Detection of monochromatic x-ray emission in the interaction of ultrarelativistic electrons with a diamond single crystal

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A yield of monochromatic radiation with an energy of about 19 keV has been detected in the scattering of 600- and 900-MeV electrons by the (100) planes of a diamond. The orientational and spectral characteristics that were measured indicate that a parametric (quasi-Čerenkov) x-radiation has been detected for the first time.

The emission of x-ray photons at Bragg angles caused by ultrarelativistic electrons entering a single crystal has been studied theoretically in many papers (see, for example, the monographs of Refs. 1 and 2 and the bibliography cited in them).

When an ultrarelativistic electron is transmitted through a single crystal (after such a transmission, it corresponds to within a term γ^{-2} to a beam of electromagnetic radiation with a continuous spectrum) in the direction corresponding to the reflections in the Laue diffraction pattern, it causes a monochromatic radiation whose frequency is determined by the type of crystal used and by its orientation:

$$\omega_n = \frac{\cdot\, \pi n}{a\,|\cos\ \psi\,|} \,. \tag{1}$$

Here a is the lattice constant, ψ is the angle between the electron momentum and the reciprocal-lattice vector (Fig. 1), and $n = 1,2,3$ is the diffraction order. Ter-Mikaelyan[3] has also indicated the possibility for the existence of such an effect.

Although this problem has been studied theoretically in detail (see Refs. 4–6, for example), no experimental studies have yet been carried out. In the present letter, we attempt to close this gap.

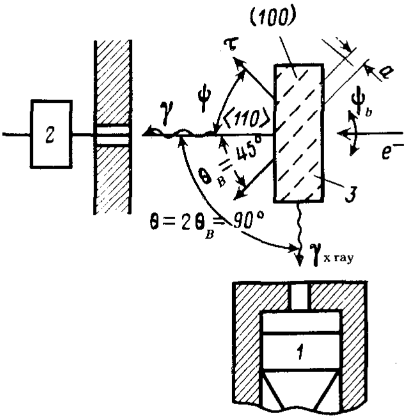

FIG. 1. Experimental arrangement. 1—X-ray spectrometer; 2—Wilson γ detector; 3—diamond single crystal.

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The experiment was carried out in the internal electron beam of the Tomsk synchrotron. A $10\times6\times0.35$-mm diamond single crystal (the $\langle 110\rangle$ axis was directed almost perpendicular to the main face), which was placed in a goniometer with two axes of rotation directed perpendicular to the electron beam, was used as a target. The single crystal in the goniometer was mounted in such a way that the $\langle 001\rangle$ crystallographic axis coincided with the goniometer's vertical axis as closely as possible. The electron beam with an energy $E_0 = 900$ MeV, a divergence of 10^{-4} rad, and monochromatic properties of 0.5% bombarded the target during the time $\tau = 15\times10^{-3}$ s. An induction pickup was used to monitor the number of accelerated electrons.[7]

As an x-ray detector we used a scintillation spectrometer [a 1-mm-thick NaI(Tl) single crystal with a beryllium entrance window, scanned by an FM-85 photomultiplier], whose energy resolution was $\Delta\omega/\omega = 35\%$ for the 14-keV line of ^{57}Co and 25% for the 34-keV line of ^{139}Ce.

The spectrometer was positioned at an angle $\theta = \pi/2$ with respect to the electron beam in a plane precisely at right angles to the vertical axis of the goniometer at a distance $L = 1$ m from the crystal. The entrance collimator corresponded in size to the angular collimation $\Delta\theta = \pm 3\times10^{-3}$ rad (Fig. 1). The spectrometric data were fed to the UHO-1024 analyzer, which was activated during the electron bombardment of the target. The energy equivalent of the threshold was $\omega_{\text{thr}} = 12$ keV.

Since the angular divergence of the radiation under study is on the order of γ^{-1} ($\sim$0.6 mrad, in our case), the orientation of the single crystal (i.e., matching the reflection from any crystallographic plane with the detector axis) is a rather difficult task. To solve this problem, we took advantage of the following situation. When electrons move along the $\langle 110\rangle$ axis, the (100) planes are situated at an angle $\theta_B = 45°$ with respect to the electron momentum, i.e., the condition for the onset of radiation is satisfied in our case. The matching of the crystallographic axis with the direction of motion of electrons, which makes use of the channeling-induced radiation, is a rather simple procedure.[7]

Figure 2a is a plot of the orientational dependence of the current from a Wilson γ-ray detector (curve 1), which measures the total energy of the hard γ radiation in the forward direction (at an angle $\Delta\theta = \pm 0.6$ mrad). The peak in the orientational dependence corresponds to the motion of electrons along the crystallographic axis (the conventional zero point of the goniometer). Also shown in this figure is the simultaneously measured orientational dependence of the x-ray spectrometer counts. At an angle $\psi_{b\,\max} = 2.3$ mrad, we see a sharp peak. After rotating the crystal through a given angle, we measured the orientational dependences again as the crystal was rotated around the horizontal axis (Fig. 2b). These figures show that the orientation corresponding to the maximum number of counts of the spectrometer does not coincide with the orientation corresponding to the axial channeling ($\psi_{b\,\max} = 2.3$ mrad; $\psi_{c\,\max} = 1.9$ mrad). This lack of orientational compatibility stems, in our view, from the errors of the optical alignment of the detector. Figure 3a shows the emission spectrum measured for the orientations $\psi_{b\,\max}$ and $\psi_{c\,\max}$ (curve 1). We note that the spectrum has a peak at an energy $\omega_0 = 19.5 \pm 0.3$ keV and that the total width at half-maximum is $\sim$30%. This value agrees with the resolution of the detector for this energy.

We have measured the spectrum at an emission angle $\theta = 85°$ for this orientation

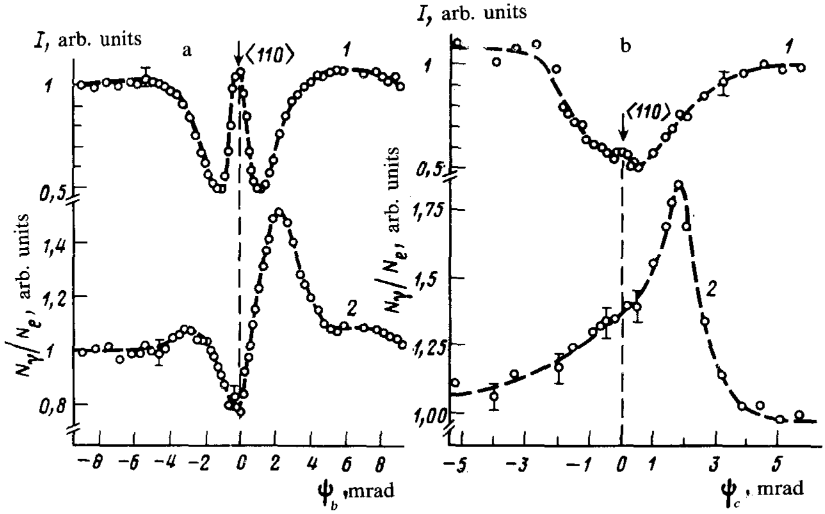

FIG. 2. Orientational dependences of the current from a Wilson γ detector (curve 1 in Figs. 2a and 2b) and of the yield of the x-ray photons (curve 2 in Figs. 2a and 2b).

of the crystal (curve 2 in Fig. 3a). No structural features were observed in the spectrum.

To check our results, we carried out some spectral measurements in the previous geometry ($\theta = 90°$) at an electron energy $E_0 = 600$ MeV. For the orientations $\psi_{b\,\max}$ and $\psi_{c\,\max}$, the spectrum reveals an identical peak with an energy $\omega_0 = 19.3 \pm 0.2$ keV (curve 1 in Fig. 3b).

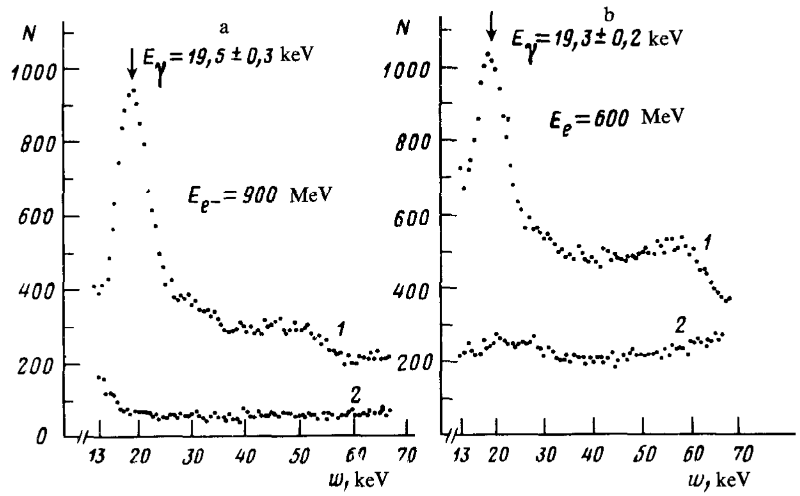

FIG. 3 (a) Emission spectra measured at an exposure to 6×10^{12} accelerated electrons with $E_0 = 900$ MeV for the orientations $\psi_{b\,\max}$ and $\psi_{c\,\max}$ at photon emission angles $\theta = 90°$ (curve 1) and $\theta = 85°$ (curve 2); (b) the same arrangement at an emission angle $\theta = 90°$ and $E_0 = 600$ MeV for orientations $\psi_{b\,\max}$ and $\psi_{c\,\max}$ (curve 1) and for a disoriented crystal (curve 2).

The peak disappears when the orientation of the crystal is changed to an angle $\psi_b = 25$ mrad (curve 2 in Fig. 3b).

In our geometry, a nonzero contribution to the diffraction pattern comes from diffraction orders $n = 4, 8,...,$ which corresponds to an energy of the emitted photons $\omega_n = 9.8, 19.6,...$ keV [see Eq. (1)]. The value $\omega_4 = 9.8$ keV lies below the threshold of our instruments, but the value $\omega_8 = 19.6$ keV is in good agreement with the measured values.

The yield of photons of a given energy (the area under the peak) was estimated with allowance for photon absorption in the target and in the output flange and with allowance for the spectrometer efficiency and line shape:

$$N_\gamma = (0{,}8 \pm 0{,}3) \times 10^{-8} \text{ photon}/e^- \quad (E_0 = 900 \text{ MeV})$$

$$N_\gamma = (0{,}5 \pm 0{,}2) \times 10^{-8} \text{ photon}/e^- \quad (E_0 = 600 \text{ MeV})$$

The orientational and spectral characteristics of the radiation described here suggest that a parametric x-radiation[8] (or a quasi-Cerenkov radiation, according to the terminology of Garibyan and Yan Shi[2]) has been observed experimentally for the first time.

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