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Generation of Parametric X-Ray Radiation from Ultrafine Powder of Burnt Magnesia

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Abstract—Parametric X-ray radiation from an oxide two-component powder is detected for the first time. The consistency of spectral peaks to the kinematic theory of parametric X-ray radiation is shown. Parametric X-ray spectra are measured upon the interaction of a 7 MeV electron beam with burned magnesia (MgO) powders. The results obtained show the possibility of identifying the parameters of the structure of oxide two-component powders based on the analysis of the measured spectra of parametric X-ray radiation.

Keywords: parametric X-ray radiation, relativistic electrons, powder targets, X-ray diffraction analysis

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1. INTRODUCTION

The research area of the interaction of accelerated charged particle beams with matter is interesting for many reasons, mostly due to various possible applications, e.g., such as generation of various radiations or development of instruments for studying materials. To date, many radiation generation mechanisms are known, which are implemented during the interaction of accelerated charged particles with matter, among which, within the present study, coherent mechanisms of X-ray generation should be distinguished, whose spectral—angular characteristics are controlled by the parameters of the atomic and cluster structure of materials. This feature makes it possible to solve the inverse problem, i.e., to determine characteristics of the atomic and cluster structure of matter by measuring generated radiation spectra. In the case at hand, an analogy with X-ray diffraction methods should be noted, where wide-spectrum X-rays are used as probe radiation. Parametric X-ray radiation (PXR) under study is coherent radiation formed due to the coherent response of medium in which a charged particle moves, which makes spectrum of this radiation dependent on the atomic and cluster structure of medium.

PXR is studied from late 20th century; in the first works, single crystals were considered as targets [1–3]. First of all, interest in this subject was caused by new possibilities of generating directed monochromatic X-rays. Then it was proposed to generate PXR in polycrystals [4], which was implemented in experimental works [5, 6]. In this line of research, the main objective is to determine the possibility of developing a new method for diagnosing the atomic structure of condensed matters with partially ordered atomic structures. Within the performed studies, the possibility of identifying the atomic structure of one-component polycrystalline media by analyzing PXR spectra was successively shown. This direction was continued in the study of properties of PXR generated in powder targets [7] which feature the absence of preferred grain orientation. The experiments were successfully implemented with targets consisting of tungsten powders of with an average grain size of 0.8–1.7 μm [8, 9], with diamond powders with 0.3–60 μm grain size [10], and with platinum powders with average grain sizes less than 10 nm [11].

This present study continues experimental research of PXR generation in nanodispersed powders. The possibility of PXR generation in a two-component oxide powder is shown for the first time. Observations were performed in the geometry where radiation propagates in the direction opposite to the elec-

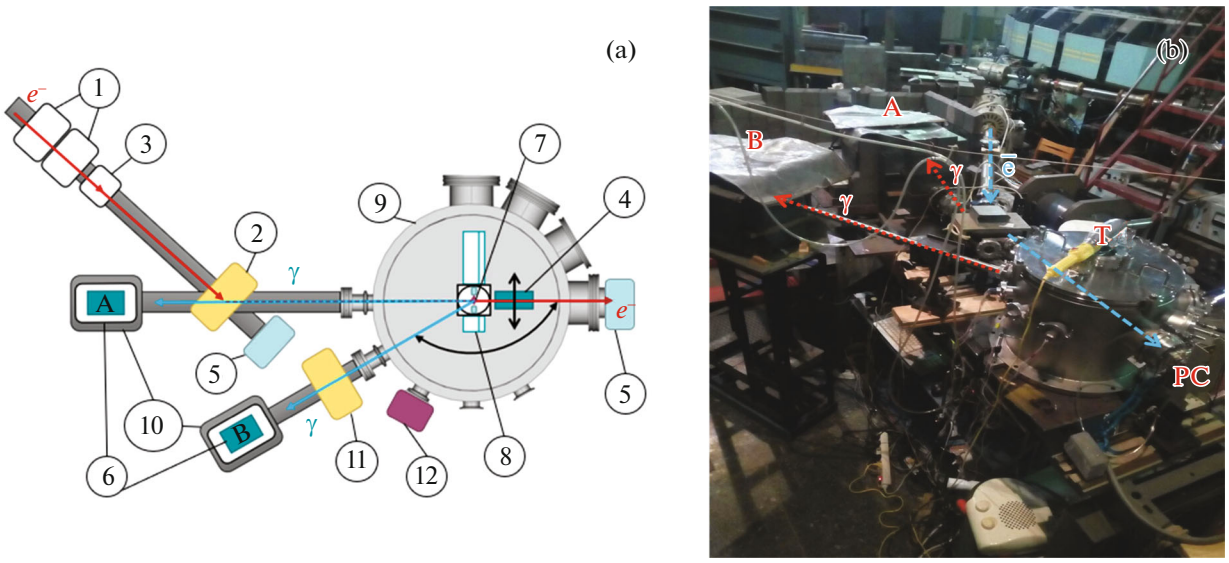

Fig. 1. (a) "Rentgen-1" experimental setup: (1) pair of quadrupole lenses, (2) bending magnet, (3) magnetic corrector Y, (4) Faraday cup, (5) proportional chamber, (6) semiconductor detectors, (7) target, (8) goniometer, (9) target vacuum chamber, (10) lead shield, (11) magnetic filter of charged particles, (12) web camera. (b) Photograph of the "Rentgen-1" setup: A and B are photon channels at 180° and 150°, T is the target chamber, PC is the proportional chamber.

tron motion [12, 13]. The applicability of the kinematic PXR theory to polycrystalline media [14] was first shown not only for metal powders, but also for more complex oxide compounds.

2. EXPERIMENTAL SETUP AND POWDER TARGET

The experimental procedure of the study was performed at the Department of High Energy Physics of the Lebedev Physical Institute, at the "Pakhra" accelerator facility using the "Rentgen-1" setup intended for low-background studies of the interaction of radiation with matter [15]. A source of relativistic electrons is a microtron with an accelerated electron energy of 7 MeV, a repetition rate of 50 Hz, and a pulse duration of 4 μs. The schematic of the setup and the experimental geometry are shown in Fig. 1a, the photograph of the target chamber and photon channels is shown in Fig. 1b.

The electron beam shape and size were formed by a pair of quadrupole lenses (1), horizontal control was provided by a bending magnet (2), vertical control was provided by a magnetic corrector Y (3). The beam current was measured using a Faraday cup (4) placed on a linear displacement platform to move away it from the electron beam during PXR measurements to avoid additional background from cylinder structural elements. A voltage of 300 V was applied to a secondary electron suppressor grid of the cylinder; thus, the beam current was measured with high accuracy from 1 to 10 nA. The electron beam position and shape were determined by a gas-filled proportional chamber (5).

To increase the number of grains involved in emission, the magneto-optical system was tuned to an electron 10 mm in diameter with an initial divergence less than 15 mrad.

Radiation was recorded by semiconductor drift detectors (6) Amptek X-123 SDD and FAST SDD installed in photon channels at observation angles (B) $\theta = 150°$ and (A) $\theta = 180°$ with respect to the electron motion velocity. Photon channels were strictly collimated, solid angles were 1.43×10^{-6} sr for 150° and 3.7×10^{-6} sr for 180°. The energy resolution of detectors under experimental conditions was 146 eV for X-123 and 154 eV for FAST SDD at the energy of 5.9 keV. The energy resolution was determined during detector calibrations by the characteristic X-ray line (CXR) of calibration targets (silicon, titanium, nickel, and platinum).

The detection efficiency of detectors in the energy range from 2 to 10 keV is more than 80%.

The target is produced as follows: in a plexiglas framework 1 mm thick, a rectangular hole 23 mm × 9 mm in size was made. One hole side was coated with a Mylar foil 20 μm thick (biaxially oriented polyethylene terephthalate BoPET); a powder was sifted into a cavity, filling the entire accessible space; then powder was covered by the second Mylar film 20 μm thick. Then the target (7) was placed in a goniometer (8)

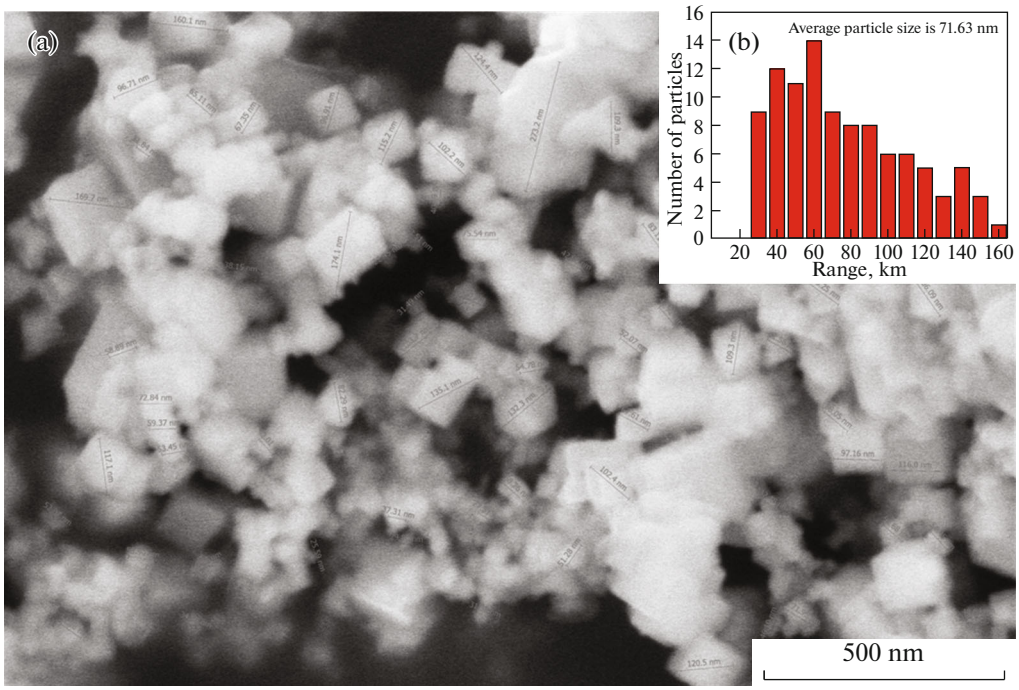

Fig. 2. (a) SEM micrograph of MgO powder. (b) Histogram of the MgO powder particle size; 100 particles were used for determination.

which in turn was installed in the target vacuum chamber (9) to control the target orientation and position. The target was filled with dead-burned magnesia MgO of 99.8% purity, with Fe_2O_3 impurities no more than 0.1% and with SiO_2 no more than 0.1%. The powder represented individual mostly spherical particles with an average size of 71.63 nm. The crystallite size was determined by SEM methods; a statistical analysis of the nanodispersed powder size was performed. In Fig. 2a, particles are indicated with sizes which were taken into account in processing of the results shown in Fig. 2b.

The dead-burned magnesia powder was chosen because of the following properties: the average grain size is less than 100 nm, it consists of light elements, which allows observation of stronger signals due to low radiation absorption within the target; the powder does not contain heavy element impurities, which allowed observations of purer signals (the magnesium K-line CXR energy is from 1.25 to 1.3 keV, oxygen $K_\alpha = 0.525$ keV); it has a face-centered cubic (fcc) lattice, which allowed observation of a great number of PXR reflections in the range from 2 to 6 keV.

The operating pressure in the target chamber did not exceed 10^{-5} Torr.

3. RESULTS AND DISCUSSION

It was possible to detect radiation from crystallographic (111), (200), (220), (311), (222), and (400) planes which coincide in energy with the calculated values listed in Table 1. Reflections from (311) and (222) planes have close energies; therefore, the detector could not resolve peaks of these planes. The PXR yields from (111) and (400) planes have low intensity; furthermore, the PXR peak energy is in the CXR range of chlorine $K_\alpha = 2.6$ keV, manganese $K_\alpha = 5.9$ keV, and iron $K_\alpha = 6.4$ keV, which could be formed in the target and emitted by chamber structural elements.

Figure 3 compares the obtained PXR spectra with theoretical calculations according to the PXR kinematic theory for polycrystalline media; good agreement in the peak shape, position, and intensity is observed. The structure factors for MgO calculations were taken from the paper by Jean-Michel Gillet et al. [16]. The theoretical curve was calculated taking into account the detector energy resolution determined under experimental conditions, the PXR signal attenuation in the target and Mylar foil covering the powder, as well as a beryllium window of the detector.

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

Plane	Peak energy, keV	
	for observation angles of 150°	for observation angles of 180°
1 1 1	2.639	2.549
2 0 0	3.047	2.944
2 2 0	4.310	4.163
3 1 1	5.054	4.881
2 2 2	5.278	5.098
4 0 0	6.095	5.887

We can see that PXR exhibits only two pronounced peaks from (200) and (220) planes, which is caused by the MgO structure factor. For example, in studies with metal powders [8–11], pronounced peaks from four and more planes were observed.

4. CONCLUSIONS

The possibility of PXR generation in a two-component oxide powder was shown for the first time. Good agreement of the PXR kinematic theory and experimental data for magnesium oxide powders in the shape, position, and relative intensity of spectral peaks was achieved. Thus, it was shown that the PXR kinematic theory is valid for both metal targets with micro- and nanometer grain sizes and oxide targets with nanometer grain sizes.

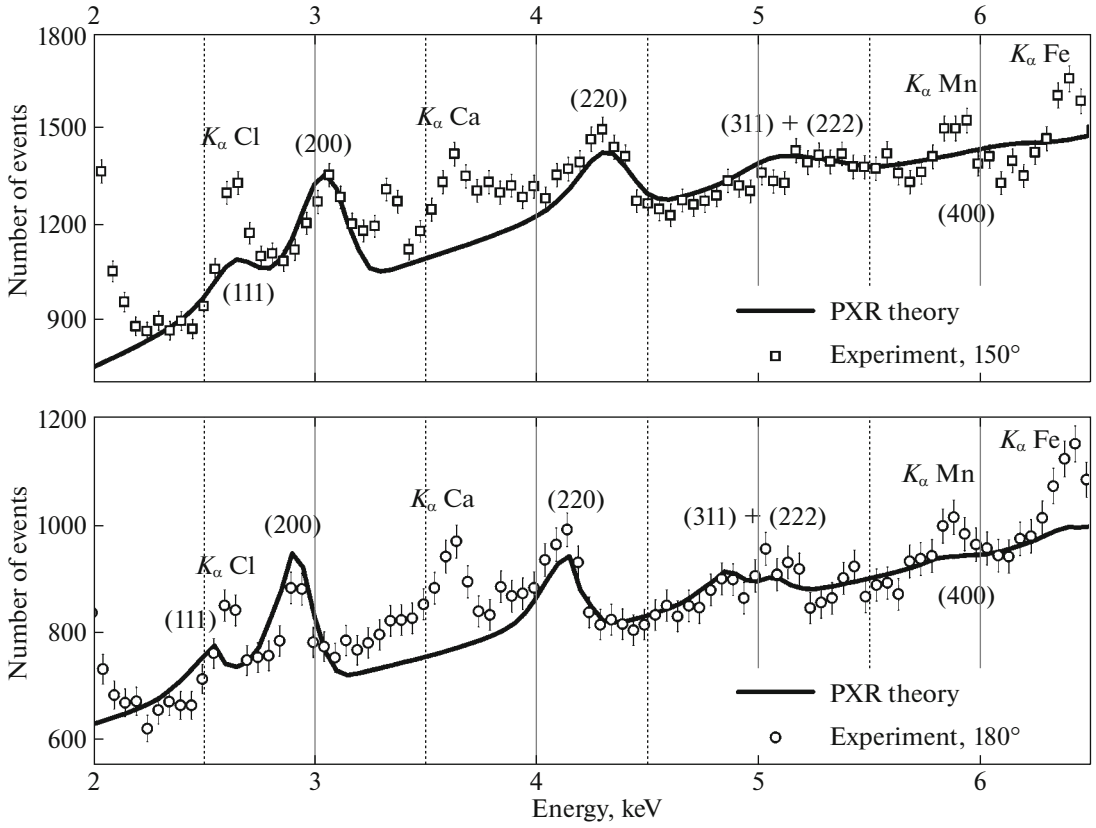

Fig. 3. Comparison of experimental data with calculated theoretical values for dead-burned magnesia powder. Squares and circles are experimental data for observation angles of 150° and 180°, respectively; solid curves are theoretical calculations according to the PXR kinematic theory.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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