ANGULAR DISTRIBUTIONS OF GAMMA-RADIATION OF 1.2 GEV ELECTRONS IN SILICON MONOCRYSTALS OF GREAT THICKNESS

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PACS number: 29.25.-t

In the motion of relativistic electrons at a small angle to one of the crystallographic axes, coherence and interference effects manifest themselves in the radiation, owing to which the gamma-radiation intensity of particles in the crystal may far exceed the intensity of radiation in amorphous medium. These effects can be used as the basis for creation of intense radiation sources with a high spectral-angular density of radiation.

The intensity of electron radiation in the crystal is known to be proportional to the target thickness. Therefore, to create gamma-sources, it is advantageous to use thick crystals. However, with an increasing target thickness the average square of the angle of multiple electron scattering by atoms also increases, and this results in broadening of the angular distribution of gamma-quanta emitted, and also in the attenuation of the coherence effect of electron radiation in the crystal. Besides, in thick crystals the radiation yield can be appreciably influenced by electron energy losses and by the absorption of emitted gamma-quanta.

The present paper is concerned with investigating spectral-angular distributions of 1 GeV electron radiation in thick single crystals. The main attention is here focused on the analysis of influence of the above-mentioned factors on the radiation, and to the determination of the optimum crystalline target thickness from the viewpoint of elucidating the conditions, at which the maximum spectral-angular gamma-radiation density magnitude is attained.

Let us consider the radiation with the relativistic electron beam incident on the crystal along one of its crystallographic axes. In thick crystals the greater part of beam particles executes an infinite above-barrier motion with respect to crystal atom strings lying parallel to the crystallographic axis. Therefore, to the first approximation one can assume that this group of particles makes the decisive contribution to the radiation. In its above-barrier motion the electron sequentially collides with different strings of atoms. If the motion occurs at angles to the crystallographic axis, ψ, of about several critical angle values of axial channeling, ψ_c, the scattering and radiation of the particle from different atom strings can be considered independent [1]. In this case, the spectral-angular radiation distribution will be determined, first of all, by the special features of electron radiation in the field of a single atom row string.

As a result of incoherent multiple scattering of the particle by crystal atoms, the particles are redistributed in the angles ψ. If the average scattering angle values exceed the characteristic value of the angle of relativistic electron radiation $\upsilon_k \sim \gamma^{-1}$, then the formation of spectral-angular distribution of radiation is significantly influenced by multiple scattering of the particle in the crystal.

With due regard for the multiple scattering, the average spectral-angular radiation density can be written as

$$< \frac{d^2 E}{d\omega do} >= n\int_o^T dt \int d^2\psi \cdot f(\psi, t) d^2 b \frac{d^2 E_R(\psi, b)}{d\omega do}, \quad (1)$$

where n is the density of atom strings in the plane orthogonal to the crystal axis, and $d^2E_R(\psi,b)/d\omega do$ is the spectral-angular radiation density of the electron on the crystal atom string, which is determined by the angle ψ and the impact parameter of the string b (the corresponding formulae for this quantity are given in ref. [1]).

The $d^2E_R(\psi,b)/d\omega do$ value was calculated in the framework of the modified theory of coherent radiation that takes into account the distortion of the electron trajectory as the electron moves in the field of a single atomic string [5]. The calculations were made in the dipole approximation, neglecting the recoil during radiation. The use of this theory to describe the electron radiation in the light-element crystals of relatively moderate thickness has provided good qualitative and quantitative agreement with the previously obtained data [4, 5].

The experiments performed previously at NSC KIPT on scattering of relativistic electrons in oriented crystals have shown that in thick crystals with the electron beam incidence along the crystallographic axis, the function of particle distribution in the angles $f(\psi,t)$ has practically the same Gaussian form as is the case in the amorphous medium, with the only difference that the average square values of the multiple scattering angle somewhat differ from similar values for the amorphous target. This difference is due to electron beam redistribution in the angles under the action of the average field of the atomic string at particle entry into the crystal.

In the passage of electrons through a rather thick crystal ($T \sim L_R$, where L_R is the radiation length) the electron energy losses must be taken into account. These losses by ~1 GeV electrons in the crystal mainly go through the radiation losses given by the equation

$$L_R \frac{d\varepsilon}{dt} = -(\alpha\varepsilon^2 + \beta\varepsilon), \quad (2)$$

where the constants α and β are determined by the radiation losses for coherent and incoherent bremsstrahlung in the crystal ($\alpha \approx 0.73$ (GeV)$^{-1}$, $\beta = 1$).

Solving this equation we obtain the average particle energy as a function of depth t of particle penetration into the crystal, ε(t). The gamma-quanta radiated in a thick crystal can be absorbed in the same crystal due to secondary electrodynamic processes such as pair production, Compton scattering, etc. The effect of gamma-quanta absorption in the crystal can be taken into account by multiplying the spectral density $\frac{d^2E_R}{d\omega do}$ by the factor $\exp(-(T-t)/L_a)$, where L_a is the characteristic absorption length ($L_a \approx 2L_R$ for gamma-quanta in the energy range from 10 to 100 MeV), with a subsequent integration over *t* in expression (1).

The above-presented model of calculations was used in the analysis of experimental data on the spectral-angular distributions of electron gamma-radiation in thick crystals. The experiment was conducted at NSC KIPT using the 2 GeV electron linac. The 1.2 GeV electron beam was incident on silicon crystals of various thicknesses along the <111> axis. The original technique GROM, previously developed at NSC KIPT and based on the Compton scattering effect [2], was used to measure spectral-angular distributions of the radiation. The measurements have shown that the maximum of the spectral density of 1.2 GeV electron radiation in thick silicon crystals lies in the region of gamma-quantum energies ω = 10 - 15 MeV.

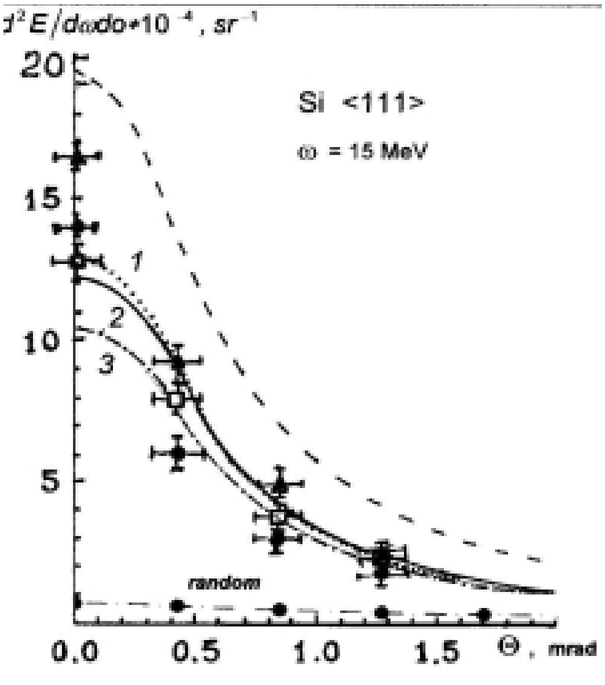

Fig. 1.

Fig. 1 shows the measured angular distributions of gamma-radiation with ω = 15 MeV for the <111> axis-oriented silicon crystals of thickness T = 15 mm (circles), T = 30 mm (triangles) and T = 63 mm (squares) [3]. Fig. 1 also gives the corresponding calculated results for the angular distributions of gamma-radiation with ω = 15 MeV produced in silicon crystals of thicknesses 15 mm (. . .), 30 mm (- - -) and 63 mm (- · -) (curves 1, 2, 3, respectively). The dashed curve shows the calculated radiation angular distributions for the T = 63 mm silicon crystal without taking into account the electron energy losses and the gamma-quanta absorption in the crystal. The comparison of this curve with curve 3 shows that the mentioned factors exert an essential effect on the radiation yield from thick crystals and must be taken into account.

Within the experimental errors, the results of measurements for disoriented crystals (amorphous targets) of the same thicknesses agree very closely between themselves (black circles) and with the theoretical calculations (dash-dotted curves). This agreement is explained by the fact that an increase in the quantity of gamma-quanta emitted with a growing target thickness is practically compensated by the effect of their absorption. The present results indicate that, compared to the disoriented crystal even thick (about a few cm) oriented crystals exhibit a significant (nearly 20-fold) increase in the yield of “forward” gamma-quanta with the energy ω = 15 MeV. The halfwidth of angular distributions of these gamma-quanta in a thick crystal appears approximately equal to $\Delta\theta \approx mc^2/E$, this being essentially narrower than in the amorphous target.

The comparison between theoretical and experimental data shows their fair agreement, and this gives evidence for the validity of the proposed model. A certain discrepancy between the data at θ=0 is probably due to a complicated dynamics of the electrons moving in the vicinity of the crystallographic axis; this calls for an additional analysis and, before all, a more careful consideration of the absorption of 10 to 20 MeV gamma-quanta in single crystals.

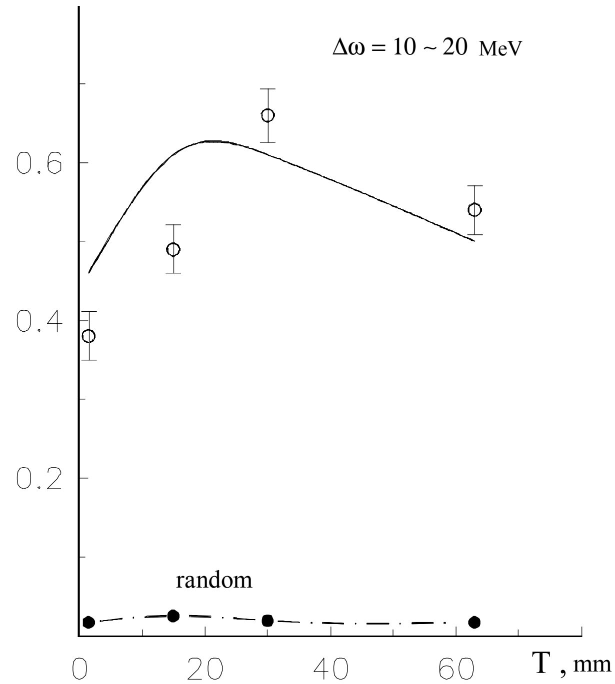

Fig. 2.

The results obtained here suggest the conclusion about the optimum crystal thickness for attaining the maximum spectral-angular radiation density. Figure 2 shows the yield of gamma-quanta of energies ranging between 10 and 20 MeV as a function of the crystal thickness, the gamma-quanta being concentrated in the cone with an opening $\Delta\theta \approx mc^2/E$ along the direction of the incident electron beam. For comparison, the same figure shows the results for the amorphous target (dash-dotted curve). These data give evidence that the optimum crystal thickness for obtaining the maximum spectral-angular radiation density is approximately equal to 15-30 mm, this being in agreement with the previous data on the total energy losses of gamma-radiation in single crystals of various thicknesses [4].

It must be also noted that the angular distributions of 15-20 MeV gamma-radiation show a "dip" in the forward direction, that has previously been observed in a 1.5 mm thick silicon single crystal [5].

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