THE SIMULTANEOUS OBSERVATION OF A CHANNELING RADIATION AND COHERENT BREMSSTRAHLUNG FROM SINGLE CRYSTALS

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We present the results of investigation of gamma radiation spectra generated by an electron beam with initial energy $E_0 \sim 1.2$ GeV in diamond and silicon single crystals, under conditions when the simultaneous apprearance of two types of radiation is possible: coherent bremsstrahlung and channeling or above-barrier radiation. It is possible under condition when electrons move in parallel to densely packed crystal planes under angles to the crystal axis more than the critical channeling angle. At the same time, these angles should be such that the coherence length for photons with energy close to the initial energy of electrons be less than the distance between atom strings of the crystal along the direction of movement of electrons.

Introduction

The bremsstrahlung spectra of electrons and positrons in crystal and amorphous targets differ essentially. It is a consequence of a periodic crystal structure that, in turn, leads to the generation of interference maxima in the radiation spectra in a process of radiation formation. If an incoming angle ψ of an electron to close-packed atomic strings or planes is more than the critical channeling angle ψ_c [1], but not too large, so-called coherent bremsstrahlung (CB) is generated. A theory based on the first Born approximation describes this phenomenon satisfactorily [2 ¯ 4]. The noncoherent part of radiation is described in this theory as an ordinary bremsstrahlung. Radiation spectra under these conditions do not depend on the charge sign of incoming particles.

For small incidence angles of electrons (positrons) to the crystalline atomic planes (strings) ($\psi \sim \psi_c$), the Born approximation is inapplicable. For description of the spectra in this region, the theory of electron channeling radiation (CR) in crystals has been developed [5 ¯ 8]. Within the frames of this theory, the enhancement of radiation occurs in a relatively low energy region; and the radiation spectra for electrons and positrons differ essentially, what was confirmed by experiments [9 ¯ 14].

Earlier in our experiments, some difference with the predicted intensities of incoherent radiation spectra was revealed if incoming electrons are parallel to the cryslat planes or axes. This difference is especially large for thin crystals. In those experiments, it was also shown that the noncoherent part of radiation is linearly polarized if the electron momentum is parallel to the crystal plane [15]. The polarization vector is parallel to this plane. These phenomena are explained by none of the existing theories.

Earlier, the radiation spectra corresponding to channeling and coherent bremsstrahlung were measured separately. The measurements of CR were performed with very large incidence angles to the strings forming the crystalline planes. Therefore, CB was not observed in these experiments. We note that there are some difficulties in measurements of broad energy range spectra to observe CR and CB similtaneously.

In this work, the radiation spectra of electrons incident in parallel to the crystalline atomic planes were investigated in a wide energy range with incidence angles to the atomic strings, forming the crystalline plane, larger than the critical angle of the axial channeling but rather small for the generation of CB. These conditions are favorable for the manifestation of both channeling and coherent radiation together.

Experimental Results

The experiment was carried out at a 1.2 GeV electron linac, with a pulse duration of about 1.5 μs and repetition rate of 50 Hz. Electron intensities of about 20 electrons per an accelerator pulse or less were selected to ensure a small superposition of pulses from a γ-detector appearing due to the small linac pulse

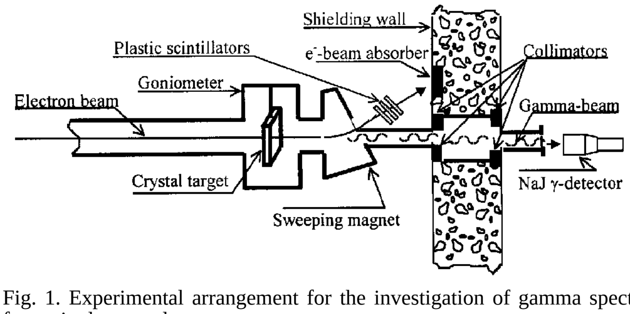

Fig. 1. Experimental arrangement for the investigation of gamma spectra from single crystals

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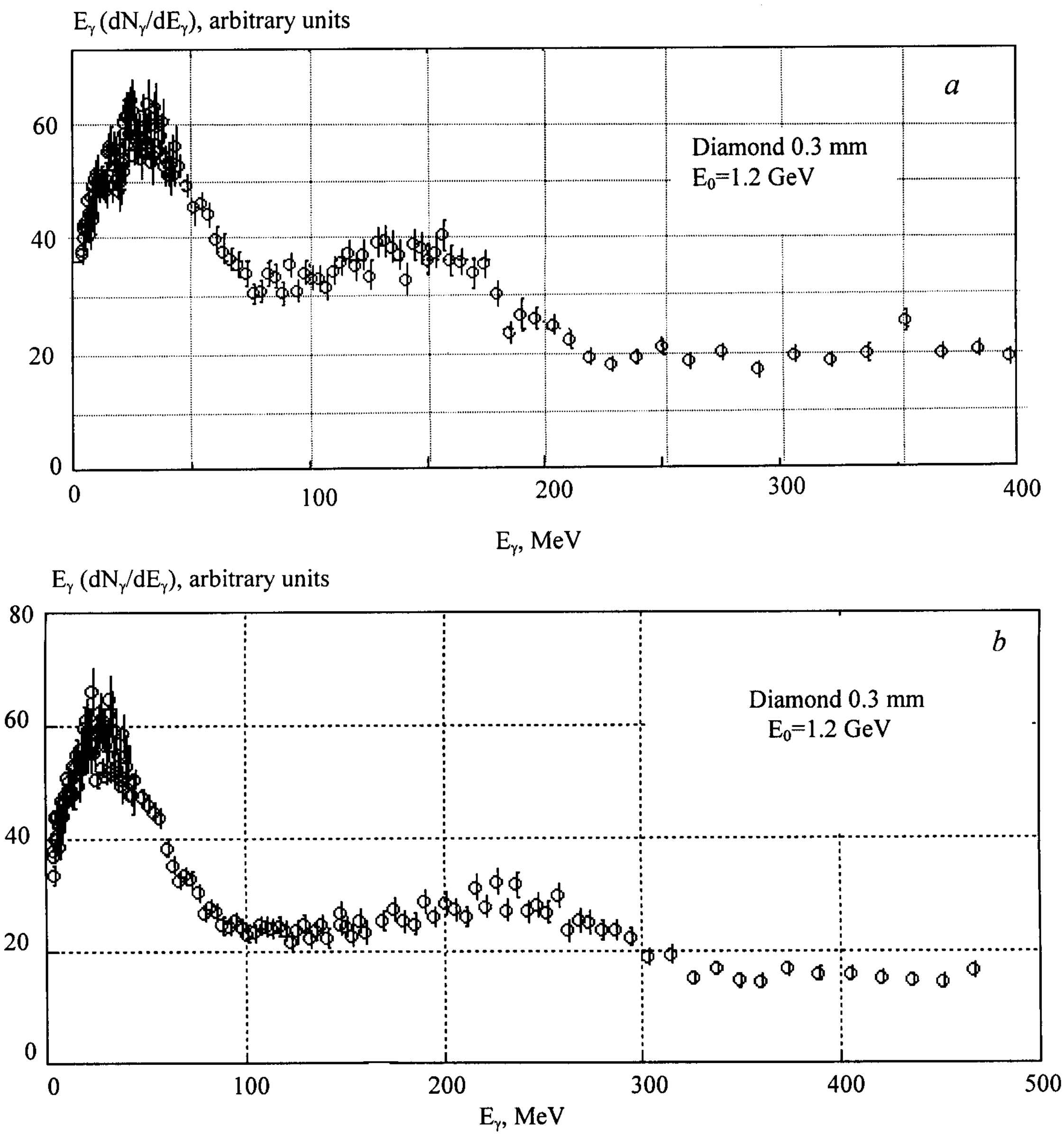

Fig. 2. Gamma radiation spectrum intensity of 1.2 GeV electrons in the diamond crystal 0.3 mm thick; *a* — incoming electrons are parallel to the crystal plane (001), the angle to axis ⟨110⟩ is $\psi = 5.5$ mrad; *b* — incoming electrons are parallel to the crystal plane (001), the angle to axis ⟨110⟩ is $\psi = 9$ mrad

duration. NaI scintillation detector of ∅ 20× 20 cm was used for the detection of γ-quanta in the energy range from several MeV to the endpoint energy of 1.2 GeV. The experimental layout is shown schematically in Fig. 1.

After passing through the crystal and the bending magnet, electrons are detected by a telescope of plastic scintillation detectors and are absorbed by heavy metal absorber mounted in the concrete wall. The forming and control systems of the low-intensity electron beam are described in [13].

The gamma spectrum generated by 1.2 GeV electrons incoming in the diamond crystal 0.3 mm thick in parallel to the crystalline plane (100) at the angle $\psi = 5.5$ mrad to the ⟨110⟩ axis (for these electron energy and axis, $\psi_c \approx 0.4$ mrad) is shown in Fig. 2,*a*. The spectrum corresponding to $\psi = 9$ mrad is shown in Fig. 2,*b* (other conditions remain the same). There are two maxima in these spectra corresponding both to the low-energy (5 – 25 MeV) and high-energy regions. The position of the high energy maximum and its intensity depend only on the angle of incidence

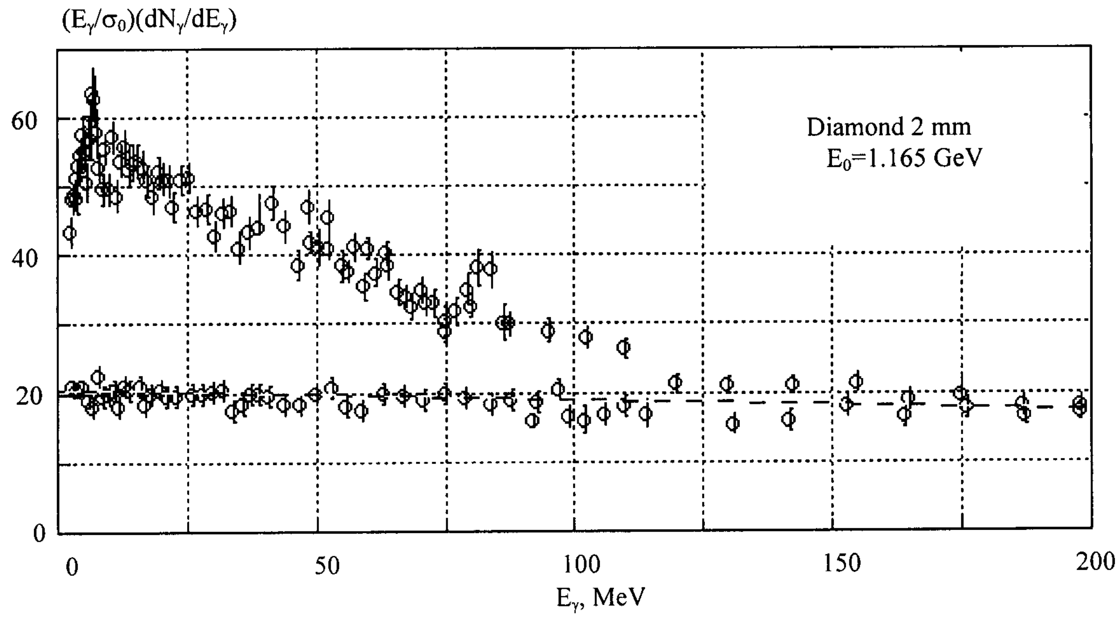

Fig. 3. Gamma radiation spectrum intensity of 1.165 GeV electrons in the diamond crystal 2 mm thick; incoming electrons are parallel to the crystal plane (001), the angle to axis ⟨110⟩ is $\psi = 150\,\psi_c$; below – the spectrum of 1.165 GeV electrons in the unaligned crystal; the dashed line represents the spectrum from an amorphous target of equivalent thickness

to the crystalline axis. With $\psi = 5.5$ mrad (Fig. 2,*a*), the position of this maximum is about 150 MeV, with $\psi = 9$ mrad is about 250 MeV (Fig. 2,*b*) (spectra in Fig. 2 is shown in arbitrary units, the others in absolute units, where $\sigma_0 = Z(Z+1.3)\,r_0^2/137$, Z-atomic number, r_0 – classical electron radius). An increase in the angle leads to an increase in the energy peak position and decrease in intensity. Both the intensity and position of the low-energy peak are independent of the angle of incidence to the atomic strings if the electron beam is parallel to the atomic plane.

Fig. 3 shows the resulting γ-spectrum for 1.169 GeV electrons incident in parallel to the (001) plane at the large angle $\psi = 150\,\psi_c$ to the atomic strings ⟨110⟩ of the thick diamond crystal (2 mm). Under these conditions, the coherent high-energy peak does not appear, but the low-energy peak exists as a broad maximum.

The γ-spectrum generated by 1.2 GeV electrons incident in parallel to the (110) plane of the silicon single crystal 0.24 mm thick at the angle $\psi = 25\,\psi_c$ to the ⟨111⟩ axis is shown in Fig. 4. In this spectrum, the coherent peak position with a photon energy of 300 MeV is similar to the spectra shown in Fig. 2,*a* and Fig. 2,*b*, which represent the results for diamond crystal.

The γ-spectra measured from the silicon single crystal 0.07 mm thick with the axis ⟨111⟩ aligned along the 1.2 GeV electron beam at the angle $\psi = 3\,\psi_c$ to this axis outside the close-packed atomic planes are shown in Fig. 5. With this axis orientation, the broad maximum is observed in the energy range of 15 – 20 MeV. The intensity in this region is 25 times higher than that from a non-aligned crystal. With the incidence angle $\psi = 3\,\psi_c$, the similar peak is observed but a gain is equal approximately to 7. For electrons incident parallel to the ⟨111⟩ axis, the intensity of the high energetic noncoherent fraction of the radiation spectrum is higher than that in the case of a non-aligned crystal.

Discussion

All the observed features of the radiation spectra can be explained qualitatively within the frames of the CB and CR theories. The qualitative behavior of the low-energy and high-energy peaks are in good agreement with the CR and CB theories, respectively.

In the frames of the CR theory, the movement of electrons is determined by the interplanar potential. In that case, periodicity of the atomic strings, forming the crystal planes, is not taken into consideration, and the 1 GeV electron motion in the interplanar potential can be described in the framework of classical electrodynamics. For the energy of radiated photons $E_\gamma \ll E_0$, the quantum recoil is negligibly small and the radiation can also be described within the frames of classical electrodynamics. A gain in the radiation intensity in the low-energy region of the spectrum is determined by the periodicity of electron motion in the interplanar potential and does not depend on the

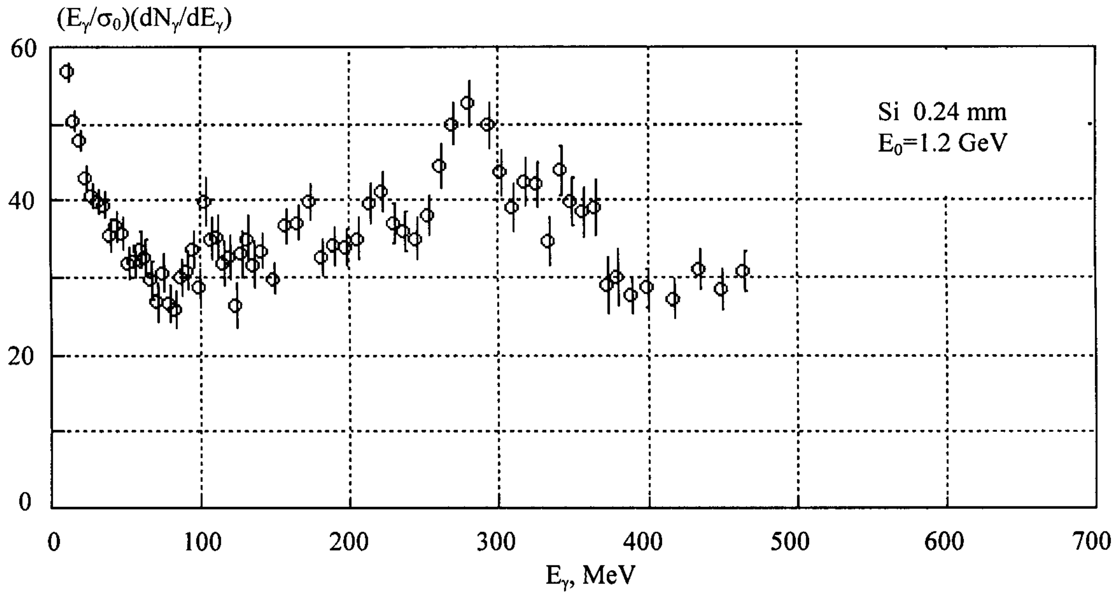

Fig. 4. Gamma radiation spectrum intensity of 1.2 GeV electrons in the silicon crystal 0.24 mm thick, incoming electrons are parallel to the crystal plane (001), the angle to axis ⟨110⟩ is $\psi = 25\,\psi_c$

angle ψ if $\psi >> \psi_c$ (ψ_c is the critical angle of axial channeling).

The spectral maximum in the high-energy region is a consequence of periodic electron collisions with atomic strings, and energy position of this maximum is proportional approximately to ψ. The angles of electron scattering by a single atomic string are not large, therefore, the radiation process can be described in the Born approximation of quantum electrodynamics (in that case, the quantum recoil could not be neglected). A period of electron collisions with atomic strings depends on the electron incidence angle ψ to atomic strings; a location of the spectral peak, caused by interference of radiation from periodic collisions, depends on this angle too ($E_{\max} \sim \gamma^2 \psi / a$, $\gamma = E_0 / m$ is Lorentz-factor, m is the electron mass, a is the lattice constant). These dependencies are observed experimentally. Interference arises when the coherent length $l_{\rm cog} \sim 2E_0 E_e / E_\gamma m^2$ is equal to space periods of electron collisions with atomic strings in crystals (E_e is the energy of a scattered electron).

In the case where incoming electrons are parallel to crystalline planes and the angle to crystalline axes $\psi > \psi_c$, it is possible to separate two main periods in the particle motion: a large period related to a periodic motion in the averaged planar potential, and a small period related to electron collisions with atomic strings. Two interference peaks correspond to these periods: a peak corresponding to CR and a peak corresponding to CB, respectively. The long-wave period of the electron motion in the planar potential does not depend on ψ, therefore, the position and intensity of the corresponding interference peak also do not depend on ψ (see Fig. 2,*a* and Fig. 2, *b*). On the contrary, the short-wave period is determined by ψ, therefore the position of the corresponding peak and its intensity depend on this angle. According to CB theory, the intensity of the interference peak drops with increase in ψ. Its position is shifted to the high-energy region, and this peak is not observed at reasonably large angles (see Fig. 3). In the CB theory, this interference peak has a sharp upper contour with a smooth decreasing in the low-energy region that is caused by the Doppler effect. The photon energy is uniquely connected with the outgoing angle of the photon for separate CB peak. The broadening of this peak toward high energies observed in experiments is caused by multiple electron scattering in the crystal.

One of the reasons for the broadening of the peak in the low-energy region is anharmonicity of the planar potential for electrons (for positrons, the potential is close to harmonic, and the upper peak contour is sharp). The other reason for the peak broadening is multiple electron scattering in the crystals, which differs essentially from the scattering in amorphous substances [16, 17]. For these reasons, the peaks observed in experiments have no sharp structure.

In the case of electron incidence along the close-packed crystalline axis, or if the angle to it does not exceed considerably the crytical angle of axial channeling, $\psi \sim \psi_c$, and the electron momentum is outside of the close-packed atomic plane, the amplification of the radiation intensity is only observed

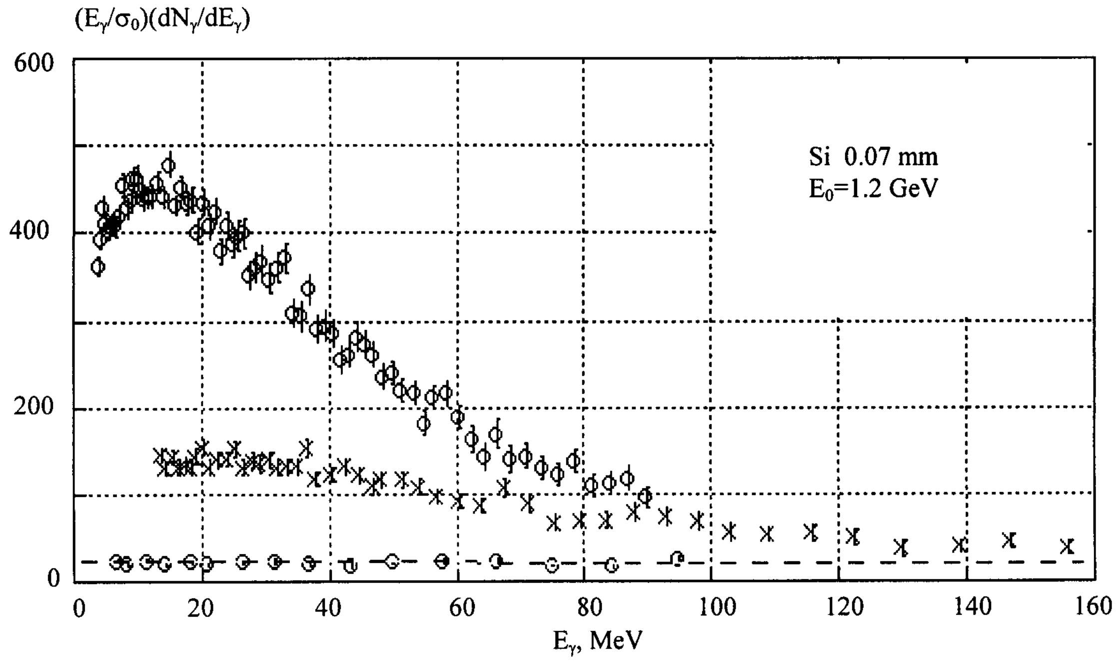

Fig. 5. Gamma radiation spectrum intensity of 1.2 GeV electrons in the silicon crystal 0.07 mm thick; ϕ ‾ incoming electrons are parallel to the crystal axis ⟨111⟩; × ‾ the angle to axis is $\psi = 3\,\psi_c$; circles ‾ spectrum for unaligned crystal; dashed line ‾ the calculated spectrum in the amorphous target of the equivalent thickness

in the relatively low-energy region of the spectrum, Fig. 5. This amplification is related to the effect of axial channeling or above-barrier axial movement of electrons, which are discussed in the frames of the CR theory. With increasing the angle of incidence to the axes, the radiation intensity decreases in this region.

In works [18, 19], the experiments were performed in a similar geometry at very high electron energies (70 ‾ 240 GeV). The interpretation of results of these works is complicated because distortions in experimental spectra caused by multiple gamma-radiation by separate electrons of very high energy under channeling conditions in aligned crystals are high.

Conclusion

The experimental results give the convincing evidence on a possibility to generate both channeling radiation and coherent bremsstrahlung simultaneously. That is possible when incoming electrons are parallel to the close-packed crystalline plane and the angle to the close-packed strings forming the crystalline planes is large in comparison with the critical angle of axial channeling. But, at the same time, this angle should be rather small, so the coherent length corresponding to photons with the upper energy must be less than the distance between the atomic strings along the direction of electron motion.