Spectral and angular characteristics of radiation emitted by 10-GeV electrons in thick silicon crystals

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Results are reported from an investigation of the angular and spectral properties of the radiation emitted by 10-GeV electrons traversing fairly thick (0.8 and 3.0 mm) silicon single crystals at small angles relative to the ⟨111⟩ crystallographic axis. Information was obtained on the increase in the spectral density of the radiation generated in crystals over the corresponding density of the radiation generated in an amorphous film.

Spontaneous gamma radiation emitted by relativistic charged particles moving under channeling conditions[1–3] increases considerably the gamma-ray yield compared with the usual bremsstrahlung generated in an amorphous target (for reviews see Refs. 4–6). Recent experimental investigations of the radiation emitted by channeled high-energy particles[7–10] have confirmed fully the theoretical predictions. The attention has been concentrated mainly on the radiation of particles channeled in thin crystals, because it is then easy to compare the experimental and calculated results. However, it would be interesting to obtain experimental characteristics of such radiation generated in relatively thick crystals.

We investigated the angular and spectral characteristics of the radiation emitted by 10 GeV electrons traversing single crystals of thickness 0.8 and 3.0 mm at low angles relative to the ⟨111⟩ crystallographic axis. The results were obtained using the Kristall facility[11] employing an electron-positron beam[12] in an accelerator at the Institute of High Energy Physics.

We used the apparatus shown schematically in Fig. 1. A focused beam was directed toward a remotely controlled goniometer where single crystals in the shape of flat disks with a polished flat surface were located; these were used for preliminary alignment with the aid of a reflected laser beam. The final positions of the axes and planes were deduced from peaks in the number of the gamma photons emitted inside the target when a crystal was rotated by the goniometer. Each division of the goniometer scale was $\approx 17\ \mu$rad. The paths of the particles before and after the target were determined employing four sets of drift chambers. This made it possible to determine very accurately the angles at which electrons entered and left a crystal (the standard deviation in the determination of the entry angles was $\approx 8\ \mu$rad and in the case of the exit angles it was $\approx 35\ \mu$rad). The photon energy was measured with a gamma spectrometer using a scintillation CsI:Tl crystal in the form of a cylinder 150 mm in diameter and 230 mm long parallel to the beam. This scintillation detector was surrounded by anticoincidence counters and a lead shield. The spectrometer resolution was at least 3% when the gamma photon energy was ~ 100 MeV (this resolution represented the full width at the midamplitude of the distribution).

Electrons were identified using a Cherenkov total absorption counter with a lead glass radiator; the momentum of the transmitted particles was determined from the deviation in an analyzing magnet (M3). The angles of emission of the gamma photons were determined using a set of drift chambers with a built-in converter[13] (DC5) placed directly in the front of the gamma spectrometer radiator. The apparatus was triggered by a system of coincidence and anticoincidence scintillation counters. The amount of background material amounted to less than 5×10^{-4} radiation lengths. The spectrometer was connected to a computer. The software used in our experiments made it possible to detect the effect during collection of data and to check on-line the stability of the beam parameters and of the functional components of the apparatus.

In the analysis of data we selected the events which satisfied the requirements needed to identify electrons by a total-absorption Cherenkov counter and which were accompanied by the emission of gamma photons of energies in excess of 3 MeV. The spectral density of the radiation was normalized to one incident electron per unit thickness of the crystal.

An analysis of the data on the transmission of channeled and above-barrier electrons by thin[10] and thick[14,15] single crystals revealed a considerable difference in the dynamics of the flux of particles in a crystal and in an amorphous substance. Figure 2 shows the distribution of the hori-

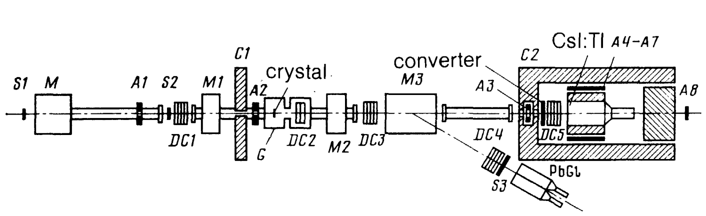

FIG. 1. Schematic diagram of the Kristall facility: S1–S3 and A1–A7 are scintillation counters; M1 and M2 are correcting magnets; M3 is an analyzing magnet; DC1–DC5 are drift chamber arrays; C1 and C2 are collimators; PbGl is a Cherenkov total absorption counter; CsI(Tl) is a gamma spectrometer; M is a magnet of the beam transport system; G is a goniometer.

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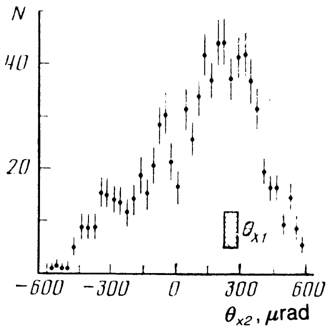

FIG. 2. Distribution of the horizontal projection of the angles of escape of electrons from a silicon single crystal of thickness 0.8 mm. The shaded region represents the range of entry angles for the same events.

zontal projection of the angle of emergence θ_{x2} of electrons from a silicon single crystal of thickness 0.8 mm for particles entering at an angle θ_{x1} from 200 to 300 μrad and θ_{y1} from -300 to -200 μrad. The asymmetry of this distribution demonstrated strikingly the influence of a chain of atoms on the nature of motion of particles and, consequently, on the angular characteristics of the emitted gamma photons. The peak in the region of -300 μrad was clearly a consequence of so-called rainbow scattering of above-barrier electrons in a circle on an axial chain of atoms.[16] A peak with the maximum at $\theta_{x2} = -70$ μrad was located almost entirely at angles less than the critical channeling angle (≈ 130 μrad) and was largely due to the process of "bulk capture" of above-barrier electrons by a channel. In an amorphous substance the interaction of a particle with atoms is chaotic and the angular divergence of bremsstrahlung is mainly due to multiple scattering. In the case of axial channeling the path of the electrons determines the average potential of the chain of atoms constraining them to move for a long time in the channel direction. The angular divergence of the radiation emitted by axially channeled electrons is governed mainly by the critical angle.

Figures 3 and 4 show the experimental distribution of the angles of emission (relative to the axis) of gamma photons from silicon crystals 0.8 and 3.0 mm thick. The rms deviation of the distributions of electrons with the polar entry angle in the range 0–130 μrad (particularly the critical

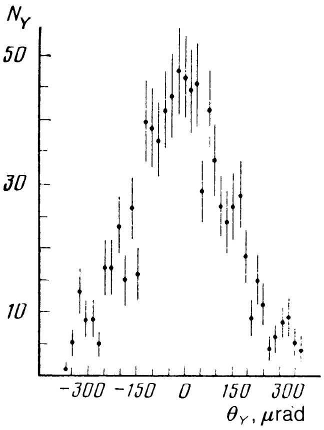

FIG. 3. Distribution of the angles of escape of gamma photons from a silicon crystal 0.8 mm thick for events characterized by entry angles from 0 to 130 μrad relative to the direction of the selected axis.

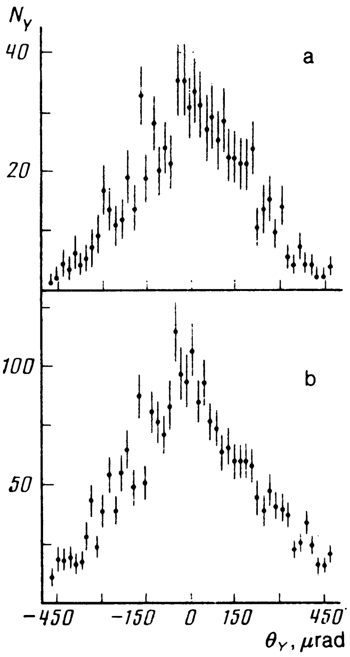

FIG. 4. Distribution of the exit angles of gamma photons from a silicon crystal 3.0 mm thick for events characterized by the following entry angles relative to the axis: a) from 0 to 130 μrad; b) from 0 to 400 μrad.

angle) was ≈ 170 μrad (in a sample of thickness 0.8 mm, see Fig. 3) or ≈ 200 μrad (in a sample of thickness 3.0 mm, Fig. 4). For events with polar entry angles from 0 to 400 μrad for a crystal 3.0 mm thick this quantity was approximately 240 μrad (Fig. 4b). However, a slight excess of the angular divergence of gamma radiation above the critical angle re-

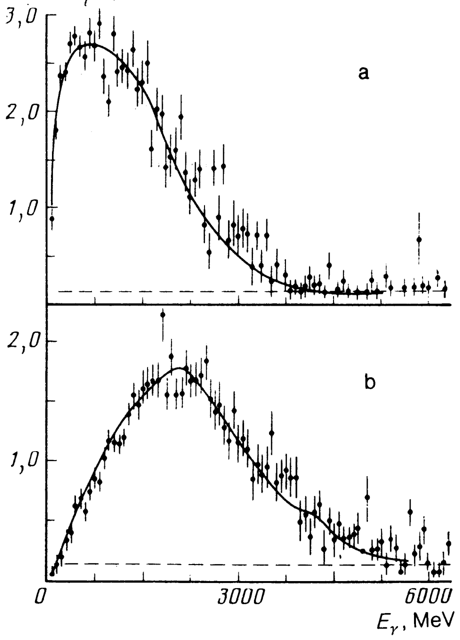

FIG. 5. Experimentally determined spectral density of the emitted radiation, reduced to unit sample thickness, obtained for silicon crystals of two thicknesses: a) 0.8 mm ($\theta_{\rm in} < 150$ μrad), b) 3.0 mm ($\theta_{\rm in} < 100$ μrad). The dashed line represents the spectral density of the radiation emitted from aluminum of the same thickness. The continuous curves illustrate the results of our simulation.

TABLE I.

Crystal thickness, mm	Multiplicity of emission		
	Experiments		Monte Carlo calculations
	$\theta_{in} = 0$–$800\,\mu$rad	$\theta_{in} = 0$–$130\,\mu$rad	
0,8	1,2	1,7	1,8
3,0	3,9	5,2	5,4

vealed a major contribution of the channeled radiation, since when ordinary bremsstrahlung dominates, the angular divergence after traversing a thick target is governed mainly by multiple scattering and should be $\approx 150\,\mu$rad for a thickness of 0.8 mm and $\approx 270\,\mu$rad for 3.0 mm. Figure 5 shows the measured spectral densities of the radiation emitted by electrons traversing silicon of thickness 0.8 and 3.0 mm at entry angles of 0–150 and 0–100 μrad, respectively, relative to the $\langle 111 \rangle$ axis.

It is known that the true spectra can be determined by also recording the single emission events, i.e., the probability for emission of a gamma photon in the target should be much less than unity or the response efficiency of a detector should be low. We estimated the average multiplicity of the emission of gamma photons in the events taking place in thick crystals by comparing the number of gamma-photon conversion vertices, recorded using the DC5 unit, for a thin ($\approx 41\,\mu$m) silicon crystal[10] with the results obtained for our targets. Estimates were obtained for events involving emission of a gamma photon of energy $\geqslant 20$ MeV (representing the threshold for recording a conversion pair in DC5 and in a CsI:Tl counter). When events of this type were recorded for a thin target, the probability for emission of a single photon was high. An increase in the number of gamma photons recorded by the DC5 unit for our samples could then be attributed to a change in the radiation multiplicity. By multiplicity we understand the number of gamma photons emitted by one electron when at least one photon of energy in excess of a certain minimum (≈ 20 MeV) is emitted. The results of estimates obtained by this method are listed in Table I.

Since for our samples the multiplicity was in excess of unity, the experimentally determined spectral density of the emitted radiation was distorted, because several gamma photons were recorded by the spectrometers as one photon and their energies were summed by the gamma spectrometer. Figure 5 illustrates the experimental distributions distorted by this effect: they represent the spectral density of the radiation emitted by electrons traversing silicon single crystals of thickness 0.8 and 3.0 mm along the $\langle 111 \rangle$ crystallographic direction.

Simulation of the processes of electron transmission and emission in thick crystals in which we utilized the data obtained employing a thin crystal[10] allowed us to calculate the "true" and the experimentally distorted (by the multiplicity of the emission) spectral densities for the sample single crystals. This simulation was based on successive (in certain steps corresponding to the thickness of a thin crystal) calculations of the photon energy from the experimental distribution for a thin single crystal[10] obtained for different intervals of the angles of entry of electrons. The entry angle of an electron into the next layer was assumed to be equal to the angle of escape from the previous layer. The latter was found by calculating the parameters of the event using the distributions of the escape angles for a thin target.

The photon energy obtained in this way was plotted in a histogram every time an emission event occurred in the actual layer under consideration. Information on the emission probability in the case of events with a given electron entry angle into a crystal, obtained for a thin sample,[10] allowed us to determine whether or not an emission event occurred and thus carry out an absolute normalization of the spectral density of radiation per incident electron. When an electron crossed all the layers, the resultant thickness of which was equivalent to the thickness of the specimen single crystal, we calculated the total energy E_γ of the emitted gamma photons. This enabled us to obtain the spectra of electron energy losses, which were compared with the corresponding experimental distributions for thick crystals (Fig. 5).

In the course of simulation we corrected the angles of entry at each step allowing for the energy lost by a particle in each layer. This was essential because the critical angle varied with the energy as $E^{-1/2}$. A shortcoming of this procedure was the absence of allowance for a shift of the energy spectrum because of the energy losses suffered by the primary particle. Only a low probability for the emission of hard gamma photons and a relatively low average value of

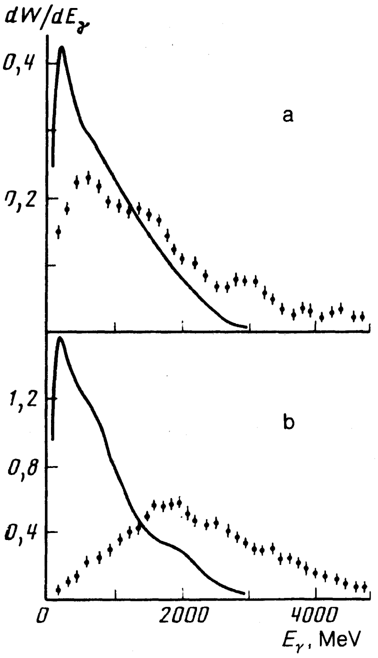

FIG. 6. Results of simulation, by the Monte Carlo method, of the true spectral density of the radiation (continuous curves) generated in thick silicon crystals: a) 0.8 mm; b) 3.0 mm. The points represent the experimentally determined spectral densities.

the energy losses (< 16%) in the investigated crystals made the results fairly reliable.

This procedure for reconstruction of the true spectral density was supported also by the observation that the energy loss spectra obtained by such simulation (solid curves in Fig. 5) were practically identical with the experimentally determined distributions. The reconstructed true emission spectra are given in Fig. 6 (solid curves). They resembled the distributions of the spectral density for a thin crystal.[10] Evidently, the maximum in these spectra was located in the photon energy range close to 200 MeV and exceeded the spectral density of an amorphous target by a factor of 44 and 43 for samples of 0.8 and 3.0 mm thickness, respectively. We included in Fig. 6 the experimentally determined spectral densities of the radiation emitted by 10 GeV electrons which crossed silicon single crystals of thickness 0.8 and 3.0 mm at low angles relative to the ⟨111⟩ axis. These distributions were normalized to one incident electron. The same procedure was used to estimate the multiplicity of the emission process and to compare the results with experiments carried out on samples of different thickness when the angles of entry were 0–130 μrad and 0–800 μrad (Table I).

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