Measurement of the Polarization Bremsstrahlung of Relativistic Electrons in Polycrystalline Targets

V. A. Astapenko[a], A. S. Kubankin[b], N. N. Nasonov[b], V. V. Polyanskiĭ[c], G. P. Pokhil[d], V. I. Sergienko[c], and V. A. Khablo[c]

[a] *Moscow Institute of Physics and Technology,*
Institutskiĭ per. 9, Dolgoprudnyĭ, Moscow region, 141700 Russia
[b] *Laboratory of Radiation Physics, Belgorod State University, Belgorod, Russia*
[c] *Lebedev Physical Institute, Russian Academy of Sciences,*
Leninskiĭ pr. 53, Moscow, 119991 Russia
e-mail: sergienk@x4u.lebedev.ru
[d] *Institute of Nuclear Physics, Moscow State University,*

The spectra of the collimated polarization bremsstrahlung of 7-MeV electrons intersecting Al, Cu, and Ni polycrystalline films have been measured. Detailed quantitative comparison of the experimental data with theoretical predictions has been performed. It has been shown that the model of a polycrystal as an ensemble of randomly oriented single crystals adequately describes the experimental results. This makes it possible to expect the development of a new method of diagnostics of the atomic structure of partially ordered solids.

Polarization bremsstrahlung appears in the process of the interaction of a fast charged particle with the electron shell of an atom. As a result, the dynamical polarization of the shell occurs and the Coulomb field of this particle is scattered by atomic electrons. The microscopic theory of polarization bremsstrahlung developed to date is used to describe well known processes such as Cherenkov, Raman, and diffraction radiations, which are traditionally described in macroscopic electrodynamics [1–3]. The characteristic feature of polarization bremsstrahlung that strongly differs it from usual bremsstrahlung is that the effective impact parameter of the collision of the incident particle with the atom is large, comparable with the atomic size. Owing to this feature, polarization bremsstrahlung formed in a condensed medium becomes very sensitive to the character of the mutual arrangement of the atoms of the medium, which will probably allow the use of polarization bremsstrahlung for the diagnostics of the atomic structure of matter.

In this work, the coherent effects caused in the polarization bremsstrahlung of relativistic electrons by the partial ordering of the atomic structure of most widespread solid polycrystalline targets is experimentally studied. The coherent peaks were previously observed [4] in the polarization bremsstrahlung spectrum of 2.4-MeV electrons intersecting a thin polycrystalline aluminum film. The polarization bremsstrahlung of 150-MeV electrons moving in polycrystalline molybdenum was experimentally investigated in [5], where the sensitivity of the polarization bremsstrahlung to the manifestation of texture in polycrystals was demonstrated. In this work, the detailed comparison of the absolute measurements of the spectra of collimated polarization bremsstrahlung from Al, Cu, and Ni films with the theoretical model [6] shows that the theory and experiment are in good quantitative agreement with each other.

An electron beam from a 7-MeV microtron passes in a magneto-optic channel through a system of collimators, quadrupole lenses, and magnets and is directed to a box, where a target is placed. Polycrystalline 8.5-μm aluminum, 15-μm cooper, and 15-μm nickel foils are used as targets. The target was mounted at an angle of 45° to the beam axis. X-ray radiation outgoing from the target into the forward hemisphere passes in a photon channel placed at an angle of 90° to the electron beam axis and is detected by a noncooled silicon–lithium pin detector. The angular acceptance of the detector is equal to 1.5×10^{-6} sr. The pointing and focusing of the electron beam onto the target before the beginning of the measurement of the spectra are controlled by means of a beam proportional chamber placed behind the target. During the measurements, the chamber is removed from the beam. The intensity of the electron beam is measured by a Faraday cylinder located behind the proportional chamber at the end of the setup. The setup is not separated from the microtron in vac-

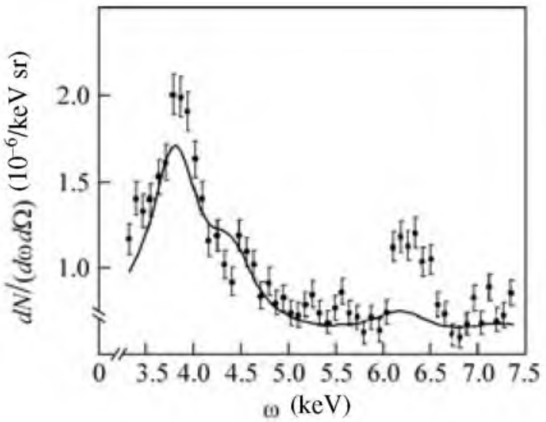

Fig. 1. Measured and calculated spectra of polarization bremsstrahlung from the aluminum foil.

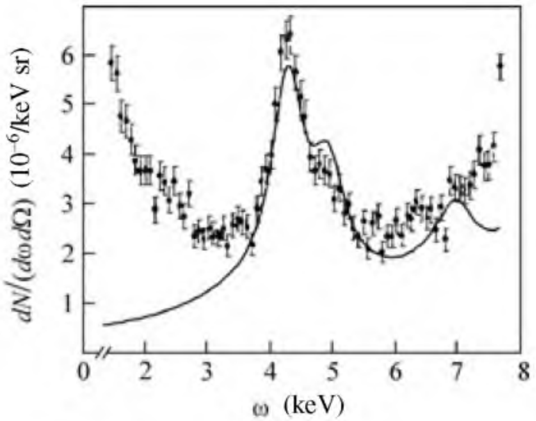

Fig. 2. Same as in Fig. 1, but for the copper foil.

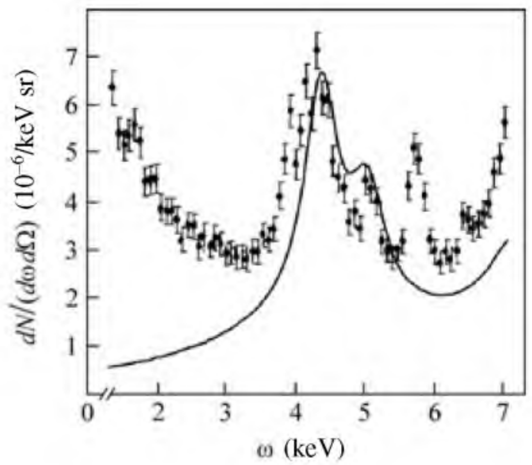

Fig. 3. Same as in Fig. 1, but for the nickel foil.

uum and a vacuum of no worse than 10^{-5} Torr is sustained inside the setup.

When collecting the data, the number of x-ray photons is measured in each spectral channel and the number of electrons passing through the target is simultaneously measured. Figure 1 shows the measured spectrum of polarization bremsstrahlung from the aluminum target. Hereinafter, the statistical errors are shown. Two peaks are clearly pronounced in the spectrum, where an indication of the existence of the third peak is also seen. According to a Gaussian fit, the positions of the peaks are 3782 ± 16, 4560 ± 36, and 6273 ± 19 eV. The spectrum contains an external background from the microtron, whose spectral shape is close to the exponential spectrum. Measurements without the target show that this background contribution is equal to 2–4% of events against the main peak. A higher exponentially distributed background comes from the target during the measurements. This background has two sources. The first of them is the bremsstrahlung of electrons in the target, as well as the incoherent component of the polarization bremsstrahlung. Theoretical estimates show that this background can be neglected. The other part of the exponentially distributed background comes from the secondary photons reemitted on the inner walls of the target box and photon channel. The covering of the inner surfaces of the box and photon channel by lead plates nearly halves this background. The third spectral peak includes the contribution of photons from the iron *K* line (6403 eV), which are formed by the scattered beam electrons and photons on the inner surface of the target chamber and photon channel.

Figure 2 shows the spectrum of polarization bremsstrahlung from the copper target. The main peak is located at the center. The left part of the spectrum is the exponential background, whereas the copper *K* line with a maximum at 8025 eV is located in the left part. The spectrum also contains the background peak of the 6.4-keV iron *K* line. The right part of the central peak of the polarization bremsstrahlung includes the second peak. According to the Gaussian fit, the positions of the peaks are 4267 ± 23 and 4886 ± 75 eV. According to the calculation, the third peak must be manifested near a photon energy of about 7 keV; however, it is difficult to separate it in the spectrum with collected statistics, taking into account its location on the increasing part of the peak of the copper *K* line, which is two orders of magnitude more intense than the polarization bremsstrahlung.

Figure 3 shows the spectrum of polarization bremsstrahlung from the nickel target. Three peaks are clearly pronounced at the photon energies of 4257 ± 15, 5070 ± 16, and 5735 ± 11 eV. The contribution of the iron *K* line is observed near a photon energy of 6400 eV. The 5735-eV peak is of known apparatus origin. The photon energy at the peak maximum is exactly equal to the difference between the energies of the *K* lines of the target (Ni, 7475 eV) and detector (Si, 1740 eV). This peak is due to the ionization of the atoms of the detector by the photons of the K line of the target. In this case, the photons of the silicon K line are emitted from the detector, and the remaining part of the energy of the K line of the target is recorded by the detector in the form of the peak.

The results of the measurements are interpreted using the model of the polarization bremsstrahlung of relativistic electrons in a polycrystal according to which the polycrystal is considered as an ensemble of randomly oriented, sufficiently large, microcrystallites so that the coherent Bragg scattering of the Coulomb field of fast charged particles is realized in each microcrystallite [6]. The important feature of the polarization bremsstrahlung in the polycrystal is almost complete suppression of the incoherent component of this radiation, which is due to the above feature of the polarization bremsstrahlung, i.e., to the large effective impact parameter of the collision of the emitting particle with an atom, which is substantial for the formation of the polarization bremsstrahlung. As a result, the polarization bremsstrahlung spectrum under these conditions is the set of coherent peaks similar to Debye–Scherrer peaks in the scattering of free x rays in powders.

For a quantitative description of the polarization bremsstrahlung spectra, the following formula is used for the spectral angular distribution of radiation [6], which is simplified by taking into account the radiation observation angle $\theta = \pi/2$ fixed in the measurements:

$$\omega\frac{d^2N}{d\omega d\Omega} = \sum_{\mathbf{g}}\omega\frac{d^2N_{\mathbf{g}}}{d\omega d\Omega},$$

$$\omega\frac{d^2N_{\mathbf{g}}}{d\omega d\Omega} = l_{\mathrm{ab}}\left(1 - e^{-\frac{\sqrt{2}l}{l_{\mathrm{ab}}}}\right)A_{\mathbf{g}}T_g\Phi_g,$$

$$A_{\mathbf{g}} = \frac{2e^6n_0^2}{m^2}\frac{1}{g^3}|S(\mathbf{g})|^2F^2(g)e^{-g^2u_T^2},$$

$$\Phi_g = \frac{\pi g^2}{2\omega^2}\left[\frac{1}{\sqrt{\left(1-2\frac{\omega^2}{g^2}\right)^2 + 4\gamma^{-2}\frac{\omega^2}{g^2}\left(1-\frac{\omega^2}{g^2}\right)}} - 1\right] \times\sigma(g-\omega).$$

Here, T_g is the number of identical crystallographic planes corresponding to a given absolute value of the reciprocal lattice vector $\mathbf{g}$, n_0 is the density of the target atoms, $F(g)$ is the atomic form factor,

$$S(\mathbf{g}) = \frac{1}{N_0}\sum_{j=1}^{N_0}e^{i\mathbf{g}\mathbf{r}_j}$$

is the structure factor of the unit cell containing N_0 atoms with the coordinates $\mathbf{r}_j$, l_{ab} is the photoabsorption length, l is the target thickness, u_T is the rms amplitude of thermal atomic vibrations, and γ is the Lorentz factor of the emitting electron.

The calculated polarization bremsstrahlung spectra are shown in the figures by solid lines drawn with allowance for the background. The figures demonstrate the agreement of the theoretical predictions with the experimental data on both the amplitudes of coherent peaks and their positions. The positions of the calculated peaks of the coherent polarization bremsstrahlung for the aluminum target (3800, 4488, and 6200 eV) are close to the measured values. The same conclusion is valid for the positions of the calculated peaks of the coherent polarization bremsstrahlung generated by fast electrons in the copper film (4263 and 4923 eV). Worse agreement between the experimental data and theoretical predictions is observed for the polarization bremsstrahlung of relativistic electrons intersecting the nickel film. Only the position of the second calculated peak (5049 eV) agrees well with the experimental value. The position of the first calculated peak (4372 eV) is higher than the measured value by 115 eV. In this case, the left slope of the experimental peak exhibits an increased spread of points, which can indicate that the peak has structure. This problem requires a series of additional, more accurate, measurements and theoretical analysis, which are under development.

The results of the investigations reported above can be briefly summarized as follows.

(i) The peaks of the coherent polarization bremsstrahlung of relativistic electrons are experimentally detected in solid polycrystalline Al, Cu, and Ni films, whose nature is similar to the nature of Debye–Scherrer peaks in the scattering of free x rays in powders.

(ii) Quantitative comparison between the measured spectra and calculations performed using the model developed for the polarization bremsstrahlung in polycrystals shows good agreement between the theory and experiment. The dominance of the coherent component in the yield of the polarization bremsstrahlung from the polycrystal makes it possible to expect the development of a new method of the polarization-bremsstrahlung-based diagnostics of the atomic structure of partially ordered solids.

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REFERENCES

1. V. M. Buĭmistrov, Ukr. Fiz. Zh. **17**, 640 (1972).
2. M. Ya. Amus’ya, V. M. Buĭmistrov, B. A. Zon, et al., in *Polarization Bremsstrahlung from Particles and Atoms*, Ed. by V. N. Tsytovich and I. M. Oĭringel’ (Nauka, Moscow, 1987) [in Russian].
3. A. V. Korol’, A. G. Lyalin, and A. V. Solov’ev, *Polarization Bremsstrahlung* (S.-Peterb. Gos. Pedagog. Univ., St. Petersburg, 2004) [in Russian].
4. S. Blazhevich, A. Chepurnov, V. Grishin, et al., Phys. Lett. A **254**, 230 (1999).
5. Y. Takabayashi, I. Endo, K. Ueda, et al., Nucl. Instrum. Methods Phys. Res. B **243**, 453 (2006).
6. N. Nasonov, Nucl. Instrum. Methods Phys. Res. B **195**, 15 (1998).