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Observation of the Enhancement of Parametric Radiation under Conditions of the Grazing Incidence of Relativistic Electrons on the Crystal Surface

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The enhancement of the yield of parametric X-ray radiation from 7-MeV electrons incident at a grazing angle on the silicon crystal surface has been experimentally detected.

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1. Parametric X-ray radiation from relativistic electrons in crystals appearing due to the coherent Bragg diffraction of the Coulomb field of a fast electron on the system of the atomic planes of a crystal makes it possible to generate beams of quasimonochromatic X rays with a smoothly tunable line [1–5]. Since the intensity of this emission mechanism is low primarily owing to photoabsorption in a target, its application is very complicated. For this reason, the search for methods for increasing the yield of parametric X-ray radiation is an important problem of radiation physics. The recently proposed scheme for generating parametric X-ray radiation under the conditions of the grazing incidence of emitting electrons on the crystal surface and asymmetric diffraction geometry [6] provides an increase in the yield by more than an order of magnitude due to the increase in the effective path of a fast electron in the absorbing crystal on which photons that can leave the target are generated.

In this work, the first experimental observation of the enhancement effect is reported [6].

2. The possibility of implementing the approach proposed in [6] with the use of the characteristic property of a fast electron to emit parametric X-ray photons at large angles to the electron velocity is illustrated in Fig. 1. Here, the y axis is normal to the crystal surface coinciding with the xz plane. The reflecting crystallographic plane R specified by the corresponding reciprocal lattice vector $\mathbf{g}$ is directed at the angle β to the crystal surface; the electron beam axis making the angle α with the surface is denoted as $\mathbf{e}_1$. The detector axis $\mathbf{e}_2$ coincides with the Bragg scattering direction so that the unit vector in the radiation direction $\mathbf{n}$ is specified by the expression $\mathbf{n} = \mathbf{e}_2(1 - 1/2\Theta^2) + \mathbf{\Theta}$, where the component $\mathbf{\Theta}$ lying in the reaction plane is shown in Fig. 1. This figure also presents the length of the generation of photons by electrons in the crystal $L_{\rm el}$. This length is related to the photoabsorption length $L_{\rm ab} = 1/\omega\chi_0''(\omega) \approx 1/\omega_{\rm b}\chi_0''(\omega_{\rm b})$, where $\omega_{\rm b} = g/2\sin(\beta + \alpha)$ is the Bragg frequency near which the spectrum of parametric X-ray radiation is concentrated and χ_0'' is the imaginary part of the dielectric susceptibility of the crystal, by the formula

$$L_{\rm el}/L_{\rm ab} = \sin(2\beta + \alpha)/\sin(\alpha). \qquad (1)$$

According to this formula, $L_{\rm el}$ can be much larger than $L_{\rm ab}$ under the conditions of small grazing angles α and large radiation angles $2(\beta + \alpha) \approx 2\beta$ (the optimal β value is close to $\pi/4$).

The kinematic-approximation calculation [6] of the number of parametric X-ray photons emitted in

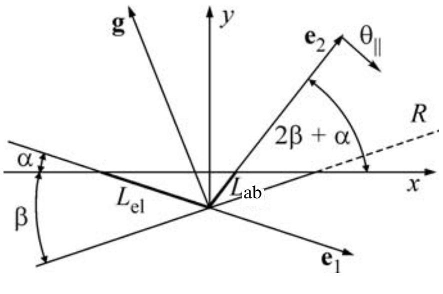

Fig. 1. Emission process geometry. The notation is given in the main text.

the grazing incidence regime provides the expression

$$N(\alpha, \beta) = \frac{2e^2\omega_g^4}{g^4}\left[\ln(1+\gamma^2\theta_d^2) - \frac{\gamma^2\theta_d^2}{1+\gamma^2\theta_d^2}\right] \times \left[\frac{\sin(2\beta+\alpha)\sin^2(\beta+\alpha)(1+\cos^2(2\beta+2\alpha))}{\sin(\alpha)\chi_0''\left(\frac{g}{2\sin(\beta+\alpha)}\right)}\right] \quad (2)$$

differing from the traditional formula in the theory of parametric X-ray radiation only by factor (1), which is the gain coefficient. Here, $\omega_g^2 = \omega_0^2 F(g)|S(\mathbf{g})|\exp -\frac{1}{2}g^2u_T^2$, where ω_0 is the plasma frequency of the target, $F(g)$ is the atomic form factor, $S(\mathbf{g})$ is the structure factor of the crystal unit cell, u_T is the rms amplitude of thermal vibrations of atoms, γ is the Lorentz factor of an emitting electron, and θ_d is the angular size of the photon collimator.

3. The experiment was performed at a setup created at the output of the microtron at the Lebedev Physical Institute. Figure 2 shows the layout of the experimental setup. Electron beam *2* with an energy of 7 MeV passed through two carbon collimators *3* with a hole diameter of 7 mm. To reduce the background from microtron *1* and collimators *3*, the magneto-optic channel of the setup was equipped with two bends with bending magnets *4* for the correction of the electron beam, which prevent the direct penetration of the background to the vacuum chamber. The electron beam is guided through the magneto-optical channel to target *7* placed in the vacuum chamber as shown in Fig. 2. Silicon crystals with thicknesses of 450 and 200 μm were used as targets. The crystals were oriented with respect to the electron beam by means of a goniometer with three rotational degrees of freedom. The target block had the capability of extracting the crystals from the electron beam. To focus the beam onto the target, we used magnetic lenses *5* placed in front of corrector *6*. Proportional chamber *11* placed behind the target was used to determine the vertical and horizontal profiles of the beam and its position on the target. X rays *10* were detected by silicon–lithium pin detector *9* whose axis was at an angle of 160° to the electron beam axis. The detector was connected to the vacuum chamber through the vacuum photon channel with lead collimator *8* and was protected from the microtron background by lead shield *13*. The electron beam current was measured by Faraday cylinder *12*. The distance between the target and detector was 3.2 m. The detector detected radiation in a solid angle of 3.1×10^{-7} sr. The target chamber was not vacuum separated from the microtron. The vacuum was maintained at a level of no worse than 10^{-4} Torr.

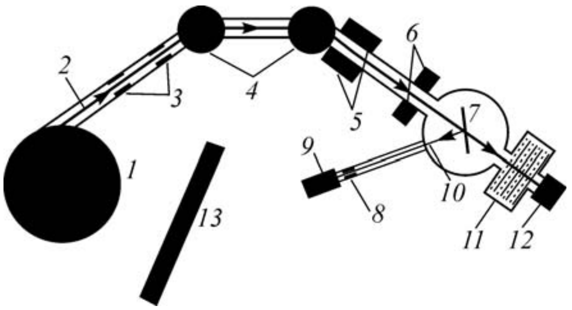

Fig. 2. Layout of the experimental setup. The notation is given in the main text.

4. The experiment was performed in two stages. At the first stage, the yield of parametric X-ray radiation from the silicon crystal target with the (111) reflecting crystallographic plane parallel to the crystal surface was measured. In this case, the angle β is zero and the angle α is 1.222 for the peak of parametric X-ray radiation in the region 2100–2200 eV, where the photoabsorption length is minimal (this region is above the *K* edge of the silicon photoabsorption, which is 1840 eV). This circumstance makes it possible to exclude the effect of the target thickness and to strongly reduce the effect of multiple scattering. The propagation direction of parametric X-ray radiation in the first experiment is close to the direction of the mirror mapping of the electron beam axis with respect to the target surface and, according to Eq. (1) at $\beta = 0$, the effective photon generation length L_{el} is close to the parametric X-ray radiation photoabsorption length L_{ab}.

At the second stage, the yield of parametric X-ray radiation was measured from the silicon target with the surface parallel to the (100) crystallographic plane and the (111) reflecting plane was at an angle of $\beta = 0.955$ to the plane. The grazing angle α was taken to be 0.267 in order for the generation regions of parametric X-ray radiation to be the same in both experiments. In the case under consideration, the effective generation length is much larger than L_{ab}.

To obtain the brightest effect, two conditions should be satisfied. The first condition is that the angle α between the beam axis and target surface should be as small as possible. The second condition is that the propagation of parametric X-ray radiation should be close to normal to the target surface (in this case, the photoabsorption is minimal). Owing to the finiteness of the cross section of the electron beam, the achievement of the first condition is the most difficult, because the beam trace on the target surface increases at small angles of incidence and a target with a large surface area is necessary at these angles. The investigations of the beam at the target place indicate that the beam has a circle cross section with a diameter of 5 mm and an angular divergence of no more than

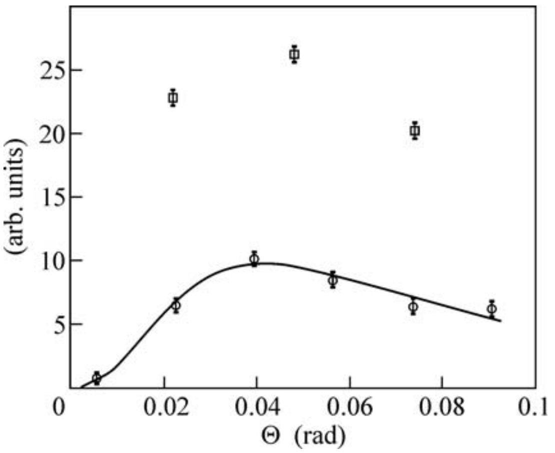

Fig. 3. Orientation dependences of the yield of parametric X-ray radiation from the silicon crystal for the (○) incidence of electrons on the target surface at large angles and (□) grazing incidence. The (111) reflecting crystallographic plane is used.

5 mrad. Such a divergence is small as compared to the width of the angular distribution of parametric X-ray radiation and only slightly affects the characteristics of the measured signal.

To control the coincidence of the numbers of electrons transmitted through the target in both experiments, we used the normalization to the yield of characteristic radiation additionally measured in both cases.

The orientation dependence of the yield of parametric X-ray radiation was measured at the first stage. The results are shown in Fig. 3 along with the corresponding orientation dependence calculated in the kinematical approximation, as well as the experimental orientation dependence of the yield of parametric X-ray radiation in the grazing regime. The last dependence is presented by three points marking its maximum. It is clearly seen that the yield is about tripled in good agreement with the calculations. The main problem for the comparison of the presented orientation dependences is the background whose intensity in the grazing case increases with a decrease in the angle of incidence of the electron beam on the target. For correct comparison of the yields of parametric X-ray radiation in both cases, Fig. 3 shows the experimental data with the subtraction of the background (the background level was no more than 20% of the total statistics).

5. In summary, the effect of the increase in the yield of parametric X-ray radiation in the regime of the grazing incidence of the emitting electron on the surface of the crystal target in the asymmetric scattering geometry has been clearly detected in the reported measurements. This result confirms that the proposed method for increasing the intensity of an X-ray source based on the parametric X-ray radiation mechanism is promising.

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