EXPERIMENTAL INVESTIGATION OF THE POLARIZATION BREMSSTRAHLUNG FROM RELATIVISTIC ELECTRONS IN AMORPHOUS AND POLYCRYSTALLINE MEDIA

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The polarization bremsstrahlung (PBS) generated by relativistic charged particles in a dense medium represents a new and important problem in the radiation physics of charged particles. In the present paper, the results of experimental investigations of PBS conducted with the linear electron accelerator developed at the Scientific Research Institute for Nuclear Physics at Moscow State University (SRINP MSU) are presented; the specific features of spectral and angular PBS distribution in an amorphous and polycrystalline target and directions for their further study are discussed.

INTRODUCTION

The polarization bremsstrahlung (PBS) arises upon collision of a fast charged particle with an atom due to scattering of the Coulomb field of the oncoming particle by atomic electrons [1]. This emission becomes collective in character for x-ray photons with energies lying in the range 1–10 keV that are most interesting for various applications, because the scattering process encompasses coherently all atomic electrons. Due to the last circumstance, the PBS intensity integrated over emission angles and the conventional bremsstrahlung (BS) become comparable in the indicated range of photon energies.

A large effective collision parameter comparable to the atomic dimensions introduces the specific PBS feature that makes it radically different from the BS generated in the same collision (small impact parameters, equal approximately to the screening radius in the Thomas–Fermi atomic model, are typical of the conventional bremsstrahlung). In this connection, in a condensed medium with the atomic separation equal approximately to the atomic dimensions, a correlation of the positions of different atoms in the medium will strongly affect the PBS properties. In principle, the above-indicated PBS property provides the basis for the development of a new method of diagnostics of the substance structure using the PBS, that is, the basis for PBS applications to the physics of the condensed state. Therefore, experimental investigations of the parameters of this radiation as functions of atomic arrangement in a substance are of great interest.

It should be emphasized that the current PBS theory has been developed to describe the PBS process upon collision of a fast particle with an isolated atom [1–3]. On the other hand, a well-known example of collective response of all the atoms in the medium to an electromagnetic perturbation of the fast particle field is the parametric x-ray generation by a fast particle in a crystal [4–6], which yields the coherent PBS component due to an ordered arrangement of atoms in the crystal [7]. The theoretical analysis performed in [8] has shown that the PBS in a partially ordered medium – a polycrystal – differs from the PBS in an amorphous medium (an interatomic correlation arises in the amorphous medium due to finite atomic dimensions [8]) and in a crystal generating parametric x rays.

Experimental investigations of the PBS were mostly performed in the region of resonant atomic frequencies (see [1]), where the interatomic correlation was insignificant (in so doing, mostly nonrelativistic charged particles were used). Up to now, only very few experimental investigations of the PBS from relativistic particles have been conducted. A series

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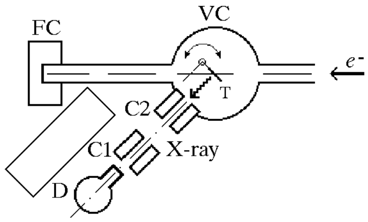

Fig. 1

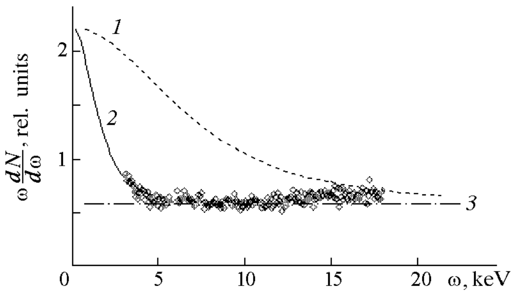

Fig. 2

Fig. 1. The design of the experiment comprising silicon-lithium detector D, graphite photon collimators C1 and C2, Faraday's cylinder FC, vacuum chamber for the target VC, and target T.

Fig. 2. Spectral distribution of the PBS from relativistic electrons with energy 6.7 keV in carbon: PBS calculated for the isolated atom (with the screening radius $R_s = 0.291 \cdot 10^{-8}$ cm) + BS (*1*), PBS calculated for the condensed target ($R_s = 1.319 \cdot 10^{-8}$ cm) + BS (*2*), calculated BS (*3*), and experiment (◊).

of such experiments was undertaken by the authors. The first experiment [9] aimed at studying of the PBS from relativistic electrons was performed with the linear electron accelerator developed at the Scientific Research Institute for Nuclear Physics at Moscow State University (SRINF MSU) to detect the theoretically predicted effect of the PBS suppression for soft photons in a dense amorphous medium.

1. EXPERIMENT ON THE STUDY OF THE PBS FROM RELATIVISTIC ELECTRONS IN AN AMORPHOUS TARGET

The design of the experiment is shown in Fig. 1. A quasi-continuous electron beam with energy 6.7 MeV was directed at an amorphous diamond-like carbon target 100 μm thick placed in a vacuum chamber and clamped on a holder which was capable of displacing it so that, remaining in the beam, the target was beyond the photon channel. This allowed us to measure the external photon background component maintaining the conditions for the electron beam propagation virtually unchanged. The photons with energies 2–20 keV from the target placed in the working position, that is, in the region of intersection between the electron and measuring photon channels, were registered with a silicon-lithium detector cooled with liquid nitrogen. The photon channel was at an angle of 45° to the direction of electron incidence on the target to optimize the relationship between the conventional BS and the PBS.

The emission spectrum measured from the target after subtraction of the external background component was compared with the results of theoretical calculations of contributions of the conventional bremsstrahlung and incoherent and coherent (for atomic electrons) PBS of carbon atoms and also with the results of calculations of the predicted effect of PBS suppression for soft photons and a dense target done for the given specific conditions of the experiment. Because the measurements were uncalibrated, the theoretically calculated spectral distributions were joined with the experimental ones for photon energies of the order of 20 keV, where the radiation intensity was determined solely by the conventional bremsstrahlung from electrons in the target. A comparison showed that the measured spectrum differed dramatically from the PBS spectrum calculated for the isolated carbon atom and dense medium. Namely, the measured spectral distribution was suppressed practically in the entire range of photon energies, and its intensity increased only at energies of the order of and less than 3 keV, whereas the results of calculations for the dense target predicted the PBS intensity maximum at energies of the order of 6 keV.

Figure 2 shows the results of measurements and calculations of the conventional BS and the total BS and PBS component for the isolated carbon atom. The results obtained call for an explanation for such a radical discrepancy between theory and experiment.

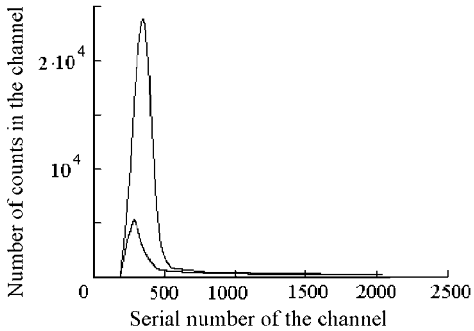

Fig. 3

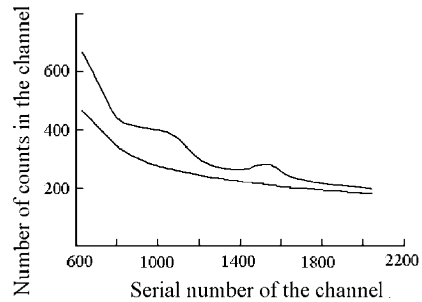

Fig. 4

Fig. 3. X-ray spectrum from electrons with energy 2.4 MeV in an aluminum leaf 2 μm thick. The radiation was registered in a small solid angle oriented in the direction perpendicular to the incident electron beam axis. The strong peak corresponds to the aluminum *K*-line. The lower curve shows the external photon background spectrum registered with the detector.

Fig. 4. Fragment of the x-ray spectrum shown in Fig. 3 for photons with energies 2–8 keV, that is, above the aluminum *K*-line.

To explain this discrepancy, we made the following assumption. Because the carbon atom is light, most of its electrons are valence ones, namely, four of six. The valence electrons in a condensed target are shifted toward adjacent atoms, thereby changing efficiently the electron distribution inside the atom, including the electron screening radius which is a parameter of the model atomic electron distribution used in calculations. According to our assumption, the PBS calculations for the isolated carbon atom were conducted for an artificially increased electron screening radius. The results of calculations for the screening radius $R_s = 1.31 \cdot 10^{-8}$ cm shown in Fig. 2 demonstrate good agreement with the experiment. However, this explanation is not unique; therefore, we continued the construction of other models, in particular, a model which considered the specific features of radiation from a relativistic electron scattered by very small crystallites or atomic clusters presented in [10]. Thus, already this first experiment on the PBS in the dense medium has shown that the examined emission mechanism is sensitive to the atomic structure of the target material. The next experiment performed with the SRINP MSU electron accelerator with energy 2.4 MeV was aimed at studying the PBS from electrons in a finely dispersed medium.

2. EXPERIMENT ON STUDYING THE PBS IN A POLYCRYSTALLINE MEDIUM

The design of this experiment was similar to that of the experiment aimed at studying the PBS in an amorphous medium. However, we selected another angle of photon registration because of the low-energy electron beam. The accelerated electron beam with energy 2.4 MeV was directed at an aluminum target placed in a vacuum chamber 2 μm thick. X rays from the target were measured with a cooled silicon-lithium detector inserted in the vacuum photon channel. The photon channel was at an angle of 90°, and the target itself was at an angle of 45° to the direction of electron beam propagation (this configuration is optimal to minimize the contribution of the conventional bremsstrahlung from the target).

Figure 3 shows the typical instrumental spectrum and the spectrum of the external background radiation component registered when the photon channel was shut with a lead flag. After subtraction of the background component, the spectrum of photons with energies 2–7 keV assumed the form shown in Fig. 4. The important feature of the experiment with the quasi-continuous beam of accelerated electrons should be emphasized. It allowed us to collect the data with statistics sufficient for PBS observations in real time. The greatest number of spectral counts was registered near the peak of the characteristic emission (CE) of aluminum centered at 1.5 keV.

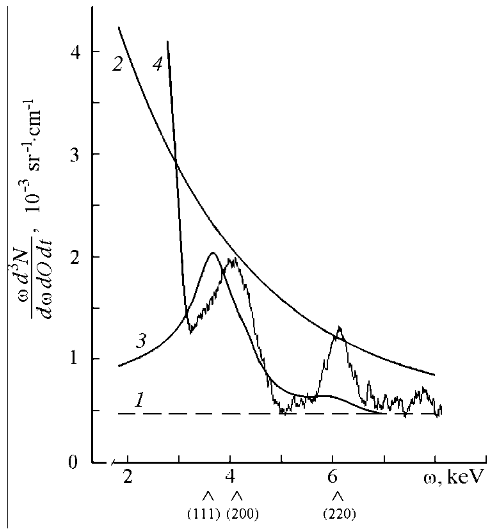

Fig. 5. Spectral and angular density of x rays from electrons with energy 2.4 MeV in the aluminum leaf: calculated conventional BS (curve *1*), PBS on the isolated atom + BS (curve *2*), PBS in the polycrystalline target (the PXR on (111), (200), and (220) planes averaged over the crystal orientations) (curve *3*), and the experimental dependence (curve *4*).

Indeed, according to the theoretical estimates, the expected PBS intensity is less than 1% of the CE intensity. For convenience of observations of the specific features in the PBS spectrum, the region of CE is not shown in Fig. 4. The level of the external radiation background in our preliminary experiment was relatively high (compared to the PBS intensity). In this connection, the detector shield from the external background radiation caused by the interaction of accelerated electrons with structural parts of the facility was modernized. In the interpretation of the data obtained, the measured spectra were smoothed in the range of energy resolution of the detector. Figures 3 and 4 illustrate the smoothed spectra. Figure 4 shows a fragment of the spectrum for energies above the aluminum *K*-line. Curve *4* in Fig. 5 shows the spectrum obtained after subtraction of the background component and the corresponding calibration against the photon energies.

3. DISCUSSION

As follows from Fig. 5, relatively broad peaks are manifested in the emission spectrum of relativistic electrons in the aluminum film. The results of theoretical calculations of the PBS spectrum of electrons with energy 2.4 MeV scattered on the isolated atom (curve *2*) and in the polycrystalline target (curve *3*) [8] are also shown in the figure for comparison with the experimental data obtained. Both calculated spectra shown in the figure were obtained with allowance for the contribution of the conventional BS. As can be seen from Fig. 5, the measured spectrum differs considerably from the PBS spectrum of electrons scattered on the isolated atom. This difference can be treated as the effect of PBS suppression in the polycrystalline medium virtually for the entire range of photon energies except the peaks. On the other hand, the PBS spectrum of polycrystalline aluminum calculated by the formulas derived in [8] describes well not only the positions but also the amplitudes of the peaks in the measured spectrum. The PBS in the polycrystal was calculated under the assumption that the main contribution to the emission of the particle moving within one crystallite comes from the PBS component coherent in the crystal plane and known as the polarization x rays (PXR). While calculating the total radiation, we averaged over all possible crystallite orientations in the polycrystal. The (111), (200), and (220) planes that yield the greatest contribution to the PXR intensity were also taken into account. Thus, the results obtained allow us to state that the target prepared from the aluminum leaf and used in our experiment is polycrystalline.

The experimentally observed peak radiation intensity corresponding to the PXR from electrons scattered on (220) planes, averaged over the crystallite orientation, considerably exceeded the corresponding calculated values. However, as our additional experimental investigations showed, this excess is caused by the contribution of the background radiation of the iron *K*-line excited on the internal surface of the chamber for the target by electrons and photons scattered on the target that were emitted by electrons in the target and on the walls of the chamber and photon channel. Iron is the main structural material of the facility; therefore, its characteristic radiation was most noticeable. Because the contribution of this peak is manifested only when the target is inserted in the electron beam, the subtraction of the background component measured without this target did not eliminate it.

Thus, in the present work we directly observed the polycrystalline structure of the target through the polarization bremsstrahlung from relativistic electrons. Moreover, in non-resonant regions of the spectrum we observed the suppression of the PBS intensity to a level much less than the PBS intensity in an amorphous target; the sharp difference between the data obtained and the PBS in the target prepared from diamond-like carbon [9] was also revealed.

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