Experimental Observation of Parametric X-Ray Radiation Directed Along the Propagation Velocity of Relativistic Electrons in a Tungsten Crystal

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Parametric X-ray radiation (PXR) due to dynamic diffraction of relativistic electrons is experimentally observed at small angles to the propagation velocity of electrons in a tungsten crystal. The specific features of the experimental method are described, and forward PXR reflections from two crystallographic planes of tungsten are reliably measured.

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Diffraction of the Coulomb field of a fast charged particle propagating in a crystal gives rise to parametric X-ray radiation (PXR) [1–3]. The theory predicts the existence of PXR reflections propagating both along the direction of Bragg scattering and along the emitting particle velocity. However, while the first of the reflections has been studied in detail theoretically and experimentally (see, for example, [4, 5] and references therein), PXR along the particle velocity, or forward PXR, has not been observed so far, although relevant attempts have been made over more than thirty years [6–8].

The forward PXR attracts interest for two reasons. First of all, the observation of such radiation would prove the existence of dynamic diffraction in the case of PXR, because the forward PXR is a purely dynamic effect [4]. In addition, the forward PXR can be interpreted as Cerenkov radiation, which appears due to a change in the refractive index of a crystal upon dynamic diffraction of the electromagnetic field of a fast particle (the effective refractive index becomes greater than unity, which opens up the channel of Cerenkov energy losses of the particle) [9]. Therefore, the observation of forward PXR would confirm the existence of a new type of Cerenkov radiation in the X-ray range.

Experimental observation of the forward PXR is mainly complicated by a small width of the PXR spectrum compared to typical energy resolution of X-ray detectors ($\Delta\omega \geq 150$ eV), which leads to the efficient averaging of the forward PXR against the background of broadband bremsstrahlung and transient radiation. This problem can be solved only by using a crystal grating spectrometer. Note that, in all experiments devoted to the search for forward PXR, targets made of light elements were used. Therefore, the width of the sought-for radiation spectrum did not exceed a few electron-volts [10], and for this reason these experiments have failed.

The observation of forward PXR produced by 855-MeV electrons on the (111) plane of a 56-μm thick silicon crystal and detected with a crystal grating spectrometer was recently reported in [11]. However, the method of suppression of the transient-radiation background in the vicinity of the Bragg frequency, where the forward PXR spectrum is located, used in this experiment is incorrect. The method is based on the use of the negative interference of transient-radiation waves appearing on the input and output surfaces of the target. As shown in [12], it is in the vicinity of the Bragg frequency, where transient radiation should be completely suppressed due to interference, that a narrow radiation peak caused by dynamic effects appears. The contribution of this mechanism to the intensity of detected radiation was not analyzed [11], and, therefore, the nature of the narrow radiation peak observed in this paper remains open.

Our paper is devoted to the experimental search for forward PXR reflection. According to the results of theoretical analysis [10], we use a crystal target made of a heavy element–tungsten. This target offers three important advantages: (i) a substantial increase (up to a few tens of eV) in the width of the forward PXR reflection, which results in a drastic improvement of the signal-to-noise ratio; (ii) an increase in the working (Bragg) frequency, which reduces absorption of photons in air with increasing the distance between the crystal and a detector and allows the use of the advantages of the measurement method [13] for analyzing radiation characteris-

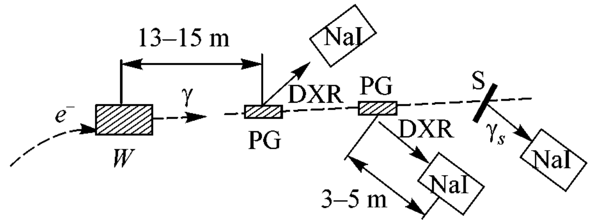

Fig. 1. Scheme of the experiment: W: tungsten crystal; PG: pyrolytic graphite crystal; NaI: NaI(Tl) spectrometers; S: scatterer.

tics; and (iii) a complete exclusion of dynamic effects, caused by diffraction of transient radiation in the crystal, due to strong absorption of detected photons in the crystal. On the other hand, as the target thickness increases, the effect of multiple scattering of electrons and the contribution of bremsstrahlung drastically increase. As shown experimentally and confirmed by a special analysis, the latter can even change the sign of the effect observed.

Measurements were performed using an inner electron beam of the Tomsk synchrotron. Figure 1 shows the scheme of the experiment. Electrons accelerated to the final energy $E_0 = 500$ MeV were incident on a single-crystal target placed in a goniometer. The radiation under study propagated through a collimator, “purified” by a magnet, and was directed to an experimental hall, where the detecting equipment was installed. The crystal was oriented with respect to the electron-beam direction according to the readings of a NaI(Tl) detector in the Compton mounting, which detected photons upon channeling and bremsstrahlung with energy $\omega >$ 0.5 MeV scattered in a converter. The parameters of the electron beam and experimental instruments and the method of orientation are considered in [14, 15].

The X-ray component of radiation was detected using two crystal grating spectrometers based on pyrolytic graphite crystals mounted in goniometers at a distance of 13–15 m from the target, where radiation was generated, and NaI(Tl) detectors of size ∅40 × 1 mm, which were located at a distance of 3–5 m from graphite crystals. Under these conditions, the energy resolution of spectrometers weakly depends on the mosaic structure of crystals but is determined by their angular aperture ($\Delta\theta_x \sim \pm 0.1$ mrad, $\Delta\theta_y = \pm 0.6$ mrad) and the collimation angle of diffracted radiation [13]. The collimation angle in the diffraction plane (horizontal) $\Delta\Theta_x \sim 0.7$ mrad provided the resolution of spectrometers $\Delta\omega/\omega \sim 1\%$. The background level for photons of energy $\omega \geq 40$ keV did not exceed 2–5%. Because of strong absorption of photons with lower energies in the air and target, the background level increased up to 20–30% for $\omega = 28.3$-keV photons (see below). The characteristics of the spectrometers and measuring methods are described in detail in [13].

As shown in [8, 10], the optimal method for searching for forward PXR is measurement of the dependence of the number of photons in a narrow spectral range on the crystal orientation. For photons with energies above 20–25 keV, the Bragg condition can be satisfied only for several low-index planes and quite specific crystal orientations. A criterion for the observation of the effect is the coincidence of Bragg energies for the orientation angles at which the peak of the photon yield is observed with the energies to which diffractometers are tuned. According to the theory [9, 10], the forward PXR intensity in a tungsten crystal becomes comparable with the transient radiation intensity only for photons with energies $\omega \leq \gamma\omega_p \sim 80$ keV, where γ is the Lorentz factor and ω_p is the plasma frequency of the medium. Therefore, we detected simultaneously the yield of photons with $\omega < \gamma\omega_p$ (67, 40, and 29 keV) and $\omega > \gamma\omega_p$ (95 and 97 keV). To control the absence of radiation during plane channeling, we measured the yield of ≥0.5-MeV photons by means of a Compton NaI(Tl) detector. This detector was also used to make the electron-beam direction coincident with the crystal axis, from which the reorientation angles of crystal planes were measured.

Measurements were performed for a tungsten single crystal of size 8.5 × 0.41 mm, with the $\langle 111\rangle$ orientation and the surface mosaic structure $\sigma < 0.2$ mrad. In tungsten crystals grown by the same method, anomalous propagation of X-rays was observed [16]. The crystal was mounted in the goniometer so that the $(11\bar{2})$ plane was almost vertical. This allowed us to study dynamic effects in radiation both for the $(11\bar{2})$ plane and two (110) planes turned by 30° with respect to this plane. The measurements of orientation dependences of the yield of scattering photons in the case of plane channeling (Fig. 2a, curve *1*) showed that the $(11\bar{2})$ plane is turned by the angle $\beta = 3.5° \pm 0.2°$ with respect to the vertical plane. Therefore, dynamic effects in radiation should be observed for each of the crystal planes at different orientation angles Θ (see Fig. 2b).

One can see from the orientation dependence of the yield of 67-keV photons (curve *2*) that the X-ray radiation intensity depends substantially on the orientation of crystal planes with respect to the electron-beam direction. Therefore, as in experiment [8], measurements were performed for the case of the intersection of the $\langle 111\rangle$ axis, when the plane channeling effect was absent.

Our measurements showed that no forward PXR peaks were observed for relatively hard photons with $\omega \geq \gamma\omega_p$ (67, 95, and 97 keV). The presence of the crystal structure manifested in the decrease in the number of photons detected by spectrometers when the Bragg energy for the given orientation of the crystal coincided

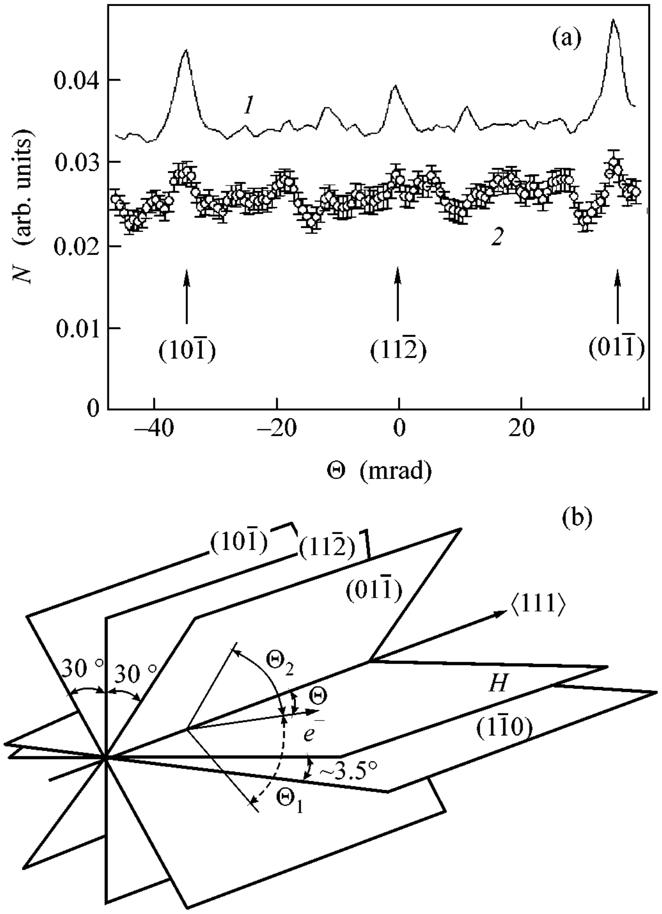

Fig. 2. (a) Orientation dependences of radiation yield. Curve *1*: signal of the detector of Compton photons with $\omega \geq 0.5$ MeV; *2*: $\omega = 67$ keV; (b) scheme of the arrangement of crystal planes: H is the horizontal plane (vertical plane is not shown); Θ is the angle between the ⟨111⟩ axis and the electron-beam direction in the horizontal plane; $\Theta_{2(1)} = \Theta\cos(30° \pm \beta)$ are angles between the propagation direction of electrons and planes $(10\bar{1})$ and $(01\bar{1})$.

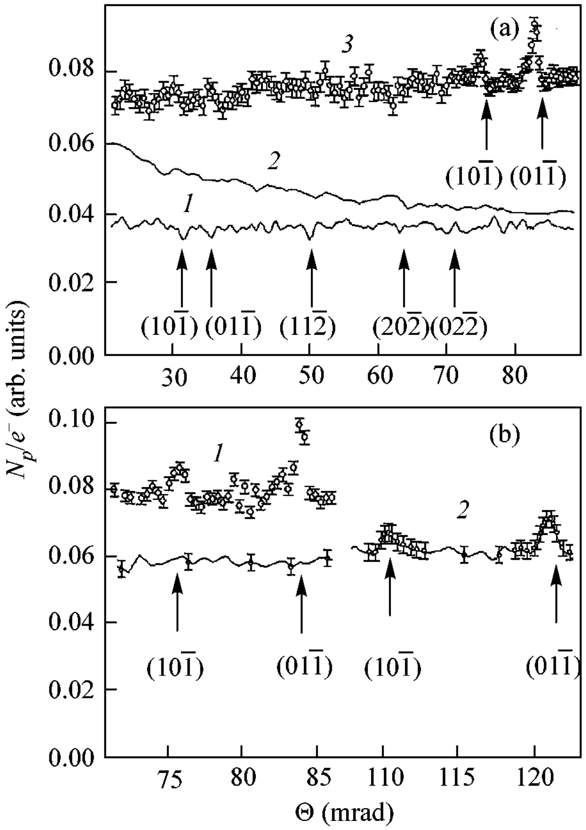

Fig. 3. Orientation dependences of soft radiation yield: (a) $\omega = 95$ keV (curve *1*); $\omega = 40$ keV (curve *2*); $\omega \geq 0.5$ MeV (curve *3*); (b) $\omega = 40$ keV (curve *1*); $\omega = 28.3$ keV (curve *3*).

with the photon energy (see Fig. 3a, curve *1*). The positions of minima of the orientation dependence correspond to the kinematic conditions for diffraction of photons directed along the electron beam with an error no worse than 1%. For example, for $\omega = 67$ keV, the calculated positions of minima for the $(10\bar{1})$, $(01\bar{1})$, and $(11\bar{2})$ reflections are 46.6, 49.9, and 72.2 mrad, whereas the measured values are 46.3, 49.5, and 71.9 mrad. The depth of minima changes from 12–15% for $\omega = 67$ keV to ~10% for $\omega > 90$ keV. The typical value of the full width of the minimum is $\Delta\Theta \sim 1.5$–2.5 mrad. The experimental curve differs from the theoretical curve (a narrow minimum with a width of the order of the Darvin table width $\Delta\Theta \leq 0.1$ mrad and depth ~0.5 from the substrate level), because graphite crystals are not parallel to the plane on which diffraction occurs and spectrometers have a finite angular aperture and a limited resolution.

The calculation of the orientation dependence of the forward PXR yield [10], taking into account multiple scattering of electrons and diffraction of bremsstrahlung in a crystal, confirmed that, for the photon energy $\omega \sim \gamma\omega_p$ and zero observation angle (the detected radiation is emitted along the electron-beam direction), diffraction of bremsstrahlung inside the crystal masks the sought-for effect. The forward PXR becomes dominant only for the photon energy $\omega \leq 0.5\gamma\omega_p$ (see Fig. 4).

The orientation dependences measured for photon energies 40 and 28.3 keV exhibit distinct maxima, whose positions, as minima for hard photons, agree with the Bragg law (see Fig. 3). These maxima are not related to radiation with a continuous spectrum or to experimental errors. This is confirmed by their absence in the yield of ≥0.5-MeV photons (Fig. 3a, curve *1*) and their different positions in the orientation dependences of the yield of photons with different energies (Fig. 3b). The position and shape of the maxima were reliably reproduced in repeated measurements.

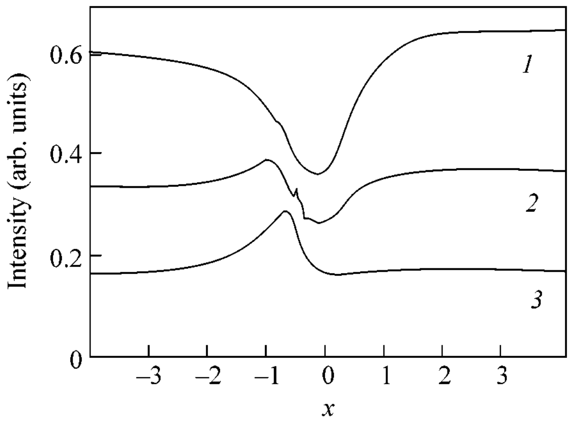

Fig. 4. Orientation dependences of the X-ray radiation yield in the (110) plane in the region of Bragg angles $x = (g^2/2\omega_g^2)(\omega - \omega_B/\omega_B)$ (see [10]). Curve *1*: ω = 65 keV; *2*: ω = 40 keV; *3*: ω = 26 keV.

Measurements of the spectra of diffracted radiation at the peak for ω = 40 keV – $\Theta_{01\bar{1}}^{\exp}$ = 83.9 mrad and at the neighboring points (Θ = 81.3 and 79.3 mrad) showed that the radiation intensity increases only for the first reflection order. The radiation intensity in the higher reflection orders coincides for all the spectra. The crystal thickness t = 0.41 mm substantially exceeds the lengths l_a ~ 42 and 19 μm at which photons are absorbed, i.e., the peaks observed in the orientation dependences of the yield of photons with $\omega < \gamma\omega_p$ are caused by radiation excited inside the crystal. The only known mechanism of radiation of electrons in crystals with such properties is parametric (quasi-Cerenkov) X-ray radiation along the electron propagation velocity in a crystal [9].

The peak positions $\Theta_{10\bar{1}}^{\exp}$ = 76.6 (110.2) mrad and $\Theta_{01\bar{1}}^{\exp}$ = 83.9 (120.9) mrad measured in experiments for photons with energy 40 (28.3) keV differ somewhat from the estimated values $\Theta_{10\bar{1}}^{\mathrm{est}}$ = 77.9 (110.2) mrad and $\Theta_{01\bar{1}}^{\mathrm{est}}$ = 83.6 (118.2) mrad. The distance between the peaks is larger by 1.5 and 2 mrad than follows from the Bragg law. For both photon energies, the width of the peak for the $(01\bar{1})$ plane is almost twice as large as that for the $(10\bar{1})$ plane. For ω = 40 keV, this peak quite distinctly divides into two peaks (Fig. 3b).

According to the theory, the forward PXR energy is determined by the angle $\theta_{\parallel}$ of escape of a photon in the direction perpendicular to the plane at which reflection occurs. The reflection intensity along the electron propagation direction is zero, while the maximum of the angular distribution corresponds to the angle $\theta_{\parallel}^{FPXR} = \frac{1}{\sqrt{3}}\sqrt{\gamma^{-2} + (\omega_0/\omega)^2}$. We detected photons caused by electrons moving at the angle θ^{FPXR} to the electron-beam direction. Radiation was generated on the planes of the tungsten crystal turned by the angle ~30° with respect to the reflecting plane of the diffractometers. Along with a finite angular aperture and limited resolution of the spectrometers, this should inevitably result in the broadening of experimental curves and in the decrease in the amplitude of the peaks compared to the theoretical predictions. We plan to take experimental factors into account and compare quantitatively the results of measurements with the theory in the next paper.

The results of the study can be summarized as follows:

(i) We have observed quasi-Cerenkov X-ray radiation of fast charge particles in a material with a medium refractive index $n < 1$.

(ii) Diffraction suppression of bremsstrahlung of relativistic electrons in a crystal has been reliably observed, and the competition between quasi-Cerenkov radiation and diffraction suppression of bremsstrahlung has been demonstrated.

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