Investigation of radiation emitted by 4.4 GeV electrons in oriented diamond, silicon, and germanium single crystals

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The radiation spectra emitted by electrons moving at small angles with respect to the axes and planes of single crystals with diamond-like structure are investigated. Relative emission yields measured in experiments are lower for silicon and germanium than for diamond in the coherent low-energy part of the spectrum. The fundamental radiation frequency does not depend on the atomic number Z of the atoms that make up the single crystal. In the high-energy incoherent region of the spectrum the emission yield has not been found to exceed its level for randomly oriented crystals, regardless of the degree of gamma-beam collimation.

A new branch of physics, the physics of relativistic crystals, has been under development for some years now. To understand how ultrarelativistic electrons interact with the fields of crystal axes and planes, it is useful to conduct thorough experimental research of both electron scattering and the emission characteristics in a wide range of $x = \hbar\omega/E$ and E ($\hbar\omega$ is the gamma quantum energy, E is the initial electron energy). The information obtained in experiments conducted on different specimens with identical crystal structure, such as diamond, silicon and germanium, is of considerable interest.

We obtained the results reported in Refs. 1, 2 mostly in experiments with diamonds at the energy 4.5 GeV. Recently[3] a study was published, in which the peaked structure of the germanium spectrum was found in the region $x \approx 0.85$ at an electron energy of 150 GeV. A relatively high yield of gamma-quanta, up to the values of $x \approx 0.4$ was observed in a still earlier work, where diamonds were studied (see Ref. 3). No interpretation of either result has yet been offered.

In this paper, an investigation of the emission of electrons with energies 4.4 GeV from diamond, silicon and germanium are presented when x is in the range 0.005–0.94. The experiment was performed on the internal electron beam of the Yerevan synchrotron, with a divergence of $\sim 5 \cdot 10^{-5}$ rad (see Fig. 1). The emission collimation angle was $\pm 1.5 \cdot 10^{-4}$ rad almost everywhere, with the exception of the hard part of the emission spectrum from diamond and germanium, where it measured $\pm 5 \cdot 10^{-4}$ rad. Relative monitoring of electrons, transmitted through the single crystal targets under investigation, was accomplished with the help of a secondary-emission detector, utilizing the method of fast discharge of the accelerated beam onto the target. To measure the integral photon yields a Wilson quantometer was used. The plots of the yields of the total photon energy as functions of orientations, normalized to the appropriate randomly directed crystal yields, are shown in Fig. 2. Comparing crystals with one another, we come to the conclusion, that the relative emission yields on the axes and planes for silicon and germanium are lower than that for diamond. All crystals have approximately equal angular widths of the central peaks in the case of electrons moving with respect to the axes, even though the channelling angle for the germanium crystal is greater than that for diamond (see Table I).

The spectra of the radiation emitted by electrons, moving either parallel or at low angles with respect to the axes and planes of diamond, silicon and germanium, are shown in Figs. 3–6. The measurements were taken, using a double magnetic spectrometer with 10% accuracy in the gamma quantum-energy range of 20–200 MeV, and 6 to 3% for energies 300 to 4300 MeV. Appropriate vacuum conditions were maintained in the double magnetic spectrometer in order to minimize background and multiple scattering everywhere along the path of the gamma-ray beam and the conversion electrons.

As one can see in the pictures, the peak values of the energies in the plane and the corresponding axes spectra are equal for the crystals studied, contradicting the functional relationship between the emission fundamental frequency and the crystal atomic number Z: $\omega \sim Z^{1/2}$ suggested in Refs. 4 and 5. Likewise, the fundamental emission frequency does not change with the electron reentry angle, the latter remaining within the limits of the Lindhard angle (see Table I).

In the case of the planes, relative yields in the hard part of the emission spectrum for silicon (Fig. 4, I), germanium (Fig. 4, II) and diamond (Ref. 2), virtually coincide, and do not differ from the appropriate yield from randomly directed crystal. The excess in the yield from the hard part of the spectrum over the yield from randomly directed crystals

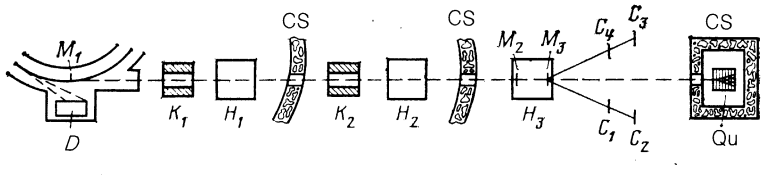

FIG. 1. Schematics of the experimental unit: M_1 is the target of the synchrotron (the single crystal under study); K_1 and K_2 are the collimators of the gamma-beam; H_1 and H_2 are the "cleaning" magnets; H_3 is the magnet of a double spectrometer (DS); M_2 and M_3 are the targets of the DS; C_1, C_2, C_3, C_4 are the counters of scintillations of the DS; Qu is the quantometer; D is detector of synchrotron emission; CS is concrete shield.

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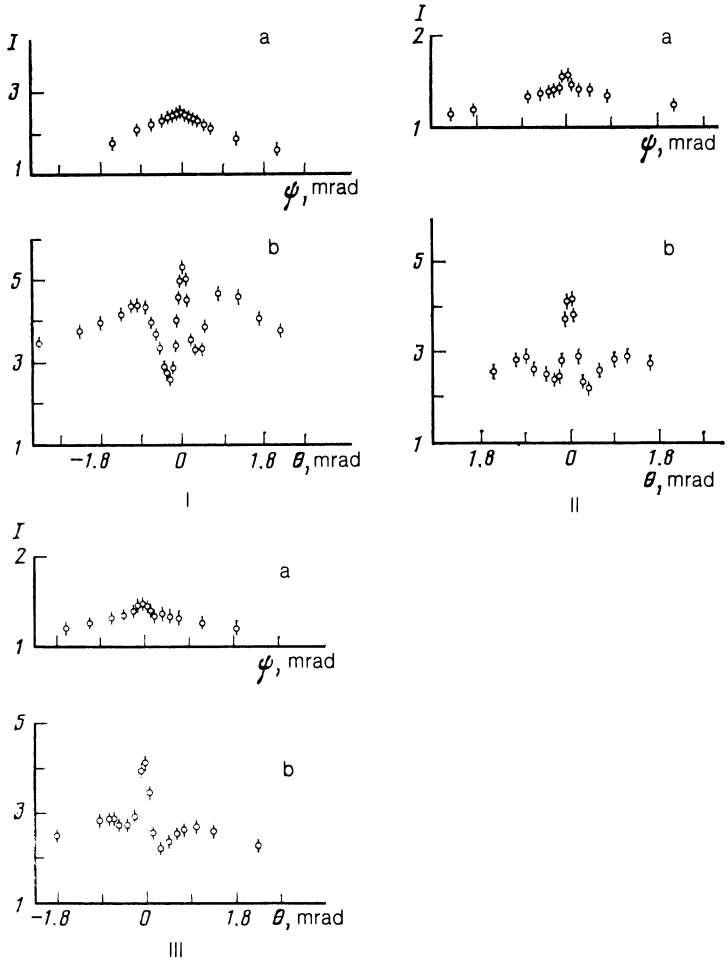


FIG. 2. Total energy of gamma-emission as a function of the reentrant angle relative to the (011) plane (a), [100] axis (b) for a single crystal of diamond with width of 72 μm (I); single crystal of silicon with the width of 90 μm (II); single crystal of germanium with the width of 110 μm (III). Here and in all subsequent figures the yields are given relative to randomly directed crystals.

when electrons repeatedly cross the closely packed crystal regions in the channelling mode, predicted in Ref. 6, may be due to collimation of the gamma-ray beam. The latter leads to the distortion of the hard part of the emission spectrum, when strong scattering of electrons, moving along the planes and axes of the crystal, is present. Since it is impossible to completely eliminate collimation when working with the double magnetic spectrometer, the collimation angle was only increased to $\pm 5 \cdot 10^{-4}$ rad. This value is not really small; it is several times greater, than the characteristic emission angle $1/\gamma$ (here γ is the Lorentz-factor of the primary electron). At the same time, the relative yields in the hard parts of the spectra of germanium (Fig. 6, a) and diamond (Fig. 3, b) did not change, compared to the appropriate data for the smaller gamma-ray beam collimation (see Fig. 4, IIb and Ref. 2).

When electrons move close to the axes of silicon (Fig. 5, II), germanium (Fig. 5, III) and diamond (Ref. 2), no ex-

TABLE I. Channelling angles (10^{-4} rad).

	(011) Plane	[100] Axis
Diamond	1.01	2.1
Silicon	1.03	2.02
Germanium	1.6	2.7

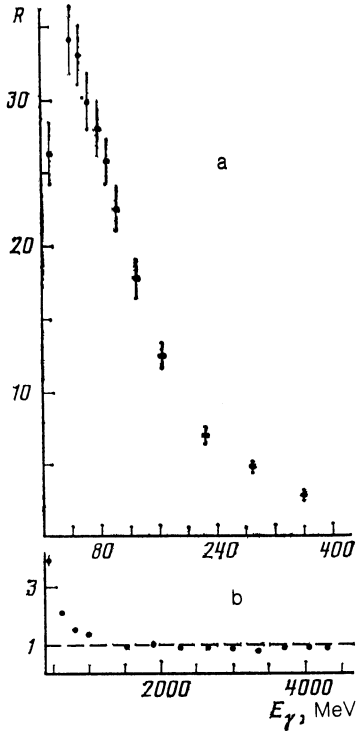


FIG. 3. Spectrum of electron emission from diamond at zero reentrant angle with respect to the (011) plane. The hard part of the "b"-spectrum was measured at a gamma-beam collimation angle of $\pm 5 \cdot 10^{-4}$ rad.

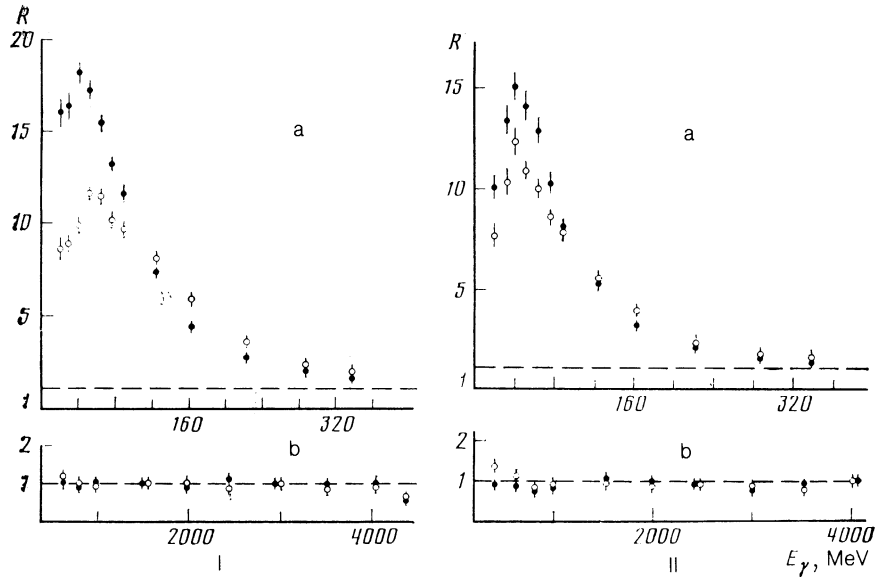
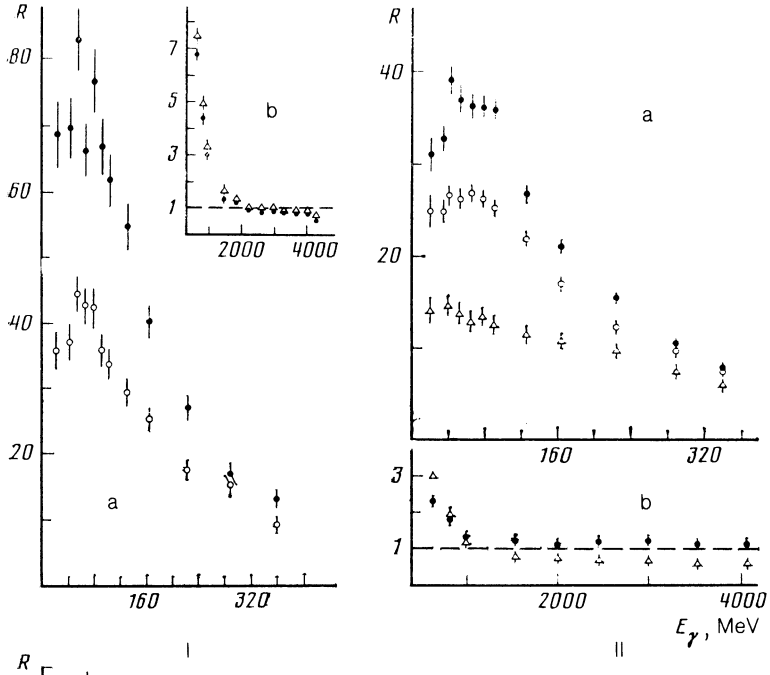


FIG. 4. Spectra of electron emission from silicon (I) and germanium (II) when the reentrant angles with respect to the (011) plane are: ●—0,○—$1.3\cdot10^{-4}$ rad.



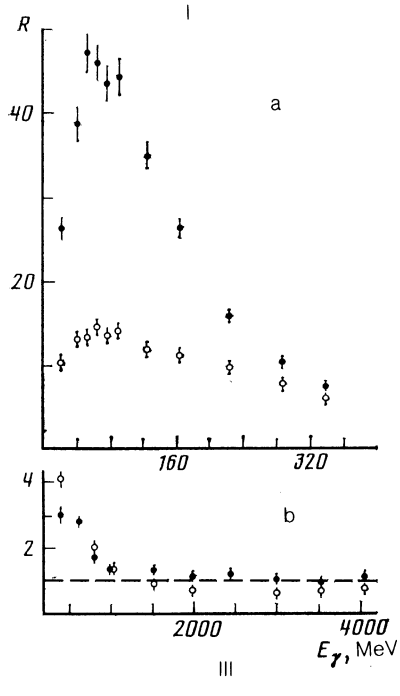


FIG. 5. Spectra of electron emission from diamond (I), silicon (II) and germanium (III) when the reentrant angles with respect to the [100] axis are: ●—0;○—$1.3\cdot10^{-4}$ rad, $\Delta = 3\cdot10^{-4}$ rad; in Fig. IIIa ○—$3\cdot10^{-4}$. The hard part of the "b"-spectrum was measured at a gamma-beam collimation angle of $\pm 5\cdot10^{-4}$ rad.

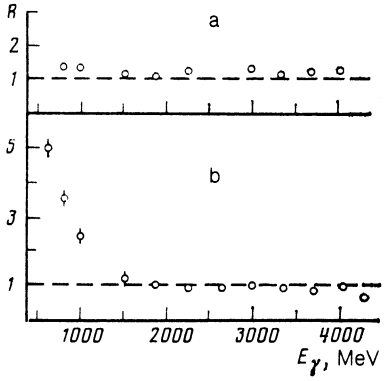


FIG. 6. The hard part of the gamma-quanta emission spectrum from the crystal of germanium with zero reentrant angle: (a) (011) plane, (b) [100] axis. The emission collimation angle is $\pm 5 \cdot 10^{-4}$ rad.

cess in the yield over the one in the randomly oriented crystal for $x > 0.4$ has been observed, even though this excess had been predicted in Ref. 6 for channelled electrons. Moreover, the peak structure in the hard part of the emission spectrum, which was observed in Ref. 3 for $x = 0.85$ is also missing. Our approach to measuring the spectra, with the help of the double magnetic spectrometer, eliminates adding the contributions made by two or more emission acts, which apparently was done in Ref. 3.

The increase in the collimation angle for diamond (Fig. 5, Ib) and germanium (Fig. 6, b) to $\pm 5 \cdot 10^{-4}$ rad has not enhanced yields from the hard part of the spectra over those for the randomly directed crystals. Quite the opposite is true, some degree of lowering in the yield of this emission has been observed for diamond (see Fig. 5, Ib and Ref. 2). Recently[7] a suggestion has been made concerning the effects of collimation on the results of Ref. 2, dealing with the reduction of the high-energy incoherent part of the emission spectrum. As can be observed now, even if the gamma-beam is collimated to $\pm 5 \cdot 10^{-4}$ rad, in the case of diamond a reduction of approximately 20% still remains (Fig. 5, I).

The relative emission yields from electrons with the energies, exceeding the threshold energy, increase with the collimation angles for diamond (Fig. 5, Ib). That follows from the comparison with the results in Ref. 2, which can be explained by the increase in the average scattering angle for the above-threshold electrons moving in the vicinity of the crystal axis. The emission yields from the hard part of the spectrum of above-threshold electrons practically coincide with those from randomly directed crystals for the increased collimation of the gamma-ray beam (Fig. 5, Ib); this last result contradicts the conclusions of Ref. 8.

When electrons move close to the axes of silicon (Fig. 5, IIb) and germanium (Fig. 5, IIIb and 6, b), unlike the case of diamond (Fig. 5, I and also the Fig. in Ref. 2), no lowering of the hard part of the emission spectrum is observed in the energy range 3.0 to 4.5 GeV.

In summary, we can conclude that our results deviated from the theoretical predictions both in the low-energy and in the high-energy parts of the emission spectrum for the three crystals under investigation. In our opinion, the existing theory of emission by electrons moving at small angles with respect to the crystal axes and planes needs some revision.

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