Experimental observation of a half-degree angular interval of x-ray reflection in backscattering ($\theta \approx \pi/2$) from a high-quality crystal

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An increase of three orders of magnitude in the angular width of the reflection interval of a high-quality crystal in backscattering has been observed experimentally. This increase had been predicted previously by Kohra and Matsushita, Brummer *et al.*, and Caticha and Caticha-Ellis. New x-ray optics elements with a high luminosity might be developed on the basis of this effect.

High-quality crystals reflect x rays which are incident precisely at the Bragg angle and also in a finite angular interval around it. The width of this interval is determined for Bragg diffraction by the size of the gap in the dispersion surface; for symmetric reflection, it is

$$\Delta\theta = \chi/\cos(\theta), \tag{1}$$

where χ is the Fourier component of the polarizability of the crystal, and θ is the Bragg angle. Ordinarily, we would have $\theta \lesssim 1$, $\chi \lesssim 10^{-5}$, so that the width of the reflection interval would be $\Delta\theta_0 \approx 2''$. This quantity determines many characteristics of x-ray optics systems using high-quality crystals, primarily the reflection brightness. Only a negligible fraction of the emission from the x-ray source, which falls in the reflection angular interval, actually contributes to observable effects during a diffraction of radiation by such crystals; the rest of the radiation is lost, and for this reason x-ray elements of this type have an extremely low luminosity.

In 1972, Kohra and Matsushita[1] pointed out that relation (1) loses its applicability at the value $\theta = \pi/2$. A rigorous analysis[1–3] showed that at

$$\lambda = 2d_{HKL} \tag{2}$$

(λ is the wavelength, d_{HKL} is the interplanar distance, renormalized for refraction), the width of the reflection interval is

$$\Delta\theta_1 = 2\sqrt{\chi}. \tag{3}$$

The maximum width of the reflection interval is reached at a slightly shorter wavelength[2]; it is

$$\Delta\theta_2 = 2\sqrt{2\chi}. \tag{4}$$

The best known matching in (2) is the matching of CoKα_1 radiation and the Ge(620) reflection.[1] For this case, we have $\Delta\theta_1 = 26'$ and $\Delta\theta_2 = 36'$.

This theoretical prediction is extremely unusual for dynamic x-ray optics, since a reflection angular interval of half a degree should be observed at a high-quality crystal. This width is three orders of magnitude greater than in the case of ordinary diffraction with $\theta \lesssim 1$. The luminosity of the reflection should increase correspondingly. We have accordingly made an attempt to experimentally observe this anomalous wide angular interval of x-ray reflection at $\theta \approx \pi/2$.

Experiments on the observation of x-ray backscattering are distinguished in several ways from conventional experiments with $\theta \lesssim 1$. In the first place, the sample must be oriented simultaneously around two axes in order to bring it into the Bragg position. To simplify this procedure, before chemically polishing the surfaces of the germanium crystals, they were set parallel, within about 4′, to the (620) planes. The initial alignment of the samples was carried out with the help of a laser beam.

Second, at Bragg angles differing by no more than $\Delta\theta_1$ from $\pi/2$, difficulties arise in measuring the diffracted beam, since it is very close to the incident beam (within 10–20′). The beams must propagate at least a meter if they are to be even a few millimeters apart. However, the cobalt radiation is strongly absorbed in air, being attenuated by a factor of two over 50 cm. We accordingly used vacuum x-ray ducts through which the x rays travelled 5 m. For a preliminary alignment of the x-ray system, we used a detector with an aperture 4 mm in diameter at the center of the sensitive area, 20 mm in diameter.

The arrangement for the x-ray measurements is shown in Fig. 1. The radiation from the x-ray tube (1) strikes a graphite crystal (2), which suppresses the continuous spectrum and lowers the background in the apparatus. The beam then passes through tube 3, which shields the detector from the background scattered in the air, into the vacuum x-ray duct (4). Crystal 5, Ge(620), is a monochromator. This crystal is

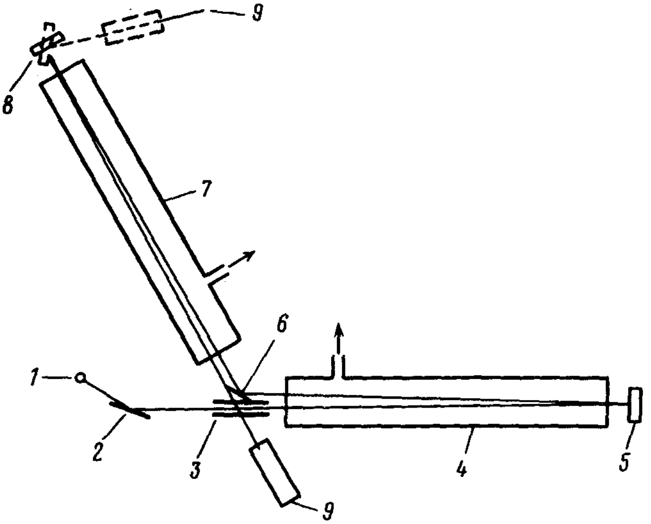

FIG. 1. Layout of the apparatus used to measure the angular width of the reflection region. 1—BSV-24 Co x-ray tube; 2—pyrolytic graphite crystal, (200); 3—copper tube 3 mm in diameter; 4,7—vacuum x-ray ducts each 1 m long with Mylar windows; 5,8—germanium single crystals, (620) surface; 6—lithium fluoride, (200), collimator; 9—detector.

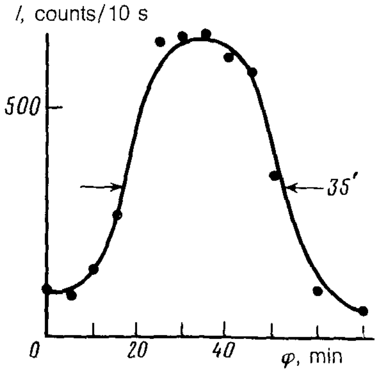

FIG. 2. Reflection curve of a germanium single crystal. (620) reflection, CoKα_1 radiation.

necessary because back diffraction is observed in a spectral interval of 0.1 eV, while the linewidth of the CoKα_1 radiation (6.93 keV) is 3.1 eV. This monochromator is used to suppress that broadening of the peak of interest which is caused by the reflection of radiation with $\lambda < 2d_{HKL}$. The calculated linewidth resulting from the use of this monochromator is 0.1 eV.

Crystal 6, LiF(200), collimates the radiation. Its rocking curve, recorded in MoKα_1 radiation, is 1.5′ wide. The radiation then passes through the x-ray duct to the sample crystal (8) Ge(620). The diffracted beam passes above tube 3 to detector 9.

Figure 2 shows the intensity of the diffracted beam versus the angular position φ of the last crystal. The width of this curve at half-maximum is 35′. Shown for comparison in Fig. 3 is the corresponding curve recorded in the x-ray arrangement represented by the dashed lines in Fig. 1, for the (511) reflection at the last crystal. The width of this curve (2′) demonstrates the instrumental resolution of this x-ray optics system.

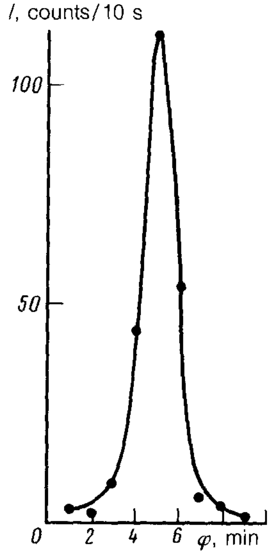

FIG. 3. Reflection curve of germanium. (511) reflection. This is the instrumental curve of the x-ray optics system in Fig. 1.

In summary, these experiments have resulted in the first observation of an anomalously broad angular interval of the reflection of x radiation from a high-quality crystal. A procedure has been developed for observing x-ray backscattering. The effect observed here raises the possibility of developing several x-ray optics elements with a luminosity three orders of magnitude higher than that of standard x-ray optics elements.

[1] K. Kohra and Y. Matsushita, Z. Naturforsch. **27A**, 484 (1972).

[2] O. Brummer, H. R. Hoche, and J. Nieber, Phys. Status Solidi a **53**, 565 (1979).

[3] A. Caticha and S. Caticha-Ellis, Phys. Rev. B **25**, 971 (1982).

Translated by Dave Parsons