PROGRAM OF EXPERIMENTAL INVESTIGATIONS OF THE MECHANISMS FOR THE EMISSION OF COHERENT RADIATION BY RELATIVISTIC ELECTRONS WITH ENERGIES OF 10–500 MeV IN ORIENTED CRYSTALS

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A program of experimental investigations of the mechanisms for the emission of coherent radiation by electrons in periodic structures is proposed. The program is aimed at developing sources of energy-tunable quasimonochromatic x radiation and γ radiation.

INTRODUCTION

The experimental complex set up on the SIRIUS synchrotron to investigate the emission of electrons in periodic structures, the techniques developed for measuring radiation characteristics, and the unique 15–70-MeV slot microtron put in operation at the Scientific Research Institute of Nuclear Physics of Moscow State University [1] open wide prospects for experimentation in the physics of x and gamma radiations of relativistic electrons in condensed matter. An urgent problem in this field of experimental physics is the creation of efficient sources of quasimonochromatic radiation with a wide range of photon energies, from a few kiloelectronvolts to tens of megaelectronvolts, based on comparatively low-cost accelerators rated at an energy $E_0 \sim 10^2$ MeV [1–3].

In solving this problem, of prime interest are the coherent mechanisms of the emission of radiation by electrons in crystals, where the periodic arrangement of atoms may give rise to an abrupt increase in radiation yield in some frequency bands due to the constructive interference of elementary waves radiated by a fast electron upon its interaction with individual atoms of the crystal [4]. An important advantage of crystalline radiators is that they can be used both for the generation of hard quasimonochromatic γ radiation by the mechanisms of emission of coherent bremsstrahlung radiation (CBR) [4, 5] or emission by channeling [5–8] and for the production of x radiation by the mechanisms of emission of parametric x radiation (PXR) [4, 9, 10] or diffracted transition radiation [11].

In the field of physics under discussion, there are a number of unresolved problems and novel approaches the study of which is the heart of the proposed program of experimental investigations. In the framework of this program, it is intended to perform experiments on the Sirius synchrotron for accelerated electron energies of 200–500 MeV and on a slot microtron recently created at the Scientific Research Institute of Nuclear Physics of Moscow State University [1], whose design allows experimentation with electron energies ranging between 15 and 70 MeV. The overlapped range of electron energies makes it possible to carry out a variety of new experiments, which could be of interest from the viewpoint of both gaining new physical information and possible applications. The goal of

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this paper is to provoke interest of researchers in possible cooperation both in implementing this program and in realizing other proposals.

RESEARCH PROGRAM

For the objectives that arise in studying photonuclear reactions, of prime interest is a source of polarized γ photons with energies of several tens of megaelectronvolts. A conventional method of production of such photons is based on the CBR mechanism where a fast electron, when moving in a crystal, collides successively with atomic chains, meeting them periodically along its path (the radiating electron moves at a small angle with respect to the chain axis) [4]. It is significant that to produce quasimonochromatic radiation in the range of tens of megaelectronvolts by this method, it is necessary to use electron beams of energy $E_0 \geqslant 10^2$ MeV.

On the other hand, it has been demonstrated [12] that quasimonochromatic radiation of relativistic electrons in a crystal can be generated due to the discreteness of an isolated atomic chain. This method, known as the B-type CBR method, was suggested [13] to be used for the production of quasimonochromatic photons of energy $\omega \sim E_0$. For the electron energy $E_0 \sim$ 50–70 MeV, the first-order maximum of the B-type CBR falls within the photon energy range $\omega \sim$ 15–30 MeV, and this allows one to harness this emission mechanism to perform investigations in the giant dipole resonance region. In the framework of the project under consideration, it is planned to investigate experimentally the process of generation of linearly polarized γ photons on the basis of the B-type CBR.

The spectral properties of the B-type CBR were investigated in an experiment with the electron energy $E_0 = 300$ MeV [14]. In this experiment, a low degree of linear polarization of the radiation was noted, which was associated with the highly symmetric potential of the crystal in the plane normal to the axis of the atomic chain. Under the proposed project, the spectral and polarization properties of the radiation will be investigated under the conditions of off-axis collimation of the photon beam, since in this case, as shown in [15], an abrupt increase in the degree of linear polarization of the radiation is possible for the coherent peak – incoherent base relation kept invariable. Another possible way of producing polarized radiation based on the B-type CBR is to harness the influence of planar channeling of electrons on the B-type CBR, as proposed in [16].

As a rule, in studying the characteristics of the coherent radiation of fast electrons along an atomic chain, of interest is the hard region of the spectrum of the radiated photons. The experiment described in [17] has demonstrated that there are some features in the x-ray frequency range as well (as shown in the cited work, the intensity of the x-radiation of relativistic electrons along oriented chains is higher than that of the Bethe–Heitler background radiation). The mentioned feature is of great interest for the creation of an efficient x-radiation source and, from the physical viewpoint, for studying the processes responsible for the formation of the radiation spectrum measured in the experiment [17].

In the framework of the project, it is intended to study the influence of various factors on the radiation characteristics, such as the density and coherent azimuthal scattering of electrons along atomic chains; the relation between the transition and coherent radiation emission mechanisms, including their interference, and the effect of suppression of the coherent radiation due to its multiply repeated scattering by atomic chains. It will be investigated how the radiation yield depends on the target thickness and material and whether it is possible to create an efficient source of quasimonochromatic x radiation based on a composite system including a crystalline target and a properly oriented crystal of pyrolytic graphite, allowing one to cut a narrow band from a wide spectrum of bremsstrahlung radiation [18].

To gain a clear knowledge of the mechanism of the process and to find optimum conditions for the creation of this type of source, the energy dependence of the efficiency of this method of production of intense beams of quasimonochromatic x radiation will be investigated. The use of both accelerators will allow one to analyze the efficiency of this type of source in the electron energy range 30–500 MeV.

The emission of PXR by relativistic electrons in a crystal is now a well-understood process. However, there are some unresolved problems in this research field, which is highly promising from the viewpoint of the development of a source of x radiation with a uniquely narrow frequency band. Among these problems is to detect PXR along the velocity of a radiating particle or to fix the effects of dynamic diffraction in conventional PXR whose photons propagate in the direction of Bragg's scattering.

The attempts to detect forward PXR transition made by now [19, 20] failed, and this, perhaps, is associated with nonoptimum conditions of the measurements. It seems that the effect under consideration was first observed in the experiment reported in [21]. The result of this experiment has not yet been interpreted theoretically. The main difficulty in detecting PXR and measuring its characteristics is the high level of the background that is created in the main by the contribution of the transition radiation to the total radiation yield. The contribution of the bremsstrahlung radiation in the range of radiating electron energies where the yield of the forward PXR is substantial is suppressed by the density effect [4].

In the framework of this project, particular attention will be given to the search for and realization of conditions under which the signal/background ratio would be high enough for the contribution of the forward PXR could be picked out. The width of the transition radiation spectrum is considerably greater than that for PXR; therefore, we plan to measure the radiation yield differentiated by observation angles. This, in view of the substantial difference in the angular distributions of PXD and transition radiation, will make it possible, in accordance with predictions of the theory described in [22], to obtain a signal/background ratio high enough for the PXR contribution could be picked out. A goal of the project is to study comprehensively, both theoretically and experimentally, the forward PXR on the Sirius synchrotron. It will be investigated how the size of the photon collimator, the electron energy, the photoabsorption factor, and the atomic number of the target material (as predicted, heavy crystals are preferable for use in experiments on detecting the radiation under consideration) on the radiation characteristics.

The great deal of measurements of the characteristics of PXR in the direction of Bragg's scattering are in good agreement with the predictions of the kinematic theory of PXR [23]. At the same time, a more rigorous theory of PXR, based on the dynamic theory of diffraction of x rays in crystals [24], predicts that there are some effects that cannot be described using of the kinetic approach, and one of these is the forward PXR. It is planned to investigate experimentally the effect of anomalous photoabsorption on PXR. As predicted [25], anomalous absorption should have only a slight effect on the integrated yield of PXR. This is because the criterion for this effect to show up can be strictly fulfilled only if the direction of propagation of photons coincides with the Bragg's direction, where the PXR intensity equals to zero. However, a more detailed analysis [26] has shown that under the conditions of anomalous absorption the maximum of the angular distribution of PXR shifts toward the small angles. As this takes place, the number of photons radiated in the region of existence of the anomalous absorption effect increases, and the angular density of PXR may increase substantially. At the same time, according to the results of numerical simulations [25], the integrated radiation yield varies insignificantly. It is planned to perform measurements for a crystal orientated so that the Bragg's energy about which the PXD spectrum is localized be close to the photon energy at which the effect of anomalous absorption in the process of scattering of free x rays was earlier observed in the given crystal. This should make it possible to perform measurements under optimum conditions for the observation of the effect.

Generally, PXR is investigated in the region of photon energies for which the average dielectric permittivity of a crystal can be described in terms of the simplest free electron gas model. One should expect considerable changes in radiation properties in the region of anomalous dispersion, where the energy of photons is close to the binding energy of atomic electrons. Experiments [27–29] performed to study PXR near the absorption edge for various elements have demonstrated a considerable effect of anomalous dispersion on the characteristics of PXR. The kinematic theory of PXR failed to describe the experimental data for germanium crystals obtained in the cited works. In the framework of the proposed project, it is planned to pursue these experiments with other crystals, such as tungsten and gallium arsenide, and to analyze the experimental data to be obtained based on the (more general) dynamic theory of PXR, since preliminary results predict that the effects of dynamic diffraction of PXR in the region of anomalous dispersion should be more pronounced.

Among the dynamic effects observed in the x radiation of fast charged particles in crystals is the diffracted oscillator radiation (DOR) that results from coherent combining of two processes: the emission of photon radiation and the diffraction of this radiation (see [30] and the publications cited therein). As shown in [30], DOR may appear in a case where a particle of energy $E_0 \sim 20$–40 MeV moves in the mode of planar channeling and the radiation energy during channeling, resulting from the level-to-level transitions in the potential well of a crystal plane, if evaluated taking into account the Doppler effect, strictly coincides with the Bragg's energy for any one of the crystal planes. According to [30], the intensity of DOR is more than an order of magnitude greater than that of diffracted bremsstrahlung radiation. Since for strictly Bragg's geometry the PXR contribution in a thin crystal is negligible, the contribution of DOR can be fixed in a rather simple manner if the crystal is disoriented from the planar channeling mode or if the particle energy is varied. We hope that the possibility of tuning the electron energy and the availability of an extracted particle beam on the microtron of the Scientific Research Institute of Nuclear Physics of Moscow State University will allow us to detect this effect experimentally.

CONCLUSION

Due to the availability of a complex of measuring equipment and the wealth of experience gained in studying the characteristics of radiations in oriented structures there is reason to hope that the proposed research program will be successfully implemented.

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