Mössbauer-diffraction observation of an induced magnetic anisotropy at the surface of slightly ferromagnetic $^{57}FeBO_3$ crystals

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Mössbauer diffraction has been used for the first time to study the magnetization of the surface layer of slightly ferromagnetic $^{57}FeBO_3$ crystals. An induced magnetic anisotropy has been observed in the basis plane in the surface layer. The structural quality of the crystal affects the energy at which the domain walls stabilize and also the energy at which the magnetization direction within a domain stabilizes.

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The reorientation of the magnetic moments of iron ions in the surface layer of $^{57}FeBO_3$ crystals under the influence of an external magnetic field has been studied for the first time. This study has been made possible by the ability to adjust the depth to which γ rays penetrate into a crystal (by changing the γ energy) and also by the high sensitivity of the Mössbauer-diffraction method to the orientation of the magnetic fields at the scattering nuclei.[1]

Iron borate ($FeBO_3$) is a weak "easy-plane" ferromagnet. The magnetic moments of the iron ions lie in the (111) basis plane and are slightly noncollinear. The results which have been obtained in studies of the magnetic properties of $FeBO_3$ crystals refer to the overall crystal (see Ref. 2, for example), while the crystal surface may have properties quite different from the volume properties.[3]

For this study of the magnetization of the crystal surface we used an experimental arrangement similar to that described in Ref. 1. We measured the intensity of the diffracted Mössbauer radiation upon a change in the strength of the magnetic field applied along the line representing the intersection of the basis plane of the crystal and the scattering plane.

All the measurements were carried out at the purely nuclear (777) magnetic maximum, at room temperature. The scattering occurred through the $3/2 \to 1/2$ nuclear transition. The γ beam was reflected from the entire surface of the crystal. To monitor the stability of the motion of the source during the experiment we used yet another Mössbauer source, mounted at the other end of the vibrator shaft, along with a calibration absorber and Si (Li) detector. As a control we used the intensity of the Mössbauer absorption line of the calibration absorber.

The following procedure was used in the experiments: A magnetic field **H** with a strength of 370 Oe was initially applied in the direction perpendicular to the scattering

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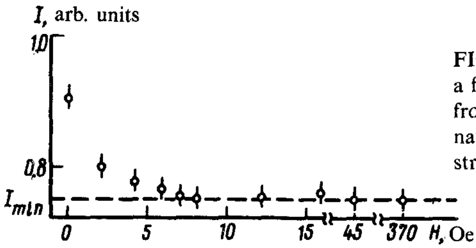

FIG. 1. Intensity of the diffracted Mössbauer radiation at a frequency slightly away from resonance (the difference from the resonant frequency is equal to five times the natural width of the Mössbauer line), plotted against the strength of the magnetic field ($\alpha = 27°$).

plane, the plane defined by the vectors **k** and **k**′, which are the wave vectors of the radiation incident on the crystal and that reflected from it. In this case the purely nuclear magnetic reflection reaches its maximum intensity.[1] We then measured the intensity of the diffracted Mössbauer radiation in the absence of a magnetic field ($H = 0$), and then again with an increasing field H, applied to the crystal in the scattering plane.

If the change in the domain structure with increasing H occurs continuously until a single-domain state forms with magnetization along **H**, then the intensity of the reflected γ radiation should fall off continuously to a value corresponding to the intensity of the reflection from a sample which is fully magnetized along the **H** direction. This is in fact the pattern which is observed experimentally, when the entire thickness ($\sim 30\,\mu$m) of the crystal participates in the scattering (Fig. 1). This situation is achieved by tuning slightly away from the γ resonance. The difference between the γ energy and the energy of the nuclear transition is 5Γ, where Γ is the natural width of the Mössbauer line.

Exactly at resonance, the γ rays penetrate a depth $\sim 0.5\,\mu$m into the crystal, and the corresponding H dependence of the reflection intensity has a form different from that in the preceding case (Fig. 2b). This dependence may be interpreted as follows: the intensity decrease in the interval 0–5 Oe apparently results from the formation of the single-domain state in the surface layers of the crystal through a displacement of domain walls.[1)] The direction of the magnetization vector **M** of this single domain is not the **H** direction, but at an angle α from it, as is implied by the fact that the reflection intensity does not assume its minimum value. The angle α can be determined from the experimental results by using the formula[1]

$$\sin^2\alpha = \frac{I_\alpha - I_{min}}{I_{max} - I_{min}}, \qquad (1)$$

where $I_{\min}$ ($I_{\max}$) is the intensity of the Mössbauer-radiation reflection for the case in which the magnetization **M** of the reflecting part of the crystal is directed parallel (perpendicular) to the scattering plane (the plane of **k** and **k**′); also I_α is the intensity corresponding to the angle α.

The fact that the intensity remains constant over the interval $\sim$5–9 Oe indicates that there is no change in the magnetic state at the crystal surface, apparently because the magnetization direction of the single domain in the surface layer of the sample is stabilized.

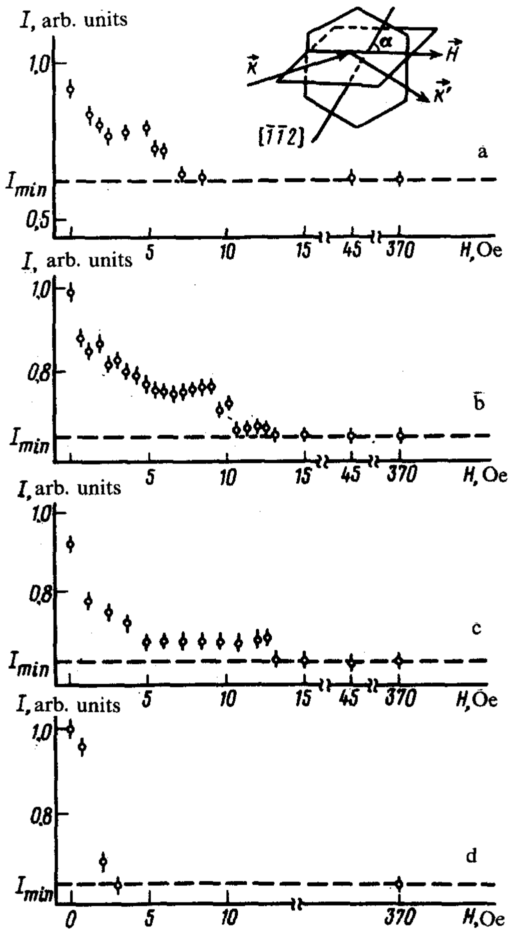

FIG. 2. Intensity of the diffracted Mössbauer radiation exactly at resonance, plotted against the magnetic field. a—$\alpha = 45°$; b—27°; c—15°; d—0.

At a higher field, $H \gtrsim 9$ Oe, the energy of the external field becomes greater than the stabilization energy of the domain magnetization direction, and the magnetization vector rotates to an orientation along the external field. The reflection intensity drops to its minimum.

It thus follows from the experimental results in Figs. 1 and 2b that the magnetic moments of the iron ions near the surface become oriented along a certain easy-magnetization direction,[2)] which makes an angle γ with **H**, at least as H is increased approximately over the interval 0–5 Oe.

Figure 2d shows the intensity of the diffracted Mössbauer radiation, plotted as a function of the strength of the magnetic field applied along this presumed easy axis, i.e., at $\alpha = 0$. The angle α was varied by rotating the crystal around the diffraction vector. In this case we do not see the plateau (at ~5–9 Oe in Fig. 2b) which was observed in the preceding case and which was caused by a stabilization of the magnetization direction along the easy axis, because the surface turns out to be fully magnetized, directly along **H**, after the displacement of the domain walls.

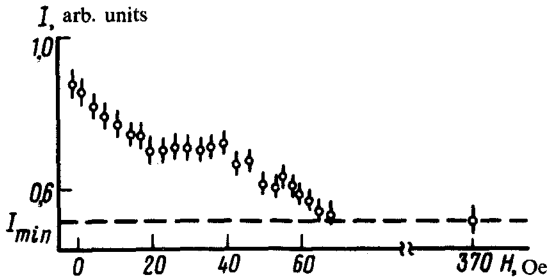

FIG. 3. Intensity of the diffracted resonant radiation for a defective crystal, plotted against the strength of the external magnetic field.

Figures 2a and 2c show similar plots of the intensity of the reflected radiation against H for $\alpha = 15°$ and $\alpha = 45°$. The observed changes in the height of the plateau agree with the angular position of the crystal, monitored with a goniometer. The rotation of **M** begins at various values, of H, depending on α (Figs. 2a–2c). Calculations from the data in Fig. 2 show that the magnetization-direction stabilization energy is independent of α.

These results show that the process by which the surface layer of the weakly ferromagnetic crystal $FeBO_3$ is magnetized differs from the magnetization process of the volume of this crystal. In particular, when the crystals are magnetized in the surface layer an important role is played by the stabilization of the domain walls and of the magnetization direction within a domain. This result means that an induced surface magnetic anisotropy is observed in the basis plane of the iron borate crystal.

The crystal used in these measurements had a very low number of structural defects.[1)] It may be assumed that an increase in the number of structural defects will increase the domain-wall stabilization energy and the energy required to stabilize the magnetization direction within a domain, as occurs in ferromagnets and ferrimagnets.[4] To check this possibility, we measured the intensity of the diffracted Mössbauer radiation for various directions of the magnetic field for a crystal containing more defects (Fig. 3). Comparison of Fig. 3 with Fig. 2 (for a given orientation of the easy axis with respect to **H**) shows that the formation of the single-domain surface state in the low-quality crystal ends at a value of H six times greater than in the case of the high-quality crystal, and the rotation of **M** of the resulting single domain is ten times greater than in the case of the high-quality crystal. These differences show that the stabilization energy of the surface-layer domain structure depends on the structural quality.

This is the first observation of an induced magnetic anisotropy in the surface layer of a weakly ferromagnetic crystal. The reason for the appearance of this anisotropy has not yet been determined.

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[1)]Further evidence for the formation of a single-domain state comes from the x-ray topograms of this crystal, obtained for various values of H. These topograms show that the elastic stresses in the crystal, related to the presence of a domain structure, are removed at $H \approx 5$ Oe.

[2)]X-ray diffraction measurements show that the easy-magnetization direction is the twofold [112] crystallographic symmetry axis (within the experimental error).

[3)]The structural quality of the crystals was determined from x-ray topograms and from rocking curves.

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