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OBSERVATION OF LARGE-ANGLE COHERENT X-RAY RADIATION OF 5.7 MeV ELECTRONS FROM (002) MOSAIC PYROLYTIC GRAPHITE CRYSTAL

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Large-angle coherent X-ray radiation associated with so called Parametric X-ray Radiation (PXR) has been observed from mosaic pyrolytic graphite crystal using low electron beam energy - 5.7 MeV. The 1-st order (002) PXR reflection results in emission of photons with energies peaked near 14 keV, at large angle $\theta_D = 28^o$ with respect to electron beam.

The parametric X-Ray radiation (PXR) first observed at Tomsk synchrotron "Sirius" [1] is emitted by relativistic electrons at large (Bragg) angles due to diffraction of virtual photons of electron eigenfield during passage through the crystal. It has been experimentally studied in details in a wide range of electron energies, from decades to thousands MeV [1-4]. The properties of PXR are:the rather high brilliance, directional, very high monochromaticity and the possibility to tune smoothly the position of maxima in the spectrum under rotation of the crystal with respect to an electron beam. In a recent paper [4], the PXR had been observed using 90 MeV electron beam and pyrolytic graphite crystal. It was shown that by means of PXR a low cost pulsed tunable X-Ray source can be created on the base of moderate energy electron accelerators. As it has been confirmed recently using 900 MeV electrons [5] mosaic pyrolytic graphite crystal enhances PXR in comparison with used earlier single crystals.

No physical reasons exist which can restrict the appearance of PXR at lower electron energies. This paper presents the first results of the search for PXR generated by 5.7 MeV electrons in pyrolytic graphite crystal. The first attempt to observe the coherent radiation emitted in Si crystal at large angle with respect to low energy electron beam was made few years ago [6], but this work was not completed.

The case of MeV-electron beam is characterized by specific properties among them the most interesting is the strong dependence of photon energy on radiation direction inside the PXR reflection which according to the theory [7] has large angular size

$$\Delta\theta_\gamma \simeq 5 \times \gamma^{-1}, \qquad (1)$$

where γ is relativistic factor. The other ones are: strong change of reflection profile under change of angle θ_0 within the range of $\Delta\theta_0 \simeq \Delta\theta_\gamma$ and the strong asymmetry of PXR reflection relative Bragg direction. These properties of spectral-angular characteristics let consider the emission of large - angle coherent X-Ray radiation by MeV-electrons as the special case of PXR with its specific properties.

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In an experiment, Fig.1*a*, the electron beam of variable-energy microtron [8] focused in the transportation system to angular divergence of order of 0.02^o was used. The electron energy was $E_e = 5.7\,\text{MeV}$. The diameter of the beam was about 0.5 mm and the average beam current was few nanoampers. The other beam parameters are: pulse duration about $4\mu s$, energy spread $\Delta E/E \simeq 10^{-3}$, repetition rate 25 Hz.

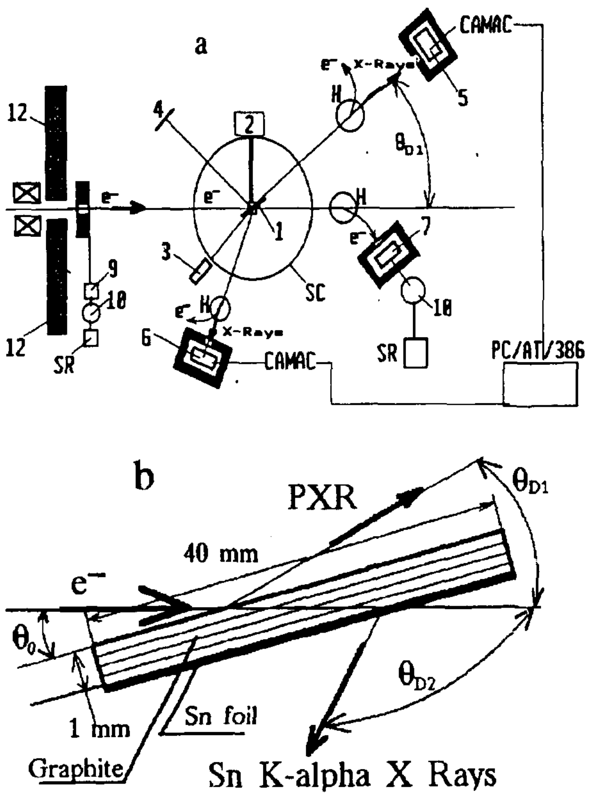

Fig.1. The experimental layout: *a*) the general scheme of experiment: microtron, electron beam, scattering chamber; *b*) graphite target, beam and detectors positions

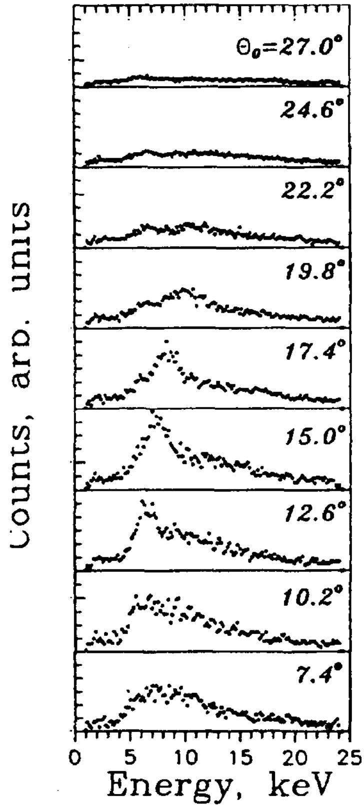

Fig.2. The "on-line" measured X-Ray spectra, for different angles between electron beam and (002) graphite planes and fixed detector position

The pyrolytic graphite crystal (Union Carbide) with the thickness 1 mm and surface $10 \times 40\,\text{mm}^2$ was placed (Fig.1*b*) in the goniometer in the center of experimental chamber. The electron beam hits the crystal surface which is parallel to (002) crystallographic planes, at definite angle θ_0 with respect to the surface. During measurements, we rocked the crystal and changed θ_0 value. In the Bragg geometry used, the photons generated in the crystal leaved the crystal through the same surface and hited the detector placed at angle $\theta_D = 28^o$ with respect to electron beam, see Fig.1*b*.

The detector used was the proportional counter with energy resolution about 21% at ^{57}Co line ($E_\gamma \simeq 6.4\,\text{keV}$) and about 15% at ^{88}Y line ($E_\gamma \simeq 14.4\,\text{keV}$). The angular size of detector given by round collimator was about $\Delta\theta_D = 12$ mrad. For our case $E_e = 5.7 MeV$, the angular size of PXR reflection $\Delta\theta_\gamma \simeq 450$ mrad and therefore $\Delta\theta_D \ll \Delta\theta_\gamma$.

The cleaning magnet H was placed on the path between crystal and detector in order to delete the charged fraction from X-Ray beam. The backside of the crystal was coated by thin (11 μm) tin foil in order to provide the electron beam monitoring using the K_α X- Ray fluorescence ($E_\gamma \simeq 24$ keV). Under present geometry, it was not possible to coat the frontside of the crystal by tin foil , since in this case the PXR quanta generated in the bulk of the graphite, will be strongly absorbed during passage through frontside to detector, for the Bragg geometry used. The K_α X-Ray radiation from tin foil was detected by additional NaI detector with angular size of order of 28 mrad and placed at angle $\theta_{D2} = -120^o$ with respect to electron beam.

In an experiment, the radiation spectra emitted by 5.7 MeV electrons were measured by fixed detector aperture at different angles θ_0 between electron beam and crystal surface. Fig.2 shows the set of "on-line" radiation spectra measured at different angles θ_0 between electron beam and crystal surface – (002) planes, emitted at angle $\theta_D = 28^o$ to electron beam. The curves correspond to θ_0=7.42^o, 10.17^o, 12.58^o, 14.5^o, 15^o, 17.4^o, 19.8^o, 22.2^o, 24.6^o, 27^o values, respectively.

All spectra are normalized to the number of K_α photons emitted by tin foil and therefore do not include corrections due to change of experimental geometry under rotation of the crystal (the rotation changes the effective thickness of generation both for PXR from graphite and K_α X-rays from tin foil).

For experimental geometry used, the incoherent part of radiation spectrum strongly depends on the orientation angle θ_0. This is explained by strong change of experimental geometry under transition from $\theta_0 = 7.4^o$ to $\theta_0 = 27^o$ which leads to enhancement of absorption of radiation leaving the crystal due to enhancement of effective depth of creation of radiation. The method of the extraction of the background from the measured spectra ($\theta_0 = 17.4^o$) is illustrated by Fig.3. Here, the experimental spectrum is given by solid line and calculated bremsstrahlung (BS) spectrum for $\theta_D = 28^o$ and $\theta_0 = 17.4^o$ is presented by dashed line. The Curve *1* is the difference between these two spectra. The BS spectrum for given emission angle $\theta_D = 28^o$ was calculated using the simple formula [9] which takes into account also the "density effect" and normalized to high-energy tail of the spectrum which is obviously pure BS:

$$\frac{dN(\theta_D)}{d\omega} \sim \left| \frac{\lambda}{q_s l_{coh}(\theta_D) + \gamma^{-2} + \omega_p^2/2\omega^2 + \theta_D^2} \right|^2, \tag{2}$$

where $l_{coh}(\theta)$ is the so-called coherence length, ω is the photon energy, $\lambda = 2\pi/\omega$ and $\omega_p$is the plasmon frequency and q_s characterizes the multiple scattering.

Fig.4. shows the set of X-Ray spectra for different values of θ_0, with background substracted as described above. As one can see, by increase of θ_0, the peak in radiation spectrum appears, increases to its maximum value at $\theta_0 \simeq 15^o$ (which almost corresponds to symmetric orientation of the crystal $\theta_0 = \theta_D/2 = 14^o$) and decreases with further increase of θ_0. This is in agreement with expected angular width of 1-st order PXR reflection, since under rotation of the crystal to an angle θ the X-Ray spot deflects to an angle $2\times\theta$. Indeed, in our case, the detector scanned the peaked spectrum within $\Delta\theta_0 \simeq 20^o$, which corresponds to $\Delta\theta_\gamma \simeq 10^o$, in accordance with above estimated angular width using the formula (1).

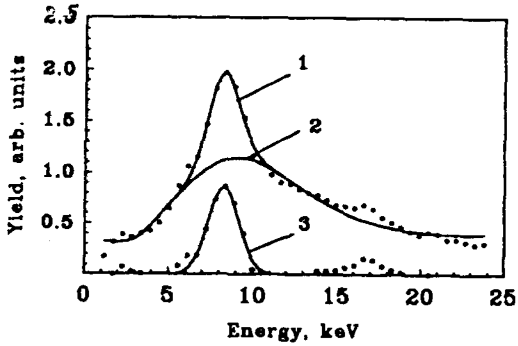

Fig.3. The example of background substraction: filled circles and curve *1* – the experimental data, curve *2* – calculated bremsstrahlung spectrum (BS) normalized to high-energy tail of the spectrum, and curve *3* – X-Ray spectrum after substraction of calculated BS

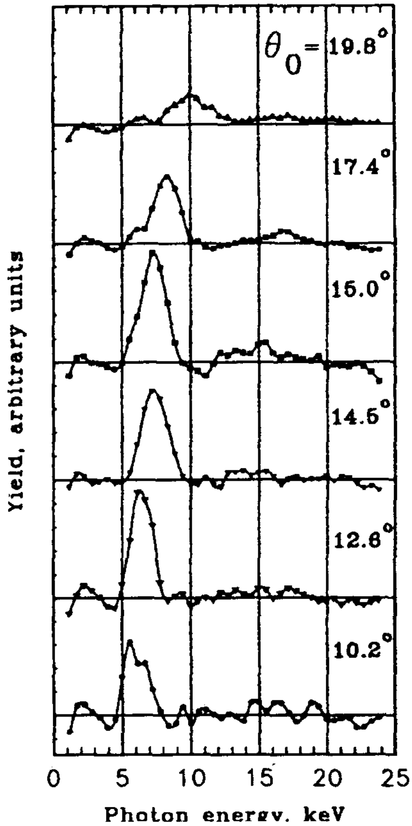

Fig.4. The set of "substracted" spectra, for different angles θ_0 between electron beam and (002) graphite planes

Moreover, with increase of an angle θ_0 between electron beam and crystal surface, the position of the peak in radiation spectra moves to more hard part of radiation spectrum, in accordance with expression [7] for the first-order PXR peak:

$$E_\gamma(PXR) = \frac{2\pi\hbar c sin\theta_0}{d(1 - cos\theta_D + 1/2\gamma^2)} , \tag{3}$$

where d is the interplanar distance between (002) graphite planes.

In order to illustrate this, in Fig.5 we compare the measured orientation dependence of peak position and calculated ones using both the formula (3) and the standard Bragg formula for the first-order diffraction of real photons

$$E_\gamma(Bragg) = \frac{\pi\hbar c}{d sin(\theta_D - \theta_0)} . \tag{4}$$

The formula (4) can be used to estimate the orientation dependence of energy of bremsstrahlung photons created and diffracted in the crystal. In Fig.5, circles

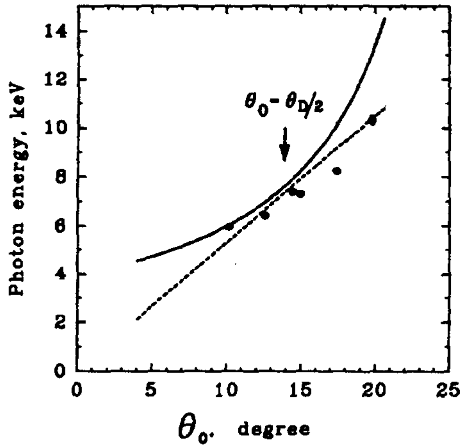

Fig.5. Position of the peak in the X-Ray spectrum in dependence on θ_0: filled circles – experimental data (taken from Fig.4); dashed and solid lines are calculated using formulae (3) and (4), respectively

are taken for peak position in measured spectra given in Fig.4: dashed line is calculated according formula (3) for PXR photon energy; solid line is calculated according formula (4) for Bragg diffraction of real photons.

In our case, the expected contribution of this type of radiation can be rather large since the characteristic value $\gamma\omega_p$ which defines the upper limit of the spectral region where the bremsstrahlung yield is damped due to density effect, is much less as the energy of detected photons. Unfortunately, the obtained results (see Fig.5) are not enough to conclude about the nature of the measured effect. It is clear that the extra measurements are necessary for $\theta_0 < 10.17^o$ and $\theta_0 > 20^o$. The present experimental setup does not allow this measurements, because at $\theta_0 < 10.17^o$ the peak will be not resolved due to detector threshold and at $\theta_o > 20^o$ - due to absorption of PXR generated in bulk graphite (large effective thickness).

In conclusion, we point out that the coherent radiation, one of possible mechanisms of which is the PXR, emitted at large Bragg angle with respect to electron momentum is observed using the 5.7 MeV electron beam. The data obtained show that the properties of PXR generated using MeV-electrons are more complicated than in case of high energies and measured spectra can be formed by photons emitted due different generation mechanisms. Even if the observed radiation is not "pure" PXR but the mixture of PXR, coherent bremsstrahlung and diffracted bremsstrahlung, our experiment extends the suggestion [4] that coherent radiation of electrons in a crystal could be perspective tunable X-Ray source on the base of low cost and low-energy electron accelerators. The experimental setup is in current improvement and new experiments are planned with use of solid state detector with better resolution, and for lower Bragg angles in order to measure more hard X-Ray spectra .

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