Experimental observation of the connection between the polarization characteristics of coherent Mössbauer scattering and the magnetic structure of a crystal

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We have observed experimentally, for the first time ever, a connection between the polarization characteristics of coherent Mössbauer scattering by a crystal, on the one hand, and the crystal magnetic structure, on the other. The dependences of the degree of polarization and of the direction of the polarization vector on the direction of the magnetic field at the nuclei in the crystal were obtained.

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In connection with the peculiarities of coherent resonance scattering of gamma quanta in Mössbauer diffraction, the polarization characteristics of the scattered radiation should reveal a dependence on the magnetic structure of the crystal.[1] The difference of the polarization properties of Mössbauer scattering from the case of scattering of other types of radiation, particularly x rays, is due to the interaction of the gamma quanta with the nuclei.

The polarization characteristics of the interaction of Mössbauer radiation with matter were investigated only in transmission experiments.[2–4] The question of polarization properties of coherent scattering of Mössbauer radiation remained experimentally uninvestigated, although interesting polarization dependences were predicted in theoretical papers.

We have investigated, for the first time ever, the polarization properties of Mössbauer coherent scattering and their dependence on the magnetic structure of the crystal, using as an example the antiferromagnetic single crystal $FeBO_3$.

In the kinematic approximation of diffraction theory, in magnetic diffraction peaks, the polarization of the scattered radiation does not depend on the crystal structure of the antiferromagnet or on the energy of the Mössbauer quanta, and is determined only by the orientation of the antiferromagnetic axis in the crystal.[1] The experi-

mental investigation of the polarization characteristic was therefore carried out on an antiferromagnetic crystal in the magnetic diffraction maximum.

According to the theory,[1] in the case of an unpolarized primary beam, the radiation scattered in the magnetic-diffraction peak turns out to be partially linearly polarized, and the orientation of the plane of polarization as well as the degree of the polarization of the scattered radiation depends on the direction of the fields at the Mössbauer nuclei in the crystal. In the case of symmetrical Bragg reflection, which was investigated by us if the antiferromagnetic axis lies in the scattering plane, the Stokes parameters ξ_i, which determine the degree of polarization P $[P = (\Sigma_{i=1}^{3} \xi_i)^{1/2}]$ and the orientation of the plane of polarization of the scattered radiation, have the following dependence on the mutual orientation of the antiferromagnetic axis and on the Bragg angle θ_B

$$\xi_1 = \frac{\cos\theta \sin 2\Phi (\cos^2\alpha - \sin^2\theta_B \sin^2\alpha) + \sin^2\Phi \sin\theta_B \sin 2\alpha (1 + \cos^2\theta)}{2\cos^2\theta + \sin^4\theta \sin^2\Phi}$$

$$\xi_2 = 0 \tag{1}$$

$$\xi_3 = \frac{\cos\theta \sin 2\Phi \sin\theta_B \sin 2\alpha - \sin^2\Phi (1 + \cos^2\theta)(\cos^2\alpha - \sin^2\theta_B \sin^2\alpha)}{2\cos^2\theta + \sin^4\theta \sin^2\Phi}$$

where θ is the angle between the antiferromagnetic axis and the direction of incidence of the primary beam, Φ is the difference between the azimuthal angles of the directions of the primary and scattered beams, measured around the antiferromagnetic axis, and α is the angle between the antiferromagnetic axis and the normal to the scattering plane.

The angles θ and Φ are expressed in terms of θ_B and α in the following manner:

$$\cos\theta = \cos\theta_B \sin\alpha$$

$$\sin\Phi = \frac{\sin^2\theta_B \cos\alpha}{1 - \cos^2\theta_B \sin^2\alpha}. \tag{2}$$

We note that, in contrast to Ref. 1, expressions (1) yield the values of the Stokes parameters in a coordinate system whose x axis lies in the scattering plane and the y axis is perpendicular to it.

The Stokes parameters ξ_i were determined experimentally by analysis of the polarization properties of the scattered radiation, under the assumption that it is partially linearly polarized ($\xi_2 = 0$). We used for this purpose an analyzer that had different orientations relative to the scattering plane and absorbed selectively the linear polarization.

The experimental setup is illustrated in Fig. 1.

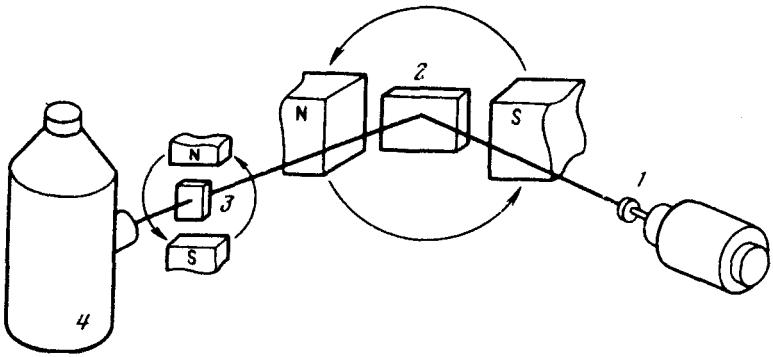

FIG. 1. Experimental setup: 1) Mössbauer source, 2) sample, 3) analyzer, 4) Si(Li) semiconducting detection block.

The analyzer was a single crystal of iron borate 50 μm thick, placed in the field of a permanent magnet, and acted as a "black" absorber for one linear polarization. The change of the orientation of the selectively absorbed polarization was effected by rotating the magnet about an axis perpendicular to the crystal surface, as a result of which the orientation of the magnetic field at the nuclei was changed.

The Stokes parameters ξ_1 and ξ_3 were determined from the measurement results by means of the formulas

$$\xi_1 = I_{135} - I_{45},$$

$$\xi_3 = I_0 - I_{90}, \tag{3}$$

where I_0, I_{45}, I_{90} and I_{135} are the intensities of the diffracted beam passing through the analyzer, making angles 0, 90, 45, and 135° respectively with the plane of polarization.

In the experiment, the scattering in the sample and the absorption in the analyzer took place via the transition 3/2→1/2.

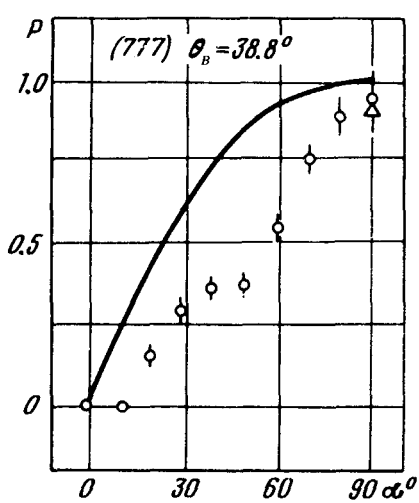

FIG. 2. Measured and calculated (solid curve) dependences of the degree of polarization of Mössbauer-radiation diffracted by an $FeBO_3$ crystal on the antiferromagnetic-axis orientation.

The sample used for the measurements of the polarization dependences was single-crystal $Fe^{57}BO_3$, detailed data on which are given in Ref. 5.

Figure 2 shows the measured and calculated dependences of the degree of polarization of the diffracted Mössbauer radiation on the orientation of the antiferromagnetic axis in the $FeBO_3$ crystal, while Fig. 3 shows the dependence of the orientation of

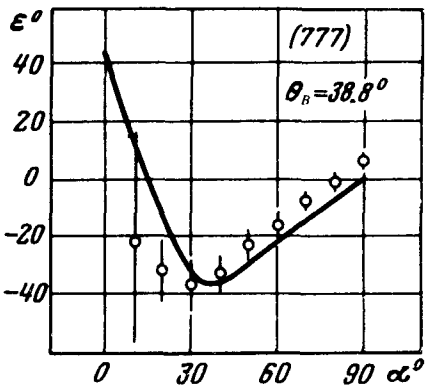

FIG. 3. Measured and calculated (solid curve) dependences of the orientation of the plane of polarization of a diffracted beam of Mössbauer quanta on the direction of the magnetic field at the nuclei in an $FeBO_3$ crystal.

the plane of polarization of the diffracted radiation on the direction of the antiferromagnetic axis in the crystal.

The experimental results are in qualitative agreement with the theoretical ones both for the degree of polarization P and for the orientation of the plane of polarization relative to the scattering plane.

The quantitative difference between the experimental and theoretical curves is not surprising, since the employed sample was perfect enough, but the curves were calculated in accordance with the kinematic theory. One should expect calculation of the curves in accordance with a more perfected dynamic theory to result in a better agreement between theory and experiment.

The kinematic approximation of the theory presupposes that the polarization characteristics of the diffracted radiation is independent of the energy of the primary beam of the gamma quanta in the case considered above. The degree of polarization obtained by a deviation of 0.25 mm/sec from the $3/2 \rightarrow 1/2$ resonance (marked by the triangle in Fig. 2) proves the validity of this statement.

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