Experimental observation of the birefringence of Mössbauer radiation in an antiferromagnetic hematite crystal

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Birefringence of polarized Mössbauer γ quanta, due to the nuclear mechanism of γ-quantum interaction with matter, was observed when the γ quanta passed through an antiferromagnetic hematite crystal.

According to the theoretical concepts developed in a number of papers,[1–3] when Mössbauer radiation passes through a crystal it is necessary to regard the transmitted wave as a superposition of a wave that experiences no scattering and a wave that is coherently scattered forward. From the theoretical studies of Mössbauer optics follows the existence of the effects of birefringence and rotation of the polarization plane. These effects were experimentally investigated[4,5] only in ferromagnetic structures.

We report here the first experimental investigation, by the methods of Mössbauer optics, of the effect of birefringence in an antiferromagnetic hematite single crystal ($\alpha-Fe_2O_3$) below the Morin temperature ($T=260\,^\circ K$), where the weak ferromagnetism possessed by the crystal at room temperatures vanishes, and the antiferromagnetic axis [111] is oriented perpendicular to the crystal surface.

The theory of Mössbauer optics shows that the refractive index (its real and imaginary parts) depends on the structure of the crystal and on its orientation relative to the incident radiation beam. For the case of an antiferromagnet with fully resolved Zeeman splitting of the Mössbauer line, the refractive indices of the natural waves near an individual line take the following form (for the nuclear transition $\Delta m=0$):

$$\kappa_1 = 1$$

$$\kappa_2 = 1 + \frac{2\pi N a_0 \Gamma e^{-z(\mathbf{k})} n}{k^3(E_\gamma - E_0 + (i\Gamma/2))(1+\alpha)} \sin^2\theta, \tag{1}$$

where N is the number of units per unit volume of the crystal, a_0 is a dimensionless factor that depends on the concentration of the Mössbauer isotope and on the magnetic quantum numbers of the nuclear transition, Γ is the width of the Mössbauer level, $\exp[-z(\mathbf{k})]$ is the Lamb-Mössbauer factor, n is the number of Mössbauer nuclei per unit cell, θ is the angle between the wave vector $\mathbf{k}$ of the γ quantum and the antiferromagnetic axis, E_γ is the γ-quantum energy, E_0 is the energy of the Mössbauer transition, and α is the internal-conversion coefficient.[3] It follows from (1) that for the nuclear transition with $\Delta m=0$ one natural wave does not interact with the nuclei of the crystal ($\kappa_1=1$), and the nuclear interaction of the other depends on the angle of incidence of the radiation on the crystal (the refractive index κ_1 is possessed by the wave linearly polarized in the ($\mathbf{k}$, [111]) plane, while the refractive index κ_2 corresponds to the wave polarized in the perpendicular direction).

The difference between the imaginary parts of the refractive index can be determined by measuring the intensity of the radiation passing through the crystal at two linear polarizations that coincide with the polarizations of the natural waves in the crystal.

Figure 1 shows the experimental setup. The γ quanta from a Mössbauer source (Cu^{57} in a chromium matrix) passed through a polarizer P and were incident on an artifically grown hematite single crystal enriched to approximately 85% Fe^{57}. The [111] crystal axis made an angle θ with the direction of the incident radiation. After passing through the single crystal, the γ radiation passed through an analyzer, which served to determine the degree of polarization of the radiation, and was registered by the radiation detector det, which was part of a Mössbauer spectrometer operating in the constant-velocity regime. A cooling system (not shown in the figure) has made it possible to produce at the hematite single crystal a temperature lower than the Morin temperature.

The polarizer and the analyzer were thin layers of Fe^{57} evaporated on beryllium substrates and placed in fields of permanent magnets, and made it possible to obtain and analyze the linearly-polarized Mössbauer radiation. The schematic diagram of the setup containing the polarizer, the investigated crystal, and the analyzer were similar to those of the corresponding classical-optics installations, and had provisions for rotating the analyzer relative to the polarizer.

The source of the Mössbauer γ quanta was moved at constant velocity in such a manner that the source emission line coincided with the $\Delta m=0$ line (in the negative frequency band) and the spectrum of the resonant absorption by the Fe^{57} nuclei in the polarizer

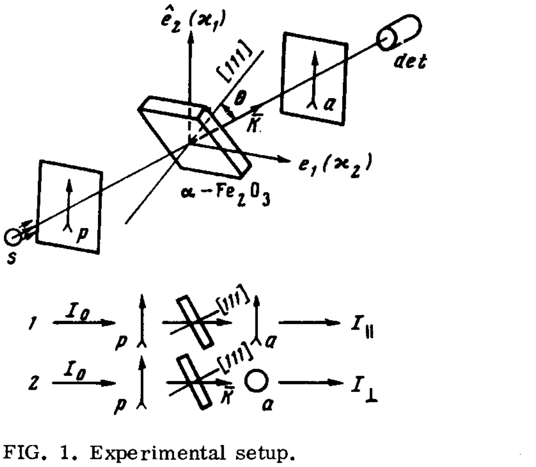

FIG. 1. Experimental setup.

θ	I_{κ_1}, %	I_{κ_2}, %
0	5.10 ±0.20	4.90 ±0.16
20	5.10 ±0.19	3.70 ±0.18

(analyzer), and differed by $\Delta E \approx 2\Gamma$ from the $\Delta m = 0$ line in the absorption spectrum of the hematite (E_0). In the experiments, the polarizer was mounted in such a way that the radiation incident on the hematite single crystal was linearly polarized along the vectors $\hat{e}_2(\kappa_1)$ and $\hat{e}_1(\kappa_2)$[$\hat{e}_2(\kappa_1)$ and $\hat{e}_1(\kappa_2)$ are the directions of the polarizations of the natural waves in the hematite single crystal].

The intensity of the radiation passing through the polarizer—hematite single crystal—analyzer system was measured at the two analyzer positions shown in Fig. 1. We measured the quantity $I_k = [(I_\parallel - I_\perp)/I_\perp] \cdot 100\%$ for the angles $\theta = 0°$ and $\theta = 20°$. The results of the measurements are listed in the table.

The results indicate that the wave polarized along $\hat{e}_2(\kappa_1)$ interacts less strongly with the crystal than the wave with polarization along $\hat{e}_1(\kappa_2)$; this is analogous to birefringence in optics and agrees with the theoretical concepts.

The ratio

$$(I_{\kappa_2}(\theta)/I_{\kappa_1}(\theta) = \exp\{-\mu(\theta)(h/\cos\theta)\}, \tag{2}$$

where h is the crystal thickness, relates the experimentally obtained quantities $I_{\kappa_1}(\theta)$ and $I_{\kappa_2}(\theta)$ with the nuclear absorption coefficient $\mu(\theta)$ of the Mössbauer radiation polarized along $\hat{e}_1(\kappa_2)$.

From (1) we get for $\mu(\theta)$

$$\mu(\theta) = \mathrm{Im} < k\kappa_2 >. \tag{3}$$

Substituting in (2) the values of I_{κ_2} and I_{κ_1} from the table at the crystal inclination angle $\theta = 20°$, we obtain

$$\mu_{\mathrm{exp}}(\theta)/\sin^2\theta = (240 \pm 60)\ \mathrm{cm}^{-1} \tag{4}$$

Calculation of the absorption coefficient μ_{theor}, based on relation (3), yields $\mu_{\mathrm{theor}}/\sin^2\theta = 235\ \mathrm{cm}^{-1}$, which is in good agreement with the experimentally obtained value of this quantity.

We note that measurements similar to those performed in this study can be used to find the Lamb-Mössbauer factor in the investigated sample. Indeed, expression (3) does not depend on the Lamb-Mössbauer factor of the source, but relates directly the experimentally measured intensity ratio (2) with the Lamb-Mössbauer factor for the investigated crystal.

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