JETP Letters, Vol. 73, No. 9, 2001, pp. 457–460. Translated from Pis'ma v Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki, Vol. 73, No. 9, 2001, pp. 517–520.

X-ray Spectrum Determination from the Angular Dispersion of Radiation in a Diamond Prism

A. G. Tur'yanskiĭ*, I. V. Pirshin, R. A. Khmel'nitskiĭ, and A. A. Gippius

Lebedev Physical Institute, Russian Academy of Sciences, Leninskiĭ pr. 53, Moscow, 117924 Russia

** e-mail: tour@mail1.lebedev.ru*

Received March 27, 2001

The X-ray spectrum of hard polychromatic radiation with energies of up to 40 keV was obtained from the angular dispersion of the radiation beam in a diamond prism. In contrast to the classical optical scheme, the beam to be analyzed is passed through the entrance face of the prism without refraction and is directed onto the exit face at a glancing angle $\sim(2\delta)^{1/2}$, where δ is the real part of the decrement of the refractive index for the short-wavelength edge of the spectrum. The spectrum distortions caused by the intersection of the reciprocal lattice points by the Ewald sphere at a fixed number of wavelengths λ are minimized by the use of the angular divergence of the beam of ~10′ in the plane perpendicular to the refraction plane. In the energy range of 8–9 keV, an energy resolution of less than 100 eV was obtained, which exceeds the corresponding parameter for cooled semiconductor detectors. The measuring scheme suggested makes it possible to solve the problem of the analysis of spectra of directional X-ray beams when studying fast nonstationary generation processes. © *2001 MAIK "Nauka/Interperiodica".*

PACS numbers: 07.85.Nc; 07.60.Hv; 41.50.+h

INTRODUCTION

The possibility of determining the spectra of hard X-ray radiation using the prism-spectrometer method that is well known in optics [1] has scarcely been considered to date. This is explained by the smallness of the real part of the decrement δ of the refractive index of any substance in the X-ray range ($10^{-6} \le \delta \le 10^{-5}$ for the radiation energy $E \sim 10$ keV) and by the spread of the dispersion picture because of diffraction effects at the edges of the refracting sample [2–4]. It was shown in our previous work [5] that the X-ray optical parameters of diamond single crystals make it possible, first, to minimize the influence of diffraction effects at the refracting face and, second, to obtain refraction contraction and a multiple increase in angular dispersion using beams that strike the refracting interface from the inside of the prism at a glancing angle $\theta < \theta_c(E)$ (where θ_c is the critical angle of the total external reflection).

In this work, we realized the scheme of a prismatic X-ray spectrometer in a practical manner and obtained the full spectrum of a polychromatic beam with an energy $E > 6$ keV, including bremsstrahlung and fluorescent lines, from the angular dispersion of radiation in a diamond prism.

RESULTS AND DISCUSSION

Figure 1 displays the experimental scheme of the spectrometer. The dispersion element is a rectangular diamond prism *5* cut along {110} planes and having optically polished faces. The exit surface of the prism facing the absorbing shield *6* had the dimensions of 2 and 5 mm along the beam and in the perpendicular direction, respectively. As a source of polychromatic radiation, an X-ray tube with a copper anode was used. The voltage at the tube was changed in steps from 15 to 40 kV. The angle γ at which the X-ray beam exits the anode, as measured from the anode mirror, was 5°. The radiation was detected with a scintillation counter *12* based on an NaI(Tl) crystal, which ensured a detection efficiency of more than 85% in the range of 6–33 keV. Prism *5* and detector *12* were placed on goniometers *4* and *10*, respectively, whose rotation axes were directed along the primary beam. This geometry permitted us to increase the accuracy of measuring small deviation angles by a factor of $(s + r)/s$, where s is the distance between the axes O_1 and O_2, and r is the distance from the axis O_2 to the entrance slit *11* of the detector *12*. The monochromator *7* and detector *9*, which could be rotated about the axis O_1, were used to adjust the spectrometer to the monochromatic spectrum line employed.

The full widths at half-maximum (FWHMs) of the beam in the measuring plane (which coincided with the

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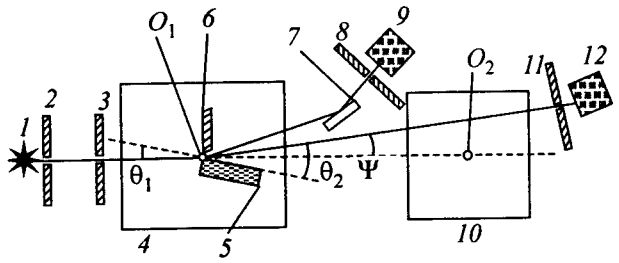

Fig. 1. Experimental scheme of measuring angular dispersion: (*1*) X-ray tube focus; (*2*, *3*, *8*, *11*) vertical collimating slits; (*4*, *10*) goniometers; (*5*) sample (prism); (*6*) absorbing shield; (*7*) monochromator; and (*9*, *12*) detectors of radiation.

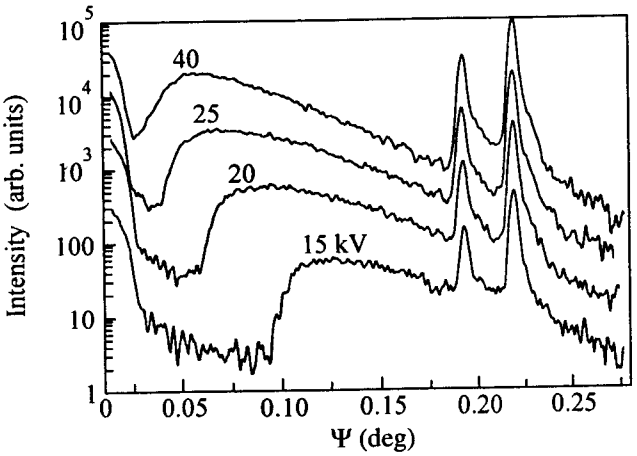

Fig. 2. Angular diagrams of the intensity of refracted radiation at various voltages at the X-ray tube with a copper anode.

plane of paper; see Fig. 1) and in the perpendicular direction, $\Delta\theta_p$ and $\Delta\theta_s$, were 25″ and 1200″, respectively. For these values of $\Delta\theta_p$ and $\Delta\theta_s$, the depths of diffraction dips in the angular dependence of the transmission coefficient of the prism upon rocking when using the Cu$K_{\alpha 1}$ line (8048 eV) did not exceed 20% of the average value in adjacent angular positions. The deepest dips corresponded to the energy band ΔE_d = 3–10 eV. As will be shown below, in spectral decomposition, the condition $\Delta E_d \ll \Delta E$ is fulfilled, where ΔE is the energy resolution of the prism spectrometer. This ensures a virtually complete smoothing of diffraction dips in the continuous spectrum that are caused by the intersection of the reciprocal lattice points of diamond by the Ewald sphere for a discrete set of bands of the spectrum.

The X-ray beam was directed onto the entrance side face of the prism at an incidence angle $\varphi = 3''$. With the above-indicated orientation of the prism, the deviation angle of the primary beam for the typical wavelength ~0.1 nm is ~0.001″; i.e., it is negligible in comparison with φ. Therefore, we have $\theta_1 \cong \varphi$, where θ_1 is the glancing angle between the plane of the exit face of the prism and the central ray of the beam to be analyzed. When calculating the deviation angle of the primary beam ($\Psi = \theta_2 - \theta_1$; see Fig. 1), the contribution of the imaginary part of the decrement of the refractive index $i\beta$ can be neglected, since in the energy range studied ($E > 6$ keV) the following condition is fulfilled for diamond: $\delta(E) \gg |i\beta(E)|$. Passing in the sine law from the sines of angles to the glancing angles themselves and using a series expansion at $\theta_1 \ll \pi/2$, we obtain the expression for the angle of deviation of the primary beam after transmission through the prism:

$$\Psi \cong \sqrt{\theta_1^2 + \frac{KZ\rho}{AE^2}} - \theta_1, \qquad (1)$$

where K is the dimensional coefficient, Z is the atomic number of the material of the refracting medium, ρ is the density of the material of the prism, and A is the atomic weight. Designating $C = KZ\rho/A$ and differentiating Eq. (1) with respect to E, we obtain the following formula for the angular dispersion of the rectangular prism:

$$D(E, \theta_1) = d\Psi/dE = -\frac{2C}{E^3\sqrt{\theta_1^2 + 2C/E^2}}. \qquad (2)$$

Figure 2 shows the angular diagrams of the intensities of the analyzed beam after the radiation passes through the prism for various voltages at the X-ray tube. The intense peaks in the diagram are due to the fluorescent copper lines (CuK_α doublet at 8028 and 8048 eV and the CuK_β line at 8906 eV); the rise in the intensity at small angles Ψ is due to the passage of part of the direct beam over the prism. As the voltage increases, the intensity of the bremsstrahlung part of the spectrum increases and the short-wavelength edge is shifted toward smaller angles Ψ.

Using expressions (1) and (2), we can pass from angular intensity distributions shown in Fig. 2 to the energy spectrum $S(E) = d^2N(E)/dEd\Omega$ measured in a given direction, where $d^2N(E)$ is the number of X-ray photons in the range (E, $E + dE$) that fall into a solid angle $d\Omega$ depending on the distance between the source of radiation and the prism and on the area of the entrance aperture of the spectrometer.

In the scheme used in this work, the effective width of the entrance aperture of the spectrometer $d_{\text{eff}}(E)$ is determined by the absorption of the radiation in the prism $A(E)$ and by the Fresnel transmission coefficient $T(E)$ at the exit face. The magnitude of $A(E)$ can easily be found in terms of geometric optics by solving the problem of beam transmission through an absorbing rectangular wedge [6]. The $T(E)$ dependence on the

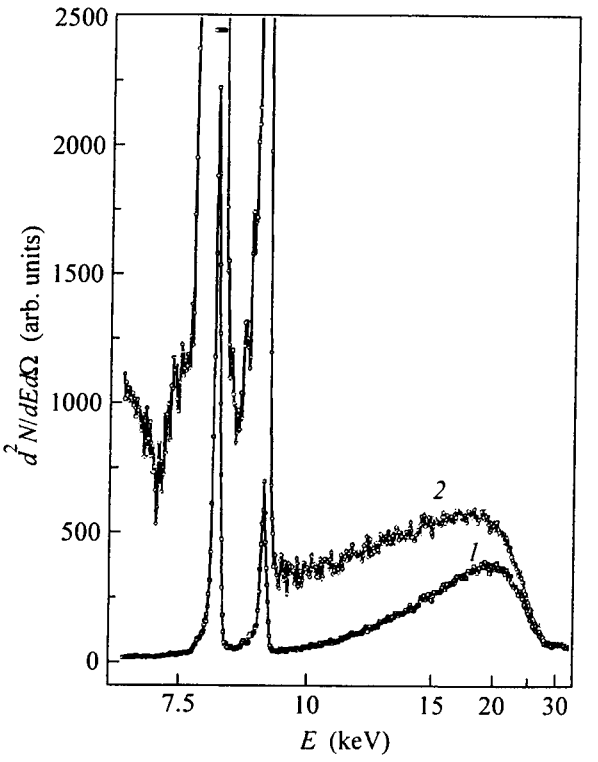

Fig. 3. Energy spectra of an X-ray tube with a copper anode and the escape angle of 5° at the voltage at the tube of 30 kV: (*1*) at the entrance window of the detector of radiation at a distance of 135 cm from the tube focus and (*2*) at the exit window of the X-ray tube.

glancing angle can be obtained from the Fresnel formulas [2, 3] by expanding into a power series at $\theta_1 = 0$:

$$A(E) = \int_0^L e^{-\frac{\mu(E)\rho y}{\cos\theta_1}} dy, \qquad (3)$$

$$T(E) \cong 1 - \left\{ \frac{\sqrt{\theta_1^2(E) + 2\delta(E)} - \theta_1}{\sqrt{\theta_1^2(E) + 2\delta(E)} + \theta_1} \right\}^2, \qquad (4)$$

where $\mu(E)$ is the energy dependence of the mass absorption coefficient, ρ is the density of the material of the prism, and y is the current coordinate for the beam outgoing from the refractive face of the prism. Note that, at the glancing angles θ_1 used in this work, the difference between the $T(E)$ values for the *s* and *p* polarizations is negligible and, therefore, the refracted spectrum is virtually polarization-independent.

Figure 3 displays the experimental energy spectrum (at a voltage at the tube equal to 30 kV) recorded by detector *12* (curve *1*) and the initial spectrum (curve *2*) at the exit window of the X-ray tube. Spectrum *2* was obtained from curve *1* with allowance for the dependences (3) and (4) and for the absorption in air and in the beryllium window (0.5 mm thick) of detector *12*. At $E = 8990$ eV, a jump of photoabsorption in copper is observed. Since the exit angle of the beam with respect to the anode mirror of the tube is relatively small, the absorption in the material of the anode exerts a significant effect on the shape of the spectrum. In particular, this leads to the appearance of a minimum in the bremsstrahlung part of the spectrum near the CuK_β fluorescent line. The observed asymmetry of spectral lines is mainly caused by the deviation of the refracting face from flatness near the prism edge.

With allowance for the instrument function, the energy resolution ΔE, characterized by the FWHM of the CuK_α line, is 97 eV, which is approximately half as large as the corresponding parameter for cooled semiconductor silicon detectors [7, 8]. This resolution is by no means limiting; an estimation shows that it can reach values of less than 40 eV with decreasing angular divergence in the plane of incidence.

The dependences shown in Figs. 2 and 3 were obtained by continuous angular scanning by the entrance slit. It is obvious that the replacement of a single-channel detector by a linear array or a matrix of detectors covering the entire angular range of the motion of the entrance slit will permit one to reject the angular rotation and, consequently, record a pulsed spectrum in a given direction without any restrictions on the duration of the pulse. Note that such a problem cannot be solved by using analyzing crystals, since, if the direction of recording is fixed in accordance with the Bragg diffraction condition, a change in the angle of rotation of the analyzing crystal is required.

CONCLUSION

The main results of this work are as follows.

(1) On the basis of a diamond prism, a scheme of a prism X-ray spectrometer was realized in a practical manner and spectra of hard X-ray radiation were obtained from the data on angular dispersion.

(2) In the energy range of 8–9 keV, an energy resolution of 97–106 eV was reached, which is half as large in comparison with that of cooled semiconductor detectors. This provides the possibility of practical application of such a prism spectrometer for analyzing spectra of intense X-ray sources.

(3) It is shown that the prism scheme with a linear array of detectors can be used for recording X-ray spectra in a given direction without any restrictions on the duration of the exciting pulse.

ACKNOWLEDGMENTS

This work was supported in part by the CRDF (grant no. RP2-2105).

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Translated by S. Gorin