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Parametric X-ray radiation from powders

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ABSTRACT

Parametric X-ray Radiation (PXR) produced in powders has been observed for the first time. PXR spectra were measured under observation angles of 150° and 180° during the interaction of relativistic 7 MeV electrons with a tungsten powder. All the PXR peaks that theoretically can be produced in the studied energy region were registered. The performed absolute comparison of the experiment with the PXR kinematical theory from randomly oriented crystallites showed a good accordance.

1. Introduction

Max von Laue discovered in 1912 that crystalline substances act as three-dimensional diffraction gratings for X-ray wavelengths comparable with interplanar spacing in a crystal lattice. Presently, X-ray diffraction is a common technique for the study of crystal structures and atomic spacing. Nowadays, the diffraction of X-rays is the main nondestructive method for the study of condensed matter structure [1–3].

An effect similar to the diffraction of X-rays occurs when charged particles move in a periodic medium. The medium radiates as a result of the interaction of the charged particle's Coulomb field with the shell electrons of the medium [4,5]. Since the medium atoms are distributed periodically, the electromagnetic waves emitted by each atom can interfere constructively which results in coherent radiation. The spectral and angular characteristics of the resulting radiation depend on the parameters of the atomic structure of the medium in which the particle moves. The mechanism is called Parametric X-ray Radiation (PXR) [5] or coherent polarization bremsstrahlung [6].

PXR produced in crystals has been studied deeply theoretically and experimentally [7,8], while PXR produced in randomly oriented crystallites has only been described theoretically [6,9]. The closest experiments studied the interaction of electrons with polycrystalline targets [10–12]. The main problem to compare the experimental results with theory was the presence of texture in the targets, which influence is reflected in the spectral and angular characteristics of the PXR spectrum [10].

Possible applications of PXR have been described for sources of quasi monochromatic X-ray radiation [13,14]; for charged particle beam diagnostics [15,16] and for diagnostics of condensed matter atomic structure: the parameters of the crystal lattice [17], size and form of the clusters [18,19], the pole figures of polycrystals [20]. In order to implement PXR in the mentioned applications, it is indispensable to validate the existing theories.

In this work, the experimental results of the first observation of PXR from powders are presented and compared with theory in order to test its validity.

2. Experiment

The experimental setup (Fig. 1) to study the interaction of 7 MeV electrons with matter is installed in the department of

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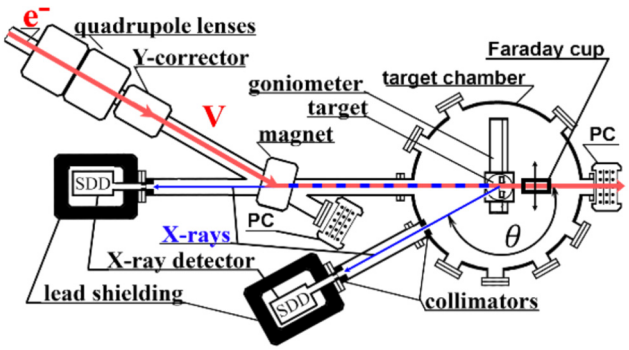

Fig. 1. Experimental setup. SDD – Silicon Driff Detector, PC – proportional chamber. An extensive description of the experimental setup was presented in [21].

High Energy Physics of Lebedev Physical Institute of the Russian Academy of Sciences.

The beam of electrons interacted with a tungsten powder constituted of crystallites which average size is distributed between 0.8 μm and 1.7 μm. Tungsten was chosen as target material because the spectral region between the Characteristic X-ray Radiation (CXR) M line (1.77 keV–2.03 keV) and the CXR L line (7.39 keV–11.67 keV), where the PXR peaks are located, is free of background peaks. The target presents a purity of 99,987%. In a 1 mm thick PMMA (methyl methacrylate) supporter a 20 mm × 9 mm rectangular cavity was made. One cavity side was covered by a 20 μm thick mylar foil (biaxially-oriented polyethylene terephthalate BoPET). The powder was sifted into the cavity without compacting it but filling all the available space. Finally, the powder was covered by a second 20 μm thick mylar foil. The orientation and position of the target were controlled by a goniometer with 3 degrees of freedom. The target normal coincides with the incident direction of the electrons.

PXR was registered by silicon drift detectors Amptek X-123 FAST SDD under observation angles $\theta = 150°$ and $\theta = 180°$ regarding the velocity of incident electrons. The detector crystal is protected by a 12.5 μm thick beryllium window. The detector collimation angle was $1.43{\cdot}10^{-6}$ sr for 150° and $3.7{\cdot}10^{-6}$ sr for 180°. The detector energy resolution for the experimental conditions was 149 eV at the 5.9 keV energy.

The position and form of the beam of electrons were monitored by a proportional chamber (PC). In order to increase the number of grains that take part in the radiation process the magnetooptical system was adjusted for the beam of electrons to have a considerable large diameter 10 mm with an initial divergence smaller than 15 mrad at the target position.

The current was determined by a Faraday cup mounted on a linear translation stage that allowed to move it off the electron beam. The secondary electron suppressor grid was set to 300 V. It was not possible to measure the current and the PXR spectrum simultaneously for $\theta = 180°$ because the characteristic radiation produced in the Faraday cup alters the studied signal.

The number of electrons that interacted with the target was determined based on a calibration parameter that connects the measurement of CXR produced by those electrons during PXR statistics collection. The calibration spectrum was detected for 60 s without the Faraday cup and then the current was measured during the same time interval. This procedure was repeated over 30 times. The performed procedure has allowed determining the number of electrons per one photon of CXR in the frame of the experimental conditions for both observation angles.

The target chamber working pressure was smaller than 10^{-5} Torr.

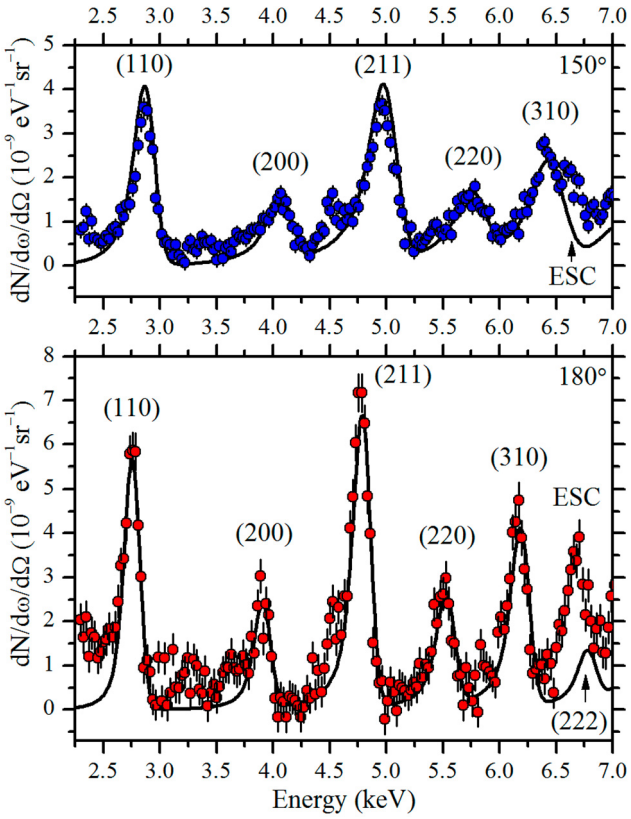

Fig. 2. Absolute comparison of PXR measurements with theory of PXR from randomly oriented crystallites. The theoretical curve was calculated for one electron and the experimental data normalized for one electron.

3. Results and discussion

The background was subtracted from the measured PXR spectra to achieve a quantitative comparison for the signal produced by one electron. For both observation angles the background was almost a constant, the substrated values of the background signal were $6.1{\cdot}10^{-9}$/(ev·sr) for $\theta = 180°$ and $4.5{\cdot}10^{-9}$/(ev·sr) for $\theta = 150°$. The results are presented in Fig. 2. It is easy to observe the manifestation of five PXR peaks simultaneously from crystallographic planes (110), (200), (211), (220) and (310). It is important to mention that all the PXR peaks that theoretically can be produced in the studied energy region were registered.

The theoretical curve in Fig. 2 was calculated based on [9] taking into account the detector energy resolution determined under the experimental conditions, the attenuation of the PXR signal in the target, the mylar foil that covered the powder and the detector beryllium window.

The calculated and measured energy values of PXR peaks are presented in Table 1. The positions of PXR peaks are determined via fitting the experimental data by gaussian functions considering the contribution of the ESC peak and the titanium X-ray line at energy 4.51 keV. The disagreement of theory and experiment can be explained by statistics and energy resolution of the detectors.

It is possible to affirm that the observed peaks in Fig. 2 are produced only by the PXR mechanism mainly for two reasons. Firstly, the peaks position in the spectrum changes with the change of the observation angle according to the theory [9], while the CXR peaks position remains constant. Secondly, it has been shown [22] that for the used experimental parameters, the contribution of the diffraction mechanism of real photons, for example bremsstrahlung or transition radiation mechanisms, is negligible.

Table 1
Calculated and measured positions of PXR peaks for observation angles 180° and 150°.

Plane	Peak energy (keV)			
	$\theta = 180°$		$\theta = 150°$	
	Theory	Experiment	Theory	Experiment
110	2.77	2.72	2.87	2.85
200	3.92	3.88	4.06	4.04
211	4.81	4.75	4.98	4.95
220	5.55	5.47	5.74	5.74
310	6.20	6.13	6.42	6.41

A special attention should be paid to the peaks spectral width. The natural spectral width of the diffracted peaks depends on both the angular distribution of pseudophotons of the relativistic electrons Coulomb field and the geometry of interaction between the electron beam with the target. This effect can be evaluated by the following expression:

$$\Delta\omega \approx \Lambda\omega_B \cot(\theta/2) \tag{1}$$

where ω_B is the Bragg energy of diffraction determined by $\omega_B = g_{i,k,l}/2 \sin(\theta/2)$ ($g_{i,k,l}$ is the reciprocal lattice vector of the crystallographic plane (i,k,l)); the variable Λ contains all the angular characteristics of the process: initial angular divergence of the electron beam, angle of multiple scattering of the beam in the target and angular distribution of pseudophotons of the relativistic electrons Coulomb field Δ_e. For the experimental conditions the value of Δ_e is much larger than others and it equals $\Delta_e = \sqrt{\gamma^{-2} + \omega_0^2/\omega^2} \approx 67$ mrad. The calculations performed according to (1) show that the spectral width maximal value for $\theta = 150°$ and the crystallographic plane (110) is $\Delta\omega = 58$ eV. It means that the spectral width of the PXR peaks is mainly determined by the detector energy resolution. Then it is possible to affirm that the apparent disagreement is produced by the detector energy resolution and existing statistics of the experimental data. It should be mentioned that even when the PXR peak spectral width is determined by the detector energy resolution, the PXR peaks form do not have a gaussian shape because its nature is highly asymmetric as shown in figure 2 of [9].

The performed absolute comparison of the obtained results with the theory shows a good agreement concerning the amplitude, form and position of the PXR peaks for both observation angles.

The performed analysis is important for the verification of the PXR theories developed for structures with randomly oriented crystallites. It should be remarked that such structures can be found only in powders since metal foils which also have a polycrystalline structure, acquire a predominant orientation of the crystallites in the surface as a result of the usually used rolling process [23]. At the same time, the crystallites orientation at the surface changes the spectral and angular characteristics of PXR.

The obtained results allow one to affirm that the target fulfills the conditions for which the theory was developed: 1) The grains are oriented randomly. At the same time this confirms that the disagreement between theory and experiment observed in works [11,22] was related to the influence of the target texture.

2) The number of atoms of a crystallite is high enough to consider the process of the Coulomb field scattering close to the Bragg scattering in a crystal. In the experiment the average size of the crystallites is close to the attenuation length (from 0.23 μm to 1.63 μm) for photons which energy corresponds to the PXR peaks energies (from 2.77 keV to 6.20 keV). Consequently, it is possible to conclude that a size of the crystallites close to the attenuation length is large enough to consider the radiation mechanism close to the Bragg scattering in a monocrystal.

4. Conclusion

Our main results can be summarized by the following highlights:

- Parametric X-ray radiation produced in powders has been observed for the first time.
- All the PXR peaks predicted theoretically in the studied energy region were registered.
- The performed absolute measurements are compared with the PXR kinematical theory and a good agreement is observed concerning the amplitude, form and position of the PXR peaks for both observation angles.
- The experimental validation of the theory has been performed.

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