Measuring Coherent Peaks of Polarization Bremsstrahlung from Relativistic Electrons in Polycrystalline Targets in Backscattering Geometry

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Abstract—The spectra of polarization bremsstrahlung (PB) in the X-ray range induced by 7-MeV electrons in a polycrystalline copper target have been measured in the backscattering geometry for various orientations of the target relative to the electron beam. It is shown that the PB backscattering is sensitive to the texture of a target. The possibility of developing a new method based on the measurement of characteristics of the coherent PB component for the diagnostics of polycrystalline materials is considered.

Polarization bremsstrahlung (PB) radiation appears when a high-energy particle moves in a target and its Coulomb field is scattered from atomic electrons of the substance [1, 2]. A large value of the effective impact parameter (comparable with atomic dimensions) for the collisions of high-energy particles with atoms of the target leads to a strong dependence of the PB characteristics on interatomic correlations in the target. It was shown [3–6] that, using the spectra of energy dispersive PB excited by relativistic electrons moving in a polycrystalline solid, it is possible to obtain information on the target structure. Experimental data on the positions and shapes of coherent PB peaks measured for the scattering angles close to 90° (relative to the electron beam direction) for aluminum, copper and nickel targets showed good coincidence with the theoretical results.

It has been theoretically predicted [7] that the energy resolution of measurements can be significantly improved by detecting PB signals in the direction opposite to the velocity of emitting electrons, that is, in the backscattering (BS) geometry. It was established that the amplitude of the PBBS peak is proportional (and the spectral peak width is inversely proportional) to the square of the electron energy. For PB peaks measured at the angles different from π, the corresponding characteristics exhibit linear (and inversely proportional) dependence on the electron energy. It addition, the PBBS is not suppressed by the Fermi density effect [8]. Attempts to detect the predicted PBBS peaks were undertaken [9, 10], but no reliable experimental data have been obtained until now.

This Letter presents the first reliable results concerning coherent X-ray PB peaks measured in the BS geometry for 7-MeV electrons in polycrystalline copper target, which show evidence for a high sensitivity of the PBBS peak characteristics to the target material texture.

Theoretical analysis [7] of the PB from relativistic electrons moving in an infinite polycrystalline medium led to the following formula for the relative width of a coherent PB peak:

$$\frac{\Delta\omega}{\omega} \approx \frac{\sqrt{\cos^2(\theta/2) - (1/4)\rho^2\cos(\theta)}}{\rho^{-1}\sin(\theta/2)}, \qquad (1)$$

where θ is the angle between the velocity of emitting electron and the direction of PB photon propagation, $\rho^2 = \gamma^{-2} + \omega_0^2/\omega^2$ is the coefficient that takes into account (second term) the density effect, γ is the Lorentz factor of electron, and ω_0 is the plasma frequency of the target material. According to this formula, the relative peak width is inversely proportional to the electron energy in cases where the observation angle θ is different from π and the average peak frequency ω exceeds $\gamma\omega_0$ (critical value for the density effect).

It can be readily seen from formula (1) that, for $\theta \longrightarrow \pi$, the spectral peak width sharply decreases and becomes inversely proportional to the square of the electron energy:

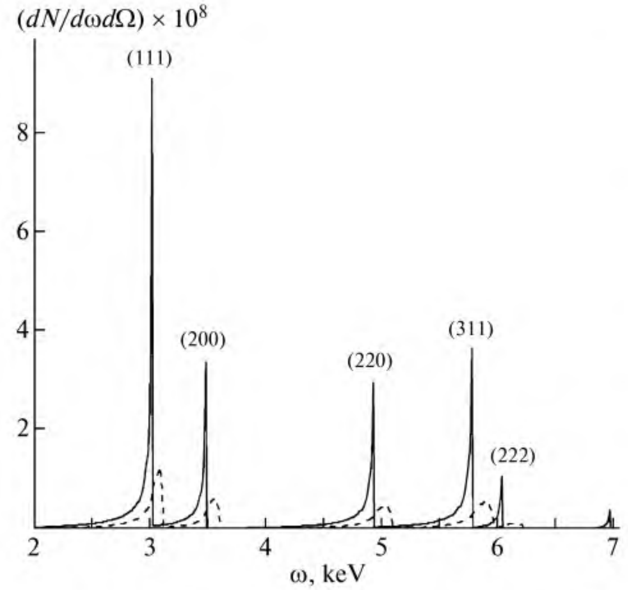

Fig. 1. Spectral-angular distribution of coherent PBBS intensity from polycrystalline copper calculated for $\theta = 160°$ (dashed curve) and 180° (solid curve).

$$\frac{\Delta\omega}{\omega} \approx \frac{\rho}{2}\sqrt{\rho^2 + (\Delta\theta)^2} \longrightarrow \frac{\rho^2}{2} \approx \frac{\gamma^{-2}}{2}, \qquad (2)$$

where $\Delta\theta = \pi - \theta$. This expression shows that the effects of multiple scattering, angular divergence of the electron beam, finite beam cross section, and beam collimation angle on the spectral width of PBBS peaks are insignificant, provided that

$$\Delta\theta \ll \sqrt{\gamma^{-2} + \omega_0^2/\omega^2}$$

(where $\Delta\theta$ includes all the aforementioned factors). Figure 1 presents examples of the spectra of coherent PBBS from polycrystalline copper calculated for $\theta = 160°$ and 180°. With allowance for suppression of the density effect [8], formula (2) in this case must be written with $\rho^2 = \gamma^{-2}$.

In this study, the PBBS measurements were performed on a modified ROENTGEN setup [5, 6] in a experimental arrangement that is schematically depicted in Fig. 2. Introduction of the third beam-rotating magnet *2* (closest to the target) rendered the experimental setup geometry a minimum background generated by 7-MeV microtron and collimators *3* of the primary electron beam *1*. The narrowing of PB spectral lies according to Eq. (2) is observed provided the minimum cross section and angular divergence of the electron beam. The third beam-rotating magnet ensured electron beam focusing in the horizontal plane on the target *7* mounted in vacuum chamber *6*. A more exact beam focusing and adjustment on the target were provided by quadrupole lenses *4* and corrector *5*. The electron beam position and profile on the target were monitored by proportional chamber *10*. The PBBS was measured by *p–i–n* X-ray detector *9* that ensured an energy resolution of 152 eV at an effective 6-mm size of beryllium window. The target was made of 25-μm-thick foil of electrotechnical grade copper. The optimum target thickness was chosen so as to provide for the saturation of PB reflections in a 3–8 keV energy range at insignificant scattering of the electron beam by the target. Collimators *8* reduced the level of background formed due to the interaction of scattered electrons with parts of the experimental setup occurring in the region of detection. The first collimator (closest to the target) was made of organic glass and had a 2-mm window, while the second collimator was mad of lead and had a 10-mm window.

The PB spectra measured in the configuration described above displayed coherent PBBS peaks from various crystallographic planes. Figure 3a shows the PBBS spectrum measured for the target plane oriented perpendicular to the electron beam, which exhibits no reflections from (200) planes and weak reflections from (111) and (311) planes. According to calculations, this manifestation of PB reflections is characteristic of textured targets. This hypothesis is confirmed by a change in the intensity of PB reflections depending on the orientation of target relative to the electron beam. The spectrum in Fig. 3b shows an increase in relative intensity of the (220) peak, while the other peaks are suppressed. The relative intensities are determined by comparing amplitudes of the PB peak and the instrumental signal at 6.3 keV (ESC) corresponding to the energy difference between the *K* line of copper and the absorption edge of silicon in the XHray detector. The PB spectrum presented in Fig. 3c, which was obtained for another random (not normal) orientation of the target, differs from the

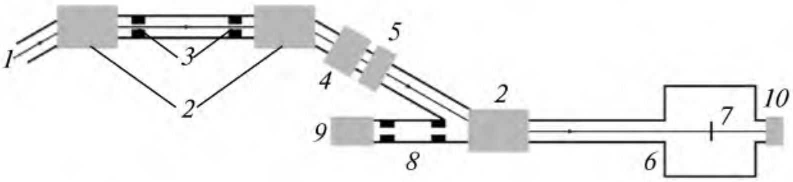

Fig. 2. Schematic diagram of experimental arrangement: (*1*) vacuum channel of primary electron beam; (*2*) beam-rotating magnets; (*3*, *8*) beam collimators; (*4*) quadrupole lenses; (*5*) bean corrector; (*6*) vacuum chamber; (*7*) target; (*9*) X-ray detector; (*10*) proportional chamber.

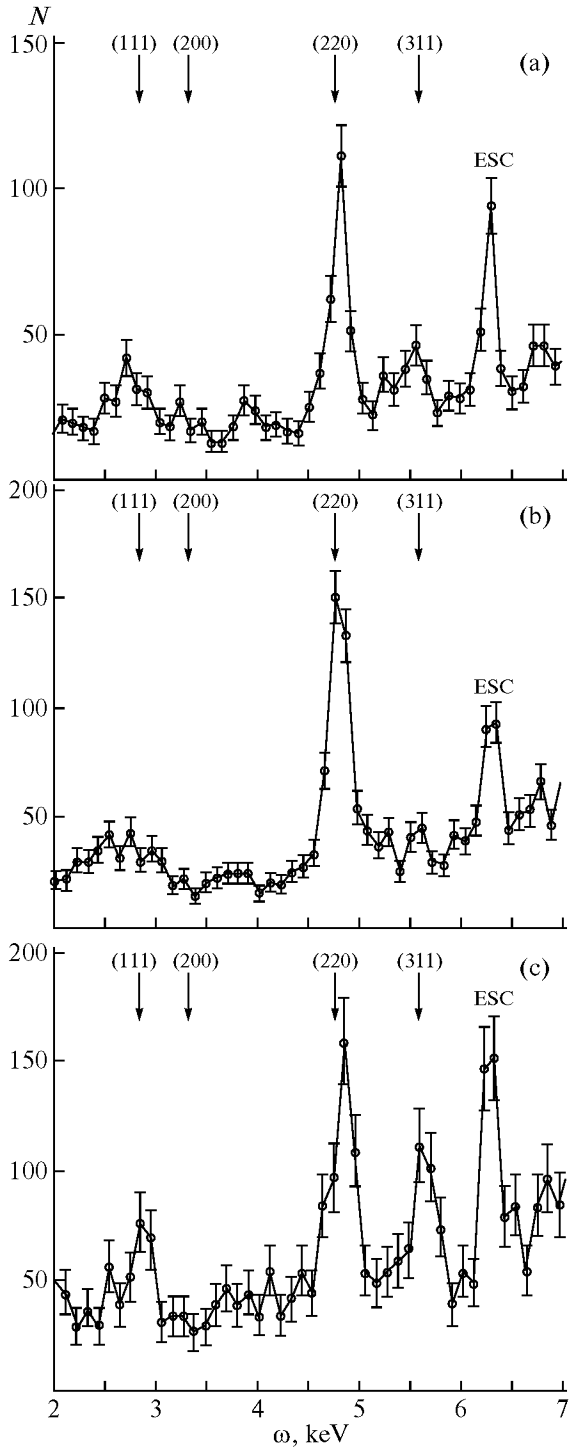

Fig. 3. PBBS spectra measured for the (a) normal and (b, c) random (different) orientations of a polycrystalline copper foil relative to the electron beam.

spectra in both Figs. 3a and 3b by a decreased intensity of reflection (220) and increased heights of the (111) and (311) peaks. A comparison of the three spectra shows that the spectral widths of the PBBS peaks and 6.3-keV signal; are approximately the same. This fact allows us to suggest that a real PBBS peak width is close to the spectral width of the characteristic X-ray *K* line of copper. Therefore, additional measurements of the PB peaks using a detector with better energy resolution are necessary.

The narrow PBBS peaks reliably detected in this investigation are extremely sensitive to the structure of polycrystalline targets. This circumstance is of considerable interest for a further development of the new energy-dispersive method of PB diagnostics of the sample structure. Potential advantages of the proposed method are the exact knowledge of the spectrum of pseudo-photons of the Coulomb field of high-energy electrons (pseudo-photons play the role of the primary probing radiation), which is necessary for the energy-dispersive method. On addition, it is possible to achieve a high spatial resolution in the PBBS measurements by means of simple magnetic focusing of the primary electron beam on the target [4].

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