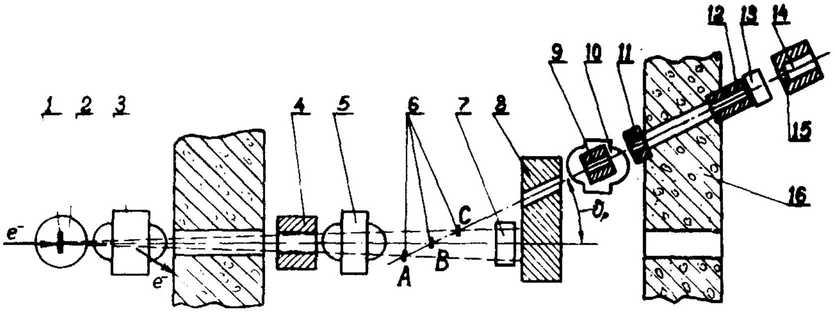

FIG. 1. Experimental layout. 1—Target; 2—goniometer; 3—turning electromagnet; 4—photon-beam collimator; 5,10—purifying electromagnets; 6— scattering target; 7—ionization chamber; 8—lead block; 9,11,12—collimators of measurement channel; 13—purifying magnet; 14—γ spectrometer; 15—protective structure; 16—concrete shielding wall.

angular distribution of the photon flux leaving the crystal. The angular resolution of the measurement complex, which is determined by the transverse dimensions of the scattering target and of the electron beam at the crystal, was $\pm 1.5\times 10^{-4}$ rad in these measurements. This new method has been used to measure the spectrum and angular distribution of the emission by 1.2-GeV electrons in silicon crystals of various thicknesses oriented with their $\langle 111\rangle$ axis along the incident electron beam.

Figure 2 shows the results of measurements of the emission flux density as a function of the emission angle for various γ-ray energies, corresponding to the passage of electrons through a silicon crystal 1.5 mm thick. Over this thickness, several γ rays can be emitted (Refs. 1 and 2, for example).

3. The results show that at low γ-ray energies ($\omega \sim 10$ MeV) the intensity of the emission by the electrons in the direction along the crystallographic axis is greater by a factor of more than 20 than the intensity emitted in a disoriented crystal. This difference is substantially greater than that observed in Refs. 5 and 6. The reason for the difference is that in Refs. 5 and 6 the emission of the γ rays was measured in an integral way over a certain region of γ-ray energies, while the new method which we are describing here yields the true spectrum and angular distribution of the emission.

For γ rays with an energy $\omega \gtrsim 50$ MeV, there is a minimum in the angular distribution of the emission along the direction of the crystallographic axis, and there is a maximum at some angle θ_m from this axis. The angle θ_m increases with increasing γ-ray energy.

Note that at low frequencies ($\omega < 30$ MeV; Fig. 2b) the width of the angular distribution is essentially independent of the γ-ray energy, while at $\omega > 30$ MeV this width increases with ω.

4. Measurements of the absolute values of the spectrum and angular distribution of the emission by electrons in thick crystals have made it possible to carry out a qualitative comparison of the experimental results with the predictions of theoretical models and to test hypotheses underlying these models. The solid lines in Fig. 2 show results calculated on the contribution to the emission from particles in above-barrier

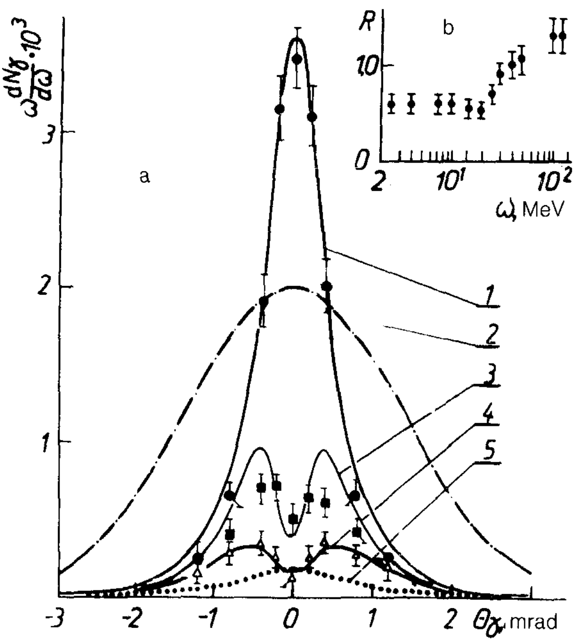

FIG. 2. a: Angular distribution of the γ-ray emission from an oriented Si crystal. 1,3,4—The energy of the γ rays is 10, 50, and 100 MeV, respectively; 5—angular distribution of the γ-ray emission from a disoriented crystal (integrated over the spectrum); 2—angular distribution of electrons (in arbitrary units). b: Ratio of the distributions of the γ emission from oriented and disoriented crystals versus the energy of the γ rays.

motion near a crystallographic axis. These calculations allowed for the evolution of the angular distribution of the electron beam in the crystal as a result of the multiple scattering of particles by lattice atoms. For particles moving at an angle ψ with respect to the crystallographic axis which is greater than the critical angle for channeling, ψ_c, the calculations were carried out from the formulas of the modified theory of coherent emission. At $\psi < \psi_c$, on the other hand, the curvature of the trajectory of an electron in the field of an atomic chain in the crystal was taken into account.[7,8] The emission by channeled particles was ignored.

The satisfactory quantitative agreement between the theoretical and experimental results is evidence in favor of the assumptions adopted in order to simplify the calculations. These results show that the behavior of the spectrum and angular distribution of the emission by electrons in a thick crystal observed in these experiments is governed by the particular features of the coherent emission by above-barrier electrons in the field of an atomic chain in a crystal. We thus see that, for the particular energies and crystal thicknesses involved here, the above-barrier particles dominate the shaping of the angular distribution of the emission. The apparent reason is that in this energy range the motion of an electron in the field of a chain of atoms under channeling conditions is extremely unstable. As a result, the particles are rapidly dechanneled, i.e., go into below-barrier and above-barrier states.[9]

This new method might also be used to measure the true spectrum and angular distribution of emission at electron energies well above 1 GeV ("true" here means free of superpositions). This method might serve as an alternative to the method based on measurements of the characteristics of the electron–positron pairs produced by emitted γ rays.

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