PARAMETRIC X-ray RADIATION IN POLYCRYSTALS

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Parametric X-ray radiation produced during the interaction of charged particles with polycrystals is regarded. A review of the existing theories, perspectives of application and performed experiments is presented. The evolution of experimental capabilities as well as the progress in the process comprehension is illustrated. The state of the art of PXR in polycrystals is presented.

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A large number of experimental and theoretical works were devoted to the research of radiation processes that take place when a charged particle moves in condensed matter. The radiation is generated in a wide spectral region during the charged particle interaction with atoms and the total generated radiation consists of the contributions from different radiation mechanisms, which can occur simultaneously. In some mechanisms the radiation is emitted by the charged particle because it moves with acceleration (Bremsstrahlung, Channelling Radiation), and in others the radiation is emitted by the polarized medium even if the particle velocity is constant (Transition Radiation, Cherenkov Radiation, Parametric X-ray Radiation, Polarization Bremsstrahlung) [1 - 5].

The mechanism describing the radiation generated during the interaction of charged particles with polycrystals was theoretically described in [6]. The Parametric X-ray radiation spectrum in polycrystals consists of a set of peaks which position is determined by the observation angle. Additionally, it was established that the intensity and the spectral width are also determined by the observation angle achieving interesting properties in the backward geometry [7].

Several attempts were performed to verify the theoretical predictions. Some properties were validated separately, however a complete study was not achieved until this year [8]. The main problem to verify experimentally the theory was the presence of texture in the targets. Metallic polycrystalline foils have a predominant orientation of the grains according the crystallographic structure and the manufacturing process [9].

For the theory validation it was a problem but on the other hand, since PXR in polycrystals is sensitive to texture, grain size, lattice constant, etc., it can be used to measure these parameters. Possible applications of PXR in polycrystals have been described for structure diagnostics due to the spectrum dependence on the medium properties [10 - 14].

Parametric X-ray radiation in polycrystals (textured polycrystals and powders) has been studied experimentally since 1999 [15]. Several experiments were performed subsequently, mainly in three experimental facilities located in Russia and Japan. In Table are described the main characteristics of the experiments. The evolution of the experimental setup and the progress in the comprehension of PXR from polycrystals can be observed. It is interesting to observe that unlike PXR in crystals [3], PXR in polycrystals was generated only by electrons.

The general scheme of the experiments is presented in Fig. 1. Charged particles interact with polycrystalline targets, then the radiation is registered at the observation angle θ for a specific value of the orientation angle φ. The main characteristics of PXR in polycrystals were studied manipulating the orientation angle and the observation angle.

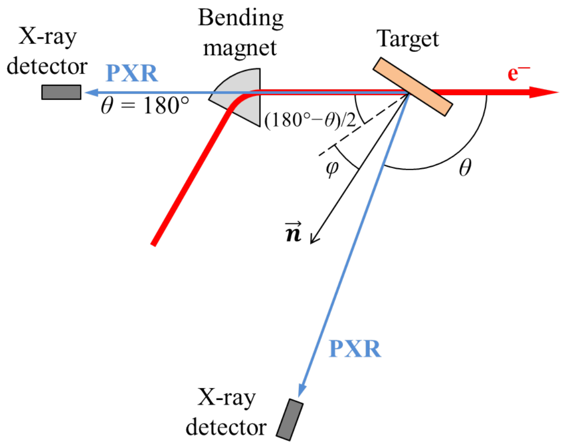

Fig. 1. Experimental scheme: θ – observation angle; φ – orientation angle; $\vec{n}$ – normal to the target surface plane

In Fig. 2 is presented a spectrum of PXR in polycrystals. It was obtained after the interaction of a 7 MeV electron beam with a tungsten polycrystalline foil when θ = 180°. It can be observed that the intensity of the PXR peaks changes when φ changes. Such behaviour confirms that the target presents texture. Additionally, theory affirms that in the analysed energy region, free from background peaks (CXR or escape peaks), five PXR peaks should manifest corresponding to crystallographic planes (110), (200), (211), (220), and (310). However, in Fig. 2 only peaks from planes (200) and (310) were reliably measured. This is the result of the texture influence and it represented the main problem to verify the theory. Unfortunately, it occurs with all kind of metallic foils.

PXR experiments in polycrystals

Year	Country, Energy	Target, planes	θ	Main findings	Detector, Energy resolution
2019 [8]	Russia, Lebedev Physical institute, department of high energy physics, 7 MeV	W powder, (110), (200), (211), (220), (310)	150.0° 180.0°	Absolute comparison of experiment with theory [6]. Agreement in position, form and amplitude for all peaks simultaneously	Silicon drift detector 145 eV at 5.9 keV
2018 [16]		W textured foil (200)	90.8° 119.6° 151.0° 180.0°	Dynamic verification that the PXR peaks intensity increases and the spectral width decreases when θ approaches 180.0°. Textured polycrystals can be described by the theory of PXR for mosaic crystals	Silicon drift detector 145 eV at 5.9 keV
2018 [17]		Textured foils of Ni (220) W (200), (310)	180.0°	Disadvantages of PXR compared to XRD to measure the rocking curves	Silicon drift detector 145 eV at 5.9 keV
2016 [18]		W textured foil (200)	180.0°	Discrimination of the contribution from diffraction mechanisms of real and virtual photons to the total radiation yield. Energy dependence of the PXR peak on φ was observed	Silicon drift detector 137 eV at 3.9 keV
2015 [19]		Al (111), (200), (220) Ni (111), (200),(220) Cu (111), (200), (220) (311) W (200)	75.0° 90.0° 83.0° 180.0°	Shift of the PXR peak position when θ changes. Agreement with theory for individual peaks. Observation of several PXR peaks not simultaneously. PXR is generated in grains which mean size is 300 nm	Uncooled Si(Li) 200 eV at 5.9 keV and Silicon drift detector 160 eV at 4.9 keV
2014 [20]		Ni (111), (200), (220)	180.0°	PXR peaks are produced in grains which average size is 50 nm. PXR spectrum changes when φ changes because of texture	Silicon drift detector 130 eV
2013 [21]		Ni (111), (200), (220)	180.0°	PXR peaks are produced in grains which average size is 300 nm	Silicon drift detector 130 eV
2012 [22]		Cu (111), (220), (311)	180.0°	PXR peaks are measured in the backward geometry.	PIN Si 159 eV at 5.9 keV
2008 [23]		Al (111)	75.0° 90.0°	Shift of the PXR peak position when θ changes	Uncooled Si(Li) PIN 200 eV at 5.9 keV
2006 [24, 25]	Japan, REFER electron ring at Hiroshima University, 150 MeV	Mo, textured polycrystalline foil (110, (220), (112)	11.2° 25.8°	PXR peaks from textured polycrystalline foil registered. Orientation dependence measured using XRD and PXR. Energy independence of the PXR peak on φ was reported	Cooled Si(Li) 380 eV at 17.5 keV
2001 [26]			25.8°	‘‘unidentified peaks’’ were observed during the experiment from an “amorphous” molybdenum foil	Cooled Si(Li) 450 eV at 7.23 keV
2004 [27]	Hiroshima University, X-ray diffractometer RIGAKU RINT2000, 8 keV	Mo, textured polycrystalline foil (110), (220), (112), (200)	50°…170°	The origin of the unidentified X-ray spectral peaks observed at the REFER was established as manifestation of the PXR from textured polycrystal	X-ray film, scintillation X-ray detector
1999 [15]	Russia, Moscow State University Linac, 2.4 Mev	Al foil, (111) and (220)	90.0°	PXR peaks observed.	Cooled Si(Li) Energy resolution not reported, estimation 500 eV at 6 keV

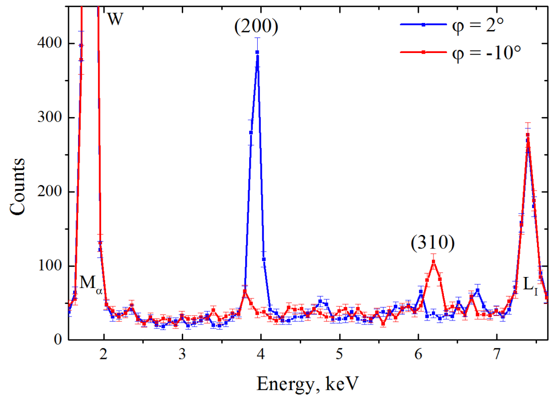

Fig. 2. PXR from a tungsten textured polycrystalline foil measured for two orientation angles φ = 2° and φ = -10°

To solve this inconvenient, experiments with powders were performed [8]. Unlike metallic foils, powders are constituted of randomly oriented grains. In this case, the manifestation of all PXR peaks was reliably fixed as shown in Fig. 3. The measurements were performed for two observation angles to highlight that the PXR peaks positions depends on θ.

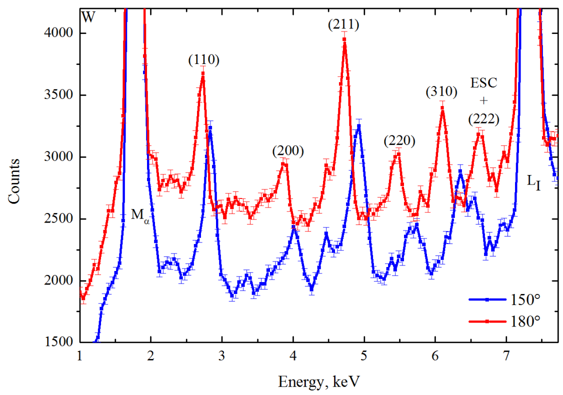

Fig. 3 PXR from tungsten powder measured for observation angles of θ = 150° and θ = 180°

The main differences of PXR from crystals and polycrystals can be observed in the spectra, the orientation dependences and the intensity.

For example, the PXR spectrum from crystals presents only one peak and its harmonics while the spectrum from polycrystals presents a set of peaks from different crystallographic planes. The case of texture polycrystals can be regarded as a transition, then the spectrum can present one or more peaks depending on the texture degree. The dependence of PXR yield on the orientation angle differs substantially also. The rocking curve for crystals presents two peaks symmetrically distributed around the specular condition at $\varphi = \gamma^{-1}$, for textured polycrystal metallic foils it was observed only one peak at the specular condition and finally it is a constant for polycrystals. The PXR energy peak dependence on the orientation angle can be listed as the last example of the differences. It changes for crystals and textured polycrystals but remain a constant for polycrystals.

It is important to mention that despite the perspectives to apply PXR in polycrystals some disadvantages have been already reported. For example, it was proposed [25] that polycrystals can be used instead of crystals to generate quasimonochromatic X-ray beams because of a higher resistance to mechanical damage produced by the charged particle beam. However, it was shown that the destruction of Si crystals is related to the heating during one micropulse, if the micro pulse duration is smaller than 5 μs, currents of 300 mA can be achieved [28]. Similarly, it was shown that the rocking curves obtained by PXR are wider than those obtained by commonly used diffraction methods because of the influence of the initial angular divergence of the charged particle Coulomb field [17].

Even though some limitations have been reported additional studies should be performed to explore the possibilities for applications and to clarify fundamental questions such as the radiation formation length, the differences in the diffraction mechanisms of virtual and real photons and others.

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ИССЛЕДОВАНИЕ ПАРАМЕТРИЧЕСКОГО РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ В ПОЛИКРИСТАЛЛАХ

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Рассмотрено параметрическое рентгеновское излучение (ПРИ), возникающее при взаимодействии заряженных частиц с поликристаллическими мишенями. Представлен обзор современного состояния исследования ПРИ в поликристаллах: существующих теорий, перспектив применения и проведенных экспериментов с учетом развития экспериментальных возможностей.

ДОСЛІДЖЕННЯ ПАРАМЕТРИЧНОГО РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ В ПОЛІКРИСТАЛАХ

В.І. Алексєєв, А.Н. Єлисєєв, Е.Ф. Іррібарра, І.А. Кищин, А.С. Кубанкін, Р.М. Нажмудинов

Розглянуто параметричне рентгенівське випромінювання (ПРВ), що виникає при взаємодії заряджених частинок з полікристалічними мішенями. Представлено огляд сучасного стану дослідження ПРВ в полікристалах: існуючих теорій, перспектив застосування і проведених експериментів з урахуванням розвитку експериментальних можливостей.