Observation of large-angle coherent x radiation from 5.7-MeV electrons in an (002) mosaic pyrolytic graphite crystal

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Large-angle coherent x radiation associated with the so-called parametric x radiation (PXR) is observed from a mosaic pyrolytic graphite crystal using a 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 a large angle $\theta_D = 28°$ with respect to electron beam. © *1995 American Institute of Physics.*

The parametric x radiation (PXR) first observed at the Tomsk synchrotron "Sirius"[1] is emitted by relativistic electrons at large (Bragg) angles due to diffraction of virtual photons of the electron eigenfield during passage through the crystal. It has been studied experimentally in detail over a wide range of electron energies, from tens to thousands of MeV.[1–4] The properties of PXR are: rather high brilliance, directionality, very high monochromaticity, and the possibility of smoothly tuning the positions of the maxima in the spectrum by rotation of the crystal with respect to the electron beam. In a recent study,[4] PXR was observed using a 90-MeV electron beam and a pyrolytic graphite crystal. It was shown that by means of PXR a low cost pulsed tunable x-ray source can be created utilizing moderate-energy electron accelerators. As has been confirmed recently using 900-MeV electrons,[5] mosaic pyrolytic graphite crystals enhance the PXR in comparison with the single crystals used previously.

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 a pyrolytic graphite crystal. The first attempt to observe the coherent radiation emitted in a silicon crystal at a large angle with respect to a low energy electron beam was made a few years ago,[6] but that work was not completed.

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

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

where γ is the relativistic factor. The other specific properties are: a strong change in the reflection profile upon a change of the angle θ_0 within the range $\Delta\theta_0 \simeq \Delta\theta_\gamma$, and a strong asymmetry of the PXR reflection about the Bragg direction. These properties of the

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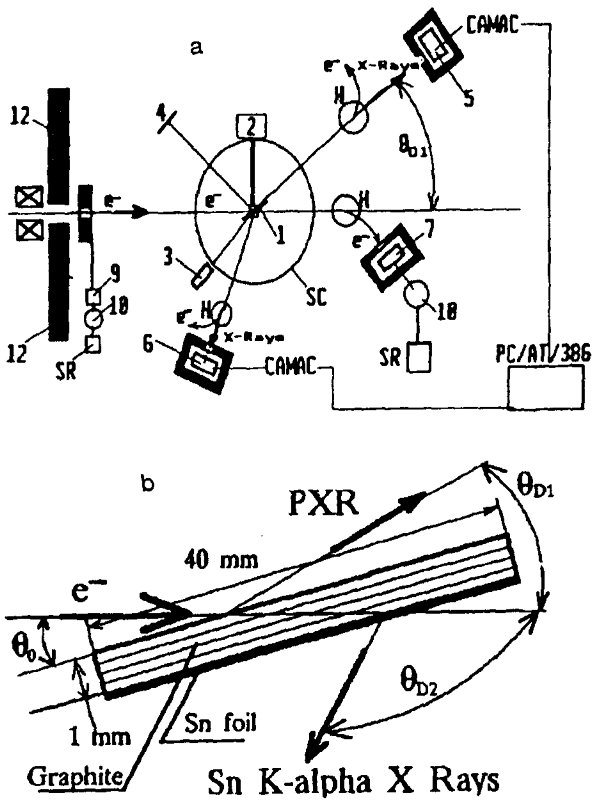

FIG. 1. The experimental layout: a) general scheme of the experiment: microtron, electron beam, scattering chamber; b) graphite target, beam and detectors positions.

spectral–angular characteristics allow one to consider the emission of large-angle coherent x radiation by MeV electrons as a special case of PXR, with its specific properties.

The experiment (Fig. 1a) utilized the electron beam of a variable-energy microtron,[8] focused in the transportation system to angular divergence of the order of 0.02 deg. The electron energy was $E_e = 5.7$ MeV. The diameter of the beam was about 0.5 mm and the average beam current was few nanoamperes. The other beam parameters were: pulse duration about 4 μs, energy spread $\Delta E/E \simeq 10^{-3}$, repetition rate 25 Hz.

The pyrolytic graphite crystal (Union Carbide), with a thickness of 1 mm and a 10×40 mm surface (Fig. 1b), was placed in a goniometer at the center of the experimental chamber. The electron beam struck the crystal surface, which is parallel to the (002) crystallographic planes, at a definite angle θ_0 with respect to the surface. During the measurements we rocked the crystal and changed θ_0. In the Bragg geometry used, the photons generated in the crystal left the crystal through the same surface and struck a detector placed at an angle $\theta_D = 28°$ with respect to the electron beam (see Fig. 1b).

The detector used was a proportional counter with an energy resolution of about

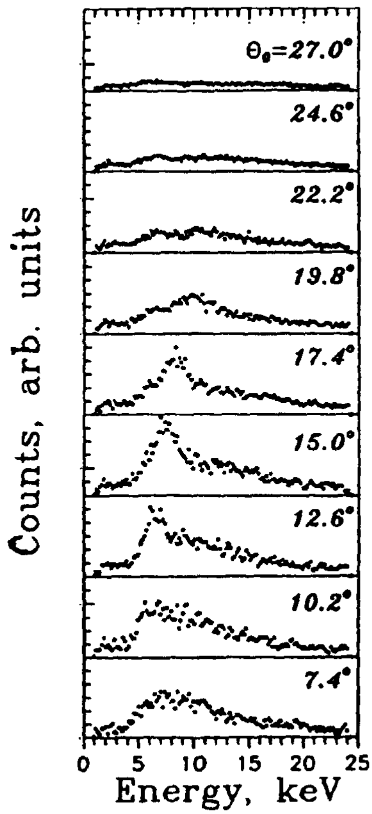

FIG. 2. The "on-line" measured x-ray spectra, for different angles between the electron beam and the (002) graphite planes and a fixed detector position.

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

A cleaning magnet H was placed on the path between crystal and detector in order to eliminate the charged fraction from the x-ray beam. The back side of the crystal was coated by thin (11 μm) tin foil in order to provide electron-beam monitoring using the K_α x-ray fluorescence ($E_\gamma \simeq$24 keV). In the present geometry it was not possible to coat the front side of the crystal by tin foil, since in that case the PXR photons generated in the bulk of the graphite would be strongly absorbed during passage through the front side to the detector, for the Bragg geometry used. The K_α x rays from the tin foil were detected by an additional NaI detector with an angular size of the order of 28 mrad and placed at angle $\theta_{D2}=-120°$ with respect to the electron beam.

In an experiment the radiation spectra emitted by 5.7 MeV electrons were measured

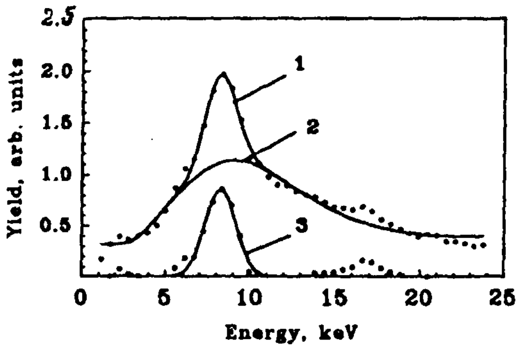

FIG. 3. An example of background subtraction: filled circles and curve *1*—the experimental data, curve *2*—calculated bremsstrahlung spectrum (BS) normalized to the high-energy tail of the spectrum, and curve *3*—x-ray spectrum after subtraction of the calculated BS.

at a fixed detector aperture at different angles θ_0 between the electron beam and crystal surface. Figure 2 shows the set of "on-line" radiation spectra measured at different angles θ_0 between the electron beam and crystal surface—(002) planes, emitted at a angle $\theta_D=28°$ to electron beam. The curves correspond to $\theta_0=7.42°$, 10.17°, 12.58°, 14.5°, 15°, 17.4°, 19.8°, 22,2°, 24.6°, 27° values, respectively.

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

For the experimental geometry used, the incoherent part of the radiation spectrum depends strongly on the orientation angle θ_0. This is explained by strong change of experimental geometry under transition from $\theta_0=7.4°$ to $\theta_0=27°$ which leads to enhancement of absorption of radiation leaving the crystal due to enhancement of effective depth of creation of radiation. The method used to remove the background from the measured spectra ($\theta_0=17.4°$) is illustrated by Fig. 3. Here the experimental spectrum is given by curve *1* and the calculated bremsstrahlung (BS) spectrum for $\theta_D=28°$ and $\theta_0=17.4°$ is shown by curve *2*. The curve *3* is the difference between these two spectra. The BS spectrum for the given emission angle $\theta_D=28°$ was calculated using a simple formula[9] which also takes the "density effect" into account and is normalized to the high-energy tail of the spectrum, which is obviously pure BS:

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

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

Figure 4 shows a set of x-ray spectra for various values of θ_0, with the background subtracted as described above. One can see that as θ_0 increases, a peak appears in the radiation spectrum, increases to its maximum value at $\theta_0 \simeq 15°$ (which nearly corresponds

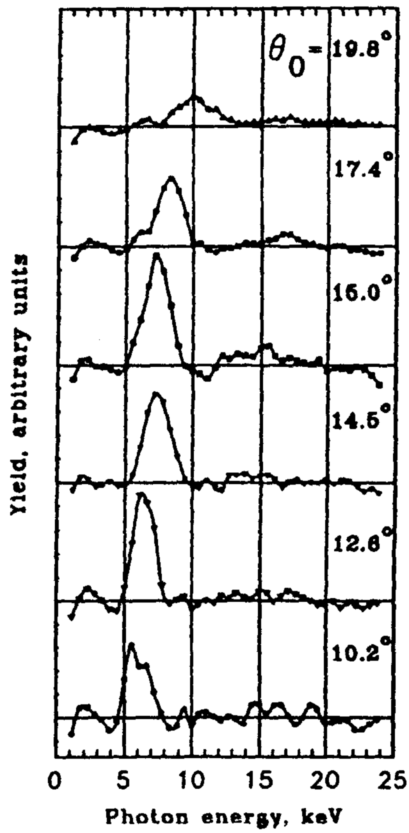

FIG. 4. The set of "substracted" spectra, for different angles θ_0 between the electron beam and the (002) graphite planes.

to a symmetric orientation of the crystal: $\theta_0 = \theta_D/2 = 14°$), and decreases with further increase of θ_0. This is in agreement with the expected angular width of the 1-st order PXR reflection, since under rotation of the crystal by an angle θ the x-ray spot deflects by an angle $2\times\theta$. Indeed, in our case, the detector scanned the peaked spectrum within $\Delta\theta_0 \simeq 20°$, which corresponds to $\Delta\theta_\gamma \simeq 10°$, in accordance with the angular width estimated above using formula (1).

Moreover, with increasing angle θ_0 between the electron beam and crystal surface, the positions of the peaks in the radiation spectra moves to the harder part of the spectrum, in accordance with expression[7] for the first-order PXR peak:

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

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

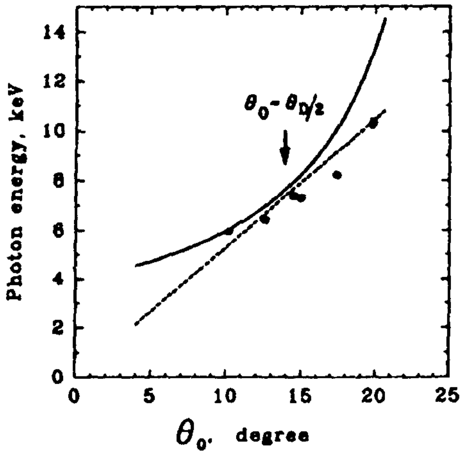

FIG. 5. Position of the peak in the x-ray spectrum as a function of θ_0: filled circles—experimental data (taken from Fig. 4); the dashed and solid lines are calculated using formulas (3) and (4), respectively.

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

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

Formula (4) can be used to estimate the orientation dependence of the energy of bremsstrahlung photons created and diffracted in the crystal. In Fig. 5, the points show the peak position in the measured spectra given in Fig. 4: the dashed line is calculated according to formula (3) for the PXR photon energy; the solid line is calculated according to formula (4) for the 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 determines the upper limit of the spectral region in which the bremsstrahlung yield is damped due to the density effect, is much less than the energy of the detected photons. Unfortunately, the results (see Fig. 5) are insufficient to draw conclusions as to the nature of the measured effect. It is clear that additional measurements for $\theta_0 < 10.17°$ and $\theta_0 > 20°$ are necessary. The present experimental setup does not allow such measurements, because at $\theta_0 < 10.17°$ the peak will not be resolved due to the detector threshold and at $\theta_0 > 20°$—due to absorption of PXR generated in bulk graphite (large effective thickness).

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

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