Spectral Structure of Polarization Radiation from Relativistic Electrons in Aluminum

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Abstract—Collective effects in polarization bremsstrahlung generated by relativistic electrons in a polycrystalline aluminum foil are studied experimentally on the basis of the 2.4-MeV electron accelerator installed at the Institute of Nuclear Physics (Moscow State University, Moscow). A peak structure found in this polarization bremsstrahlung for the first time is in agreement with theoretical predictions.

1. INTRODUCTION

Polarization bremsstrahlung results from a variable polarization of atomic electrons that is induced by the electromagnetic field of fast charged particles [1]. Owing to its special features, polarization bremsstrahlung is one of the most interesting processes observed in collisions of charged particles with atoms. By way of example, we indicate that, in the x-ray region of photon energies between a few keV and a few tens of keV, which is of importance for various applications, polarization bremsstrahlung comes to be of a collective character because the polarization process involves coherently all atomic electrons. Owing to this, the radiation intensity integrated over the angles of observation per atom is equal to that of conventional bremsstrahlung. However, angular anisotropy is less pronounced in the case of polarization bremsstrahlung than in the case of conventional bremsstrahlung. We can therefore expect that, in the interaction of fast particles with atoms, radiation at observation angles larger than $1/\gamma$, where γ is the Lorentz factor for incident electrons, will be dominated by polarization bremsstrahlung.

In the above energy region, the effective impact parameter at which the motion of an incident particle generates polarization bremsstrahlung is commensurate with atomic dimensions and, hence, with interatomic distances in condensed media. Therefore, the properties of polarization bremsstrahlung are expected to be rather sensitive to the structure of condensed substances. In particular, a tight correlation between the properties of polarization bremsstrahlung and the structure of amorphous and polycrystalline condensed media was predicted in [2].

Unfortunately, experiments studying polarization bremsstrahlung were performed predominantly in the region of resonance atomic frequencies (see [1]), where correlations between atoms are insignificant. At the Institute of Nuclear Physics in Moscow (Moscow State University) and at the Institute of Nuclear Physics in Tomsk (Tomsk Polytechnic University), experimental investigations into coherent processes in polarization bremsstrahlung generated by relativistic particles employed 6.7-MeV electrons incident on amorphous targets [3] and 900-MeV electrons incident on heavy-metal targets [4], respectively.

This article reports on new results coming from an experimental investigation of the spectral distribution of polarization bremsstrahlung from a polycrystalline aluminum foil exposed to relativistic electrons. The ensuing discussion also covers the results from [3, 4].

2. DESCRIPTION OF THE EXPERIMENT

The experiment made use of a 2.4-MeV electron beam from the continuous linear electron accelerator installed at the Institute of Nuclear Physics (Moscow State University, Moscow). The beam of cross-sectional area 2×2 mm^2 was incident on a 2-μm-thick aluminum foil arranged in a vacuum chamber at an angle of 45° with respect to the beam trajectory. The electrons that traversed the target were then absorbed in a Faraday cup. The target was fixed on a movable bench with a remote control. The quality of the incident beam was monitored with the aid of a special TV camera and a screen covered with luminophore and positioned in the same chamber. Photons emitted in electron–target interactions were recorded by a cooled SiLi detector within a small solid angle of 1.5 msr. The detector, which had an energy resolution of 200 eV, was oriented at a right angle to the beam and was positioned at a distance of 0.5 m from the target. As was mentioned above, this geometry allowed us to obtain an optimum proportion between polarization bremsstrahlung and

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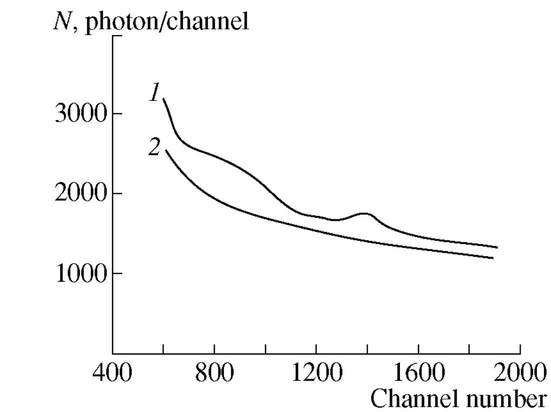

Fig. 1. Experimental spectrum of x-ray radiation generated by 2.4-MeV electrons in an aluminum target 2 μm thick (spectral section above the *K*-line of aluminum): (*1*) main signal and (*2*) external background.

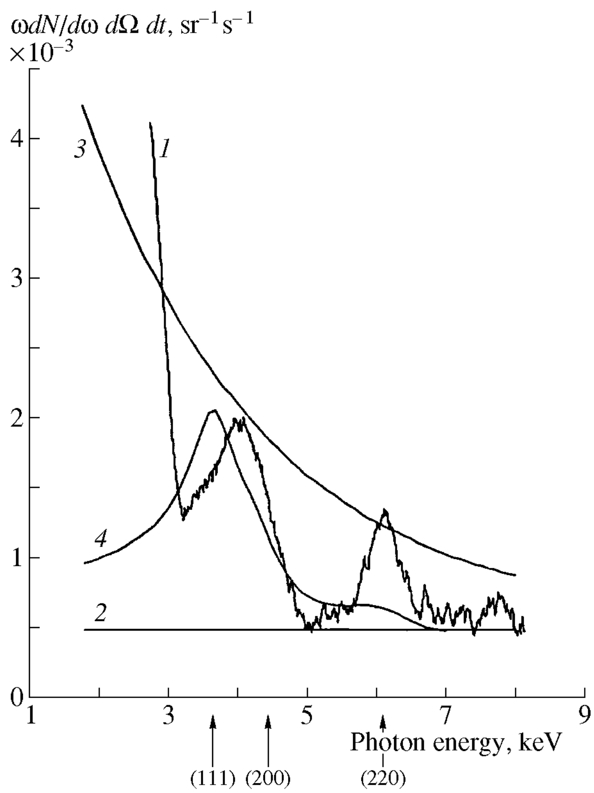

Fig. 2. Spectral distribution of polarization-bremsstrahlung intensity: (*1*) experimental data upon external-background subtraction; (*2*) conventional-background intensity; and (*3*, *4*) calculated intensities of polarization bremsstrahlung and conventional background in an amorphous and in a polycrystalline aluminum target, respectively.

conventional bremsstrahlung—the former is dominant here, since the latter is characterized by a high degree of angular anisotropy. There was also a small lead screen in the chamber, which allowed us to cover the detector along the line-of-sight direction toward the target. In that case, the detector recorded the actual external background arising in the chamber owing to target irradiation with the accelerated beam. Moreover, additional magnets shielded the detector from scattered electrons.

The photon flux was measured at a beam current whose maximum value did not exceed 10 nA, whereby nonlinear distortions were avoided in accumulating spectral data. The use of the continuous mode of accelerator operation permitted considerably reducing the time required to accumulate a statistically reliable data sample and minimizing the effect of the facility time drift.

Several runs of measurements of polarization bremsstrahlung were performed. In the first runs, whose results were reported in [5, 6], polarization bremsstrahlung for moderately relativistic electrons was separated for the first time. Because of a high background level, however, it was impossible to perform a reliable analysis of the structure of polarization bremsstrahlung. In the subsequent runs reported here, the measurements were performed at an appreciably reduced level of the external background.

Curve *1* in Fig. 1 represents a typical energy spectrum of x-ray photons according to the latest experiment. Apart from polarization radiation proper, this spectrum contains conventional bremsstrahlung and a background. The background is shown by curve *2* in Fig. 1 (the results are presented with due regard to radiation absorption in the target and the spectral sensitivity of the detector; however, the relevant corrections were insignificant in the energy region being considered). A dominant contribution to the total radiation flux comes from the peak that corresponds to the *K*-line of the aluminum characteristic radiation and which occurs in the region around 1.5 keV. This peak exceeds the level of radiation in the neighboring photon-energy region by a factor of about 3. In Fig. 1, we do not therefore display the *K*-line region in the overall spectrum.

3. DISCUSSION OF THE RESULTS

Figure 2 shows the resulting energy (frequency) spectrum of the observed-radiation intensity upon background subtraction (curve *1*). For the sake of comparison, we also show a few curves (*2*–*4*) calculated under conditions complying with the experimental conditions of radiation collimation. Curve *2* describes the spectrum of conventional-bremsstrahlung intensity—in the energy region being considered, it appears to be a horizontal line. Curves *3* and *4* represent the spectra of polarization-bremsstrahlung intensity in amorphous and in polycrystalline aluminum, respectively, the contribution of conventional-bremsstrahlung intensity being taken into account for each spectrum. The curves in question were calculated on the basis of the theoretical relations from [2].

According to the results of the calculations (see also [1]), the spectral distributions of polarization bremsstrahlung in amorphous and polycrystalline media differ markedly. In the coherent region, polarization bremsstrahlung in a polycrystalline medium has a peak structure, whose origin is similar to that in the case of Debye–Scherrer peaks observed in the scattering of an x-ray flux in a polycrystalline medium. In the photon-energy range 1–8 keV, there are three peaks at 3.75, 4.33, and 6.12 keV (these are their mean energies) corresponding to the coherent scattering of the incident-electron field on the (111), (200), and (220) aluminum crystallographic planes at a Wolf–Bragg angle of 45° in the experiment. For moderately relativistic electrons, the peaks are rather broad, the heights of the peak maxima decreasing fast as their mean energy becomes higher. Therefore, the (111) and (200) peaks are poorly resolved, merging into the first peak on curve *4* in Fig. 2.

Comparing the curves in Fig. 2, we can conclude that polarization bremsstrahlung can be singled out reliably from experimental data and that the character of this radiation is governed by the polycrystalline structure of a target material. The positions of the peaks on the measured curve are in agreement with the predictions. The measured yield of polarization bremsstrahlung in the vicinity of the (111) and (200) peaks also complies with theoretical values. The main discrepancy between theoretical predictions and experimental data, which is observed in the vicinity of the (220) peak, can be attributed tentatively to coherent Bragg reflection from the surface texture of the target and to the background of the iron *K*-line, which comes into play as the result of rescattering of secondary particles on the chamber walls.

Thus, experimental results confirm that the spectral properties of polarization bremsstrahlung generated by relativistic electrons in polycrystalline and in amorphous media differ considerably, in contrast to what is observed for conventional bremsstrahlung [7]. Bearing in mind previous experimental data on the behavior of polarization bremsstrahlung from relativistic electrons in amorphous carbon [3], we can state that the mechanism of this radiation is highly sensitive to the structure of the medium. This is supported by our preliminary data from the measurements of polarization bremsstrahlung in other media. This circumstance is of considerable importance for developing new methods for a structural analysis of substances.

The above conclusions also supplement substantially the results of Verzilov *et al.* [4], who studied radiation generated by 900-MeV electrons in heavy metals that was observed at an angle of 19° with respect to the electron trajectory. In heavy metals, the upper boundary of the coherent region of bremsstrahlung radiation falls within the region around 100 keV because, there, the effective radius of the atomic electron shell, $R = a_0/Z^{1/3}$ (where a_0 is the Bohr radius and Z is the charge number of the atomic nucleus), is less than an angstrom. On this basis, the radiation recorded in [4] near 50 keV was interpreted as polarization bremsstrahlung. However, no correlation between the properties of this radiation and the structures of the medium was found. The possible reason for this is that, under the conditions of the experiment reported in [4], the region of lower polarization-bremsstrahlung energies, where the structure of the medium could be operative, was close to the detection threshold of about 20 keV (we used a more informative presentation of the results than that in [4], displaying the intensity values instead of the flux densities of x-ray photons, whereby the conventional-bremsstrahlung intensity representing a horizontal line—see, for example, curve *2* in our Fig. 2—can be singled out easily).

4. CONCLUSION

Two important features of polarization bremsstrahlung have been revealed for the first time in the present article:

(i) The spectral distribution of polarization bremsstrahlung generated by relativistic electrons in polycrystalline substances has a clear-cut peak structure.

(ii) The yield of polarization bremsstrahlung is suppressed noticeably outside the peak region.

ACKNOWLEDGMENTS

We are grateful to V.M. Agranovich and B.M. Bolotovskiĭ for enlightening discussions on the results presented in this article.

This work was supported by the Russian Foundation for Basic Research (project no. 96-02-17109).

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Translated by E. Kozlovskiĭ