Evolution of the microwave absorption spectrum of a strongly anisotropic ferrimagnet as the orientation of the external magnetic field is varied

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The behavior of the lines of resonant microwave absorption has been studied in a $Ho_{0.4}Y_{2.6}Fe_5O_{12}$ single crystal as the orientation of the external magnetic field was varied in the (110) plane. This plane contains the principal directions of the cubic crystal: [100], [110], and [111]. Experiments were carried out in pulsed magnetic fields up to 250 kOe at liquid-helium temperature at a frequency of 40.5 GHz. A comparison reveals substantial differences between the experimental results and the results of a theoretical analysis based on the model of an Ising ordering of holmium ions.

Significant anomalies in the static properties of $Ho_xY_{3-x}Fe_5O_{12}$ are known to occur in fields comparable in magnitude to the effective field (H_{ex}) of the exchange interaction between the rare-earth and the iron subsystems of this magnetic material. The number and magnitude of these anomalies are very sensitive to the orientation of the external field with respect to the crystallographic axes.[1,2] In addition to the absorption lines associated with magnetostructural transitions induced by the magnetic field,[3,4] there are several other resonant lines, which are unrelated to such transitions. Some of these resonances were interpreted in Ref. 5 as resulting from a dynamic magnetic Jahn–Teller effect;[2] others may be due to a static magnetic Jahn–Teller effect.[6] There are no abrupt changes in the magnetization in the course of this effect, but this effect may be seen in a study of the dynamics of the magnetic system of the crystal.

In this letter we are reporting an effort to clearly distinguish these last two parts of the absorption spectrum of this holmium-yttrium iron garnet. We studied the orientational dependence of the magnetic-resonance fields at a fixed frequency $\nu=40.5$ GHz in a $Ho_{0.4}Y_{2.6}Fe_5O_{12}$ single crystal. The experiments were carried out with a pulsed reflection rf spectrometer in fields up to 250 kOe at 4.2 K. The (110) plane of the sample was cemented to the surface of a rotating panel on the wide wall of a standard 8-mm waveguide near a shorting end. The external magnetic field, produced by a pulsed selenoid, was directed along the waveguide in all cases. Since the intensity and position (along the field scale) of the absorption lines are extremely sensitive to the angle,[3] the absorption spectra were measured at small angular steps (3°–5°) over the range from 0 to 360°. The error in the positioning of the (110) plane was less than 5°. The working frequency was chosen low enough to avoid the additional complication of the observed picture of the resonance due to a splitting (along the field scale) of the resonant lines at higher frequencies—a complication not associated with the change in the orientation of the external field.[3]

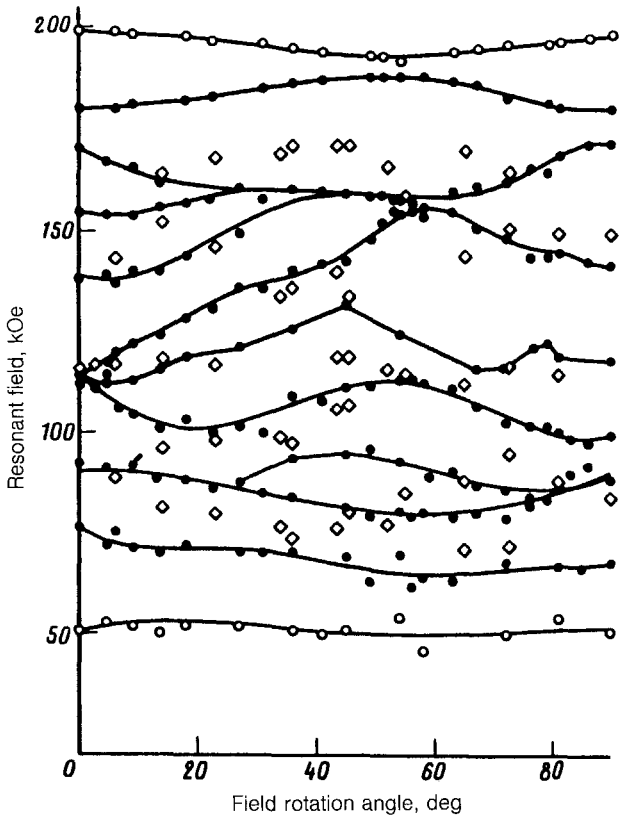

FIG. 1. Experimental H_{res}-θ and H_c-θ phase diagrams of $Ho_{0.4}Y_{2.6}Fe_5O_{12}$ in the (110) plane. Filled and open circles—resonant fields; rhombi—fields of magnetic phase transitions from Ref. 1.

Figure 1 shows the resonant field H_{res} versus the angle (θ) between the magnetic field H and the [100] direction. These results are averaged over the four quadrants. The filled circles in Fig. 1 correspond to absorption lines which were reliably identified and observed in all quadrants. The open circles show absorption lines which were observed in one or two quadrants. The solid lines are least-squares fits. The rhombi show the fields found for magnetic phase transitions in Ref. 1 from magnetization measurements (these fields were determined from the abrupt jumps in the magnetic moment $\mathbf{M}\|\mathbf{H}$). The hysteresis of the $M(H)$ curves observed in Ref. 1 has been eliminated: The field of the magnetic transition has been taken to be half the sum of the critical fields during the increase and decrease of the magnetic field.

For fields between 80 and 170 kOe, all the fields H_{res} correspond well to the points of magnetic phase transitions and are a consequence of a static Jahn–Teller magnetic effect.[4,6,7] We might also point out a characteristic feature of the $H_{res}(\theta)$ curves in Fig. 1: There is a degeneracy of the phases when the external field is oriented along the maximum-symmetry directions.

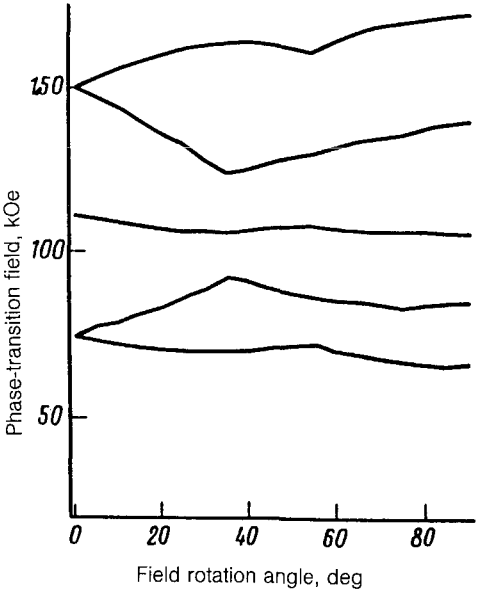

FIG. 2. Theoretical H_c-θ phase diagrams of $Ho_{0.4}Y_{2.6}Fe_5O_{12}$ as the magnetic field is rotated in the (110) plane. Here θ is the angle from the [100] direction.

The absorption lines at $H \simeq 50$ and $H \simeq 200$ kOe are due to a dynamic, rather than static, magnetic Jahn–Teller effect[2] (as was shown in Ref. 5 for the [100] and [111] directions). In the course of this dynamic effect, the time-averaged change of the magnetic structure of the crystal is zero. It can thus be asserted that the resonances at fields on the order of 70 and 180 kOe are also due to magnetic phase transitions accompanied by a static magnetic Jahn–Teller effect, in the course of which, however, there is no abrupt change in the magnetic moment.

A theoretical analysis of the magnetic-field-induced phase transitions, carried out on the basis of the model of an Ising ordering of the holmium ions in $Ho_xY_{3-x}Fe_5O_{12}$, with allowance for the three rare-earth magnetic sublattices, has shown[1,2,7] that eight phases are realized in succession (as the field is strengthened) for an arbitrary orientation of the external field. These phases are determined by the direction of the resultant magnetic moment of the rare-earth subsystem of the crystal, **m**, which may be oriented only along [111] axes according to this model. The absolute value of **m** is $\frac{1}{6}x\mu_z M^{-1}\Sigma_{1,3,5}I_r$, where M is the magnetic moment of the iron sublattice, I_r is a unit vector along the direction of the rth rare-earth sublattice, and μ_z is the projection of the magnetic moment of the rare-earth ion onto the local [100] Ising axis. The phase-transition lines are determined by[2]

$$h_{i\leftrightarrow k}=\frac{2m(q_i+q_k)}{4-m^2(q_i-q_k)^2}+2\left\{\frac{1-m^2}{4-m^2(q_i-q_k)^2}+\frac{m^2(q_i+q_k)^2}{[4-m^2(q_i-q_k)^2]^2}\right\}^{1/2},$$

where $h=H/H_{ex}$ is the reduced external field, and $q_i=\mathbf{m}_i\mathbf{h}/mh$ is the projection of the magnetic moment of the rare-earth ion in phase i onto the field.

For an arbitrary field direction, with absolutely no degeneracy among phases, the largest possible number of transitions is seven. Figure 2 shows theoretical curves of

$H_c(\theta) = h_{i \leftrightarrow k} H_{ex}$ for the case in which the external field is "rotated" in the (110) plane; here we have used the value $H_{ex} = 125$ kOe, from the results of Ref. 1.

A comparison of the theoretical results of Ref. 2 with the results of the static and dynamic experiments (Fig. 1) leads to the conclusion that there are qualitative discrepancies between theory and experiment. The apparent causes of these discrepancies are (first) that the model of an Ising ordering of the holmium ions[1,2] incorporates only the two lowest-lying levels in the spectrum of this ion, so there are only two permissible projections of the rare-earth magnetic moment onto the local quantization axis (the Ising axis), and (second) the initial umbrella-shaped magnetic rare-earth structure is treated as a set of three rare-earth sublattices, while in $Ho_3Fe_5O_{12}$ there is a double-umbrella structure, consisting of six rare-earth magnetic moments.[8,9] Study of the dynamic characteristics of the crystal (combined with the static experiments; Fig. 1) indicates that the sequence of magnetic phases which occur as the field is increased is quite different from that predicted by the theory. The reason may lie in either an effect of higher-lying levels on the ground quasidoublet of the Ho^{3+} ion or a systematic change in the two umbrella-shaped rare-earth structures.

[1] V. I. Silant'ev, A. I. Popov, R. Z. Levitin, and A. K. Zvezdin, Zh. Eksp. Teor. Fiz. **78**, 640 (1980) [Sov. Phys. JETP **51**, 323 (1980)].
[2] A. K. Zvezdin, V. M. Mateev, A. A. Mukhin, and A. I. Popov, *Rare Earth Ions in Magnetically Ordered Crystals*, Nauka, Moscow, 1985.
[3] A. S. Lagutin, Zh. Eksp. Teor. Fiz. **99**, 336 (1991) [Sov. Phys. JETP **72**, 189 (1991)].
[4] A. S. Lagutin and A. I. Popov, Pis'ma Zh. Eksp. Teor. Fiz. **54**, 90 (1991) [JETP Lett. **54**, 87 (1991)].
[5] A. S. Lagutin, Zh. Eksp. Teor. Fiz. **102**, 262 (1992) [Sov. Phys. JETP **75**, 138 (1992)].
[6] A. K. Zvezdin, A. I. Popov, and A. A. Mukhin, Zh. Eksp. Teor. Fiz. **72**, 1097 (1976) [Sov. Phys. JETP **45**, 573 (1976)].
[7] K. P. Belov, A. K. Zvezdin, R. Z. Levitin, and A. M. Kadomtseva, *Orientational Transitions in Ferrites and Antiferromagnets*, Nauka, Moscow, 1979.
[8] S. Herpin, P. Meriel, and W. C. Koeler, C. R. Acad. Sci. **251**, 1359 (1960).
[9] F. Tcheou, E. F. Bertraut, and H. Fuess, Solid State Commun. **8**, 1751 (1970).

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