Experimental observation of parametric x-ray emission

Yu. N. Adishchev,[1)] V. G. Baryshevskiĭ, S. A. Vorob'ev,[1)] V. A. Danilov, S. D. Pak,[2)] A. P. Potylitsyn,[1)] P. F. Safronov, I. D. Feranchuk, and S. V. Cherepitsa
A. N. Sevchenko Scientific-Research Institute of Applied Physical Problems; V. I. Lenin Belorussian State University, Minsk

(Submitted 12 February 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 7, 295–297 (10 April 1985)

This letter reports the first experimental observation of a new mechanism for x-ray emission by relativistic charged particles in crystals: parametric Vavilov-Čerenkov x radiation.

A charge in uniform motion is known to emit photons if the refractive index of the medium satisfies the condition $n > 1$ (the Čerenkov effect or Vavilov-Čerenkov effect). At frequencies in the x-ray range, which are higher than the characteristic atomic frequencies, the condition $n < 1$ holds,[1] and the Čerenkov effect does not occur. As has been shown by Baryshevskiĭ and Feranchuk,[2–4] however, an effect analogous to the Čerenkov effect—"parametric Vavilov-Čerenkov x radiation"—arises as relativistic charged particles move through crystals. The reason for the effect is that the periodic arrangement of atoms (or nuclei) in a crystal causes the inequality $n > 1$ to hold even in the x-ray range if the frequency ω and the momentum of the photon are near the edge of the Brillouin zone. A theory for the effect is set forth in Refs. 2–7. Parametric x radiation is analogous to the optical parametric radiation which has been studied by Faĭnberg and Khizhnyak for a one-dimensional periodic medium.[8] In the case of a thin crystal with $(\omega/c)|n-1|L \ll 1$ (L is the crystal thickness), there is no parametric emission, but the resonant emission studied by Ter-Mikaelyan[9] may occur.

A characteristic property of x radiation is the existence of diffraction peaks in the x-ray emission, at large angles from the direction in which the particle is moving. The photon emission directions θ_τ and the photon frequencies $\omega_\tau^{(n)}$ do not depend on the energy of the particle. They are determined by the reciprocal-lattice vector $\vec{\tau}$ of the crystal and by the angle (θ_0) at which the particle enters the crystal, measured from the crystallographic planes associated with $\vec{\tau}$; specifically,[6]

$$\theta_\tau = 2\theta_0; \ \omega_\tau^{(n)} = \frac{\tau}{2\sin\theta_0}\frac{\pi n}{d\sin\theta_0}; \ n = 1, 2, 3 \ldots; \ \hbar = c = 1, \qquad (1)$$

where d is the interplanar distance.

An experiment to observe parametric x radiation has been carried out on the Sirius synchrotron at Tomsk for 900-MeV electrons. The spectrum of the x-ray emission at an angle $\theta_\tau = 90°$ from the velocity $\mathbf{v}$ of electrons moving through a diamond single crystal was studied. The experimental arrangement and the parameters of the beam were the same as in Ref. 10, but the spectrum was measured with a xenon-filled proportional counter. The entrance window of the detector was made of beryllium foil 0.3 mm thick, so that this detector was sensitive to photons with energies $\omega < 40$ keV.

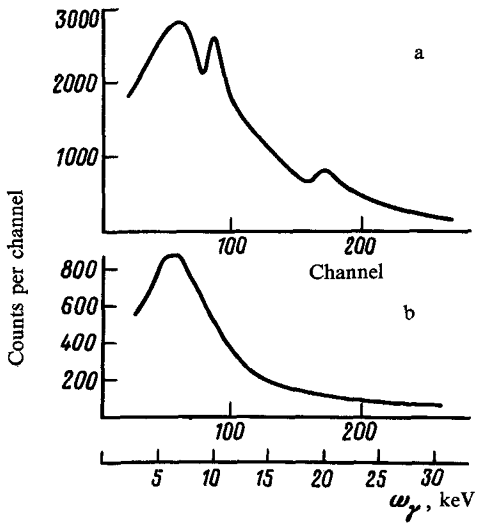

FIG. 1. a—Spectrum of the x-ray emission at an angle of 90° from the direction of the electron beam (electron energy of 900 MeV) in a diamond crystal in the ⟨100⟩ orientation; b—spectrum measured after the crystal was rotated 30 mrad.

The radiation from the vacuum chamber holding the goniometer with the diamond sample was monitored through a window $d_1 = 30$ mm in diameter cut from a plastic similar to Plexiglas with a thickness $l = 6$ mm. The distance from the sample to this exit window was $L_1 = 318$ mm, and the distance to the detector was $L_2 = 1874$ mm. The entrance window of the detector was 50 mm in diameter. An energy calibration of the detector was carried out with a standard set of isotopes. The energy resolution of the detector at the Zn^{65} line, with an energy of 8.2 keV, was 14%.

According to the theory for parametric x radiation,[6] the first peak in the emission spectrum in this particular experimental situation corresponds to Miller indices (4, 0, 0) and occurs at $\omega_{400}^{(T)} = 9.85$ keV (there is no radiation at lower indices because the structure factor vanishes). According to (1), the second peak should lie at an energy $\omega_{800}^{(T)} = 19.7$ keV.

Figure 1a shows the experimental emission spectrum, in which we clearly see two peaks, at energies $\omega_{400}^{(E)} = 9.9 \pm 0.16$ keV and $\omega_{800}^{(E)} = 19.7 \pm 0.16$ keV. Rotating the goniometer 30 mrad around the vertical axis erased the peaks from the spectrum. Figure 1b shows the spectrum of the background x rays measured in this position. The $\omega_{800}^{(E)}$ peak has been observed elsewhere,[10] but the existence of a single peak, emerging only slightly from the background in the emission spectrum, is not a reliable basis for drawing the conclusion that parametric x radiation has been observed, since such a peak might be simulated by background conditions or other processes.

When the crystal is rotated 45° around the vertical, the direction of the beam velocity becomes that of the ⟨100⟩ axis. In this orientation, a detector again making an angle of 90° with **v** should detect parametric x radiation due to the diffraction of the self-field of the particle by (110) planes. Peaks at $\omega_{220}^{(T)} = 6.96$ keV, $\omega_{440}^{(T)} = 13.9$ keV and $\omega_{660}^{(T)} = 20.9$ keV should appear in the spectrum. The experimental spectrum for this case is shown in Fig. 2a; it agrees well with the theoretical predictions, having peaks at

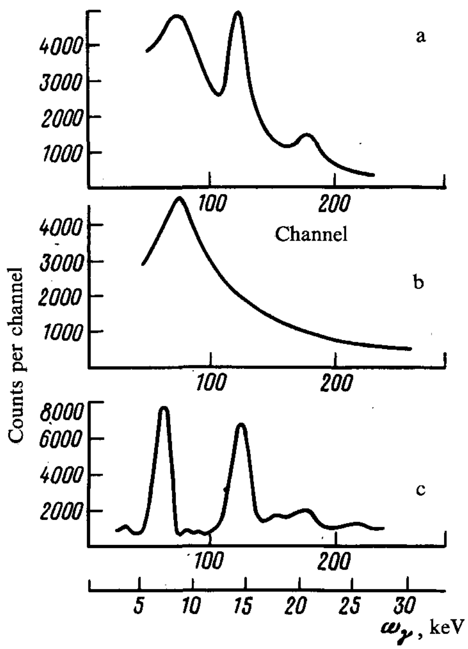

FIG. 2. a—Emission spectrum of the electrons for a crystal in the ⟨100⟩ orientation; b—spectrum after the crystal is rotated 40 mrad; c—spectrum after subtraction of the background, found by replacing the plastic similar to Plexiglas by Lavsan, a polyester.

$\omega_{440}^{(E)} = 14.0 \pm 0.16$ keV and $\omega_{660}^{(E)} = 20.7 \pm 0.16$ keV. After the goniometer is rotated 40 mrad around the vertical axis, the peak disappear from the spectrum (Fig. 2b). When we replaced the plastic similar to Plexiglas, which strongly absorbs radiation with an energy of 7 keV, in the exit window by Lavsan (a polyester), we also detected the peak $\omega_{220}^{(E)} \cong 7$ keV (Fig. 2c). The experimental value of the number of x rays per electron in the (440) peak is $(6 \pm 3) \times 10^{-7}$, while that in the (660) peak is $(0.7 \pm 0.4) \times 10^{-4}$, in good agreement with the theoretical values of 2.3×10^{-4} and 0.3×10^{-7}.

[1)]Polytechnical Institute, Tomsk.
[2)]State University, Tashkent.

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Translated by Dave Parsons