MECHANISM FOR ANOMALOUS MAGNETOCRYSTALLINE ANISOTROPY PEAKS IN FERROMAGNETIC CRYSTALS*

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Dillon[1] reported the occurrence of strong sharp peaks in the magnetocrystalline anisotropy contribution to the ferromagnetic resonance field in yttrium iron garnet (YIG) at liquid helium temperatures. His results have been confirmed by Dillon and Nielsen,[2] who have attributed the anomalous peaks to rare earth ion impurities, and striking results for Tb-doped YIG were presented. At 1.5°K at 23 kMc/sec in YIG containing 0.1% Tb three or more anomalous peaks are observed on rotation in the (110) plane, the height (always positive) of the peaks being of the order of 3 to 5 koe and the angular width at half-maximum of the order of 3 deg. The sharpness of the peaks defy reasonable analysis in spherical harmonics, and no previous theoretical attempt to explain the peaks has broached the problem, although Wolf[3] has recognized that the exchange coupling of Fe^{3+} and rare earth ions must be involved, and Dillon and Nielsen[2] state that Clogston, Walker, and Dillon are attacking the problem.

The underlying mechanism appears to be very simple, and we give here an elementary model which makes the physics clear. When the crystal field splitting parameters become known for the relevant rare earth impurities in YIG or in the gallate, it will be easy to make detailed predictions. Consider as in Fig. 1 the energy levels of a paramagnetic ion in a uniaxial crystal field and an effective exchange field arising from the ferric lattice magnetization at an angle θ with the crystal field axis. For the highly anisotropic g's characterizing most rare earth levels in crystals it is legitimate to treat the exchange interaction as an effective magnetic field.[4] To obtain an anomalous anisotropy it is necessary that the ground states cross over[5] at one or more angles θ_0. At absolute zero the ion is in the state m_1 when the magnetization lies between $\cos^{-1}0$ and $\cos^{-1}\theta_0$, and in the state m_2 between $\cos^{-1}\theta_0$ and $\cos^{-1}1$. The anisotropy field H_a in a resonance experiment is essentially defined by

$$H_a M_s = -\partial^2 E/\partial\theta^2, \tag{1}$$

where M_s is the total magnetization and E refers to unit volume. At absolute zero H_a will have a delta-function type maximum at each crossover θ_0. On either side of θ_0 there will be a weak anisotropy field of the order $mH_{ex}f\cos\theta$, where the effective quantum number or g-value m is m_1 or m_2, according to the direction, and f is the ratio of rare earth ions to unbalanced ferric ions; for $f\sim10^{-3}$ and[6] $H_{ex}\sim10^5$ this background anisotropy of ~100 oersteds from the rare earth impurities is to be added to the sources of anisotropy in pure YIG.

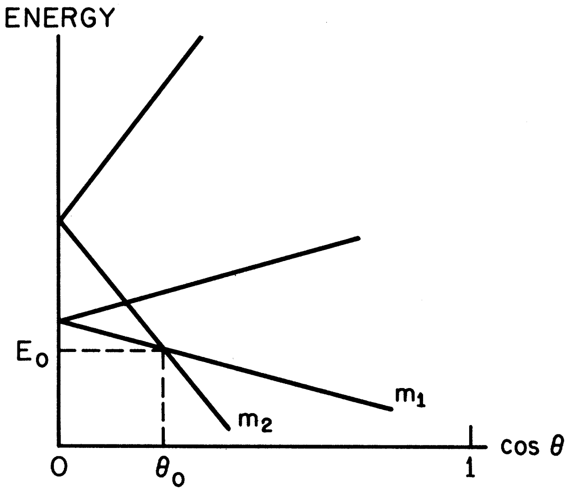

FIG. 1. Schematic crystal field level diagram in combined exchange and uniaxial crystal fields, where θ is the angle between the crystal field axis and the direction of the effective exchange field arising from the ferric lattices.

The delta-function anomaly spreads out at a finite temperature. We consider deviations $\Delta\theta$ from θ_0 such that $(\Delta m)\mu H_{ex}\Delta\theta \ll kT$. Within this angular range we see from the equilibrium population difference that

$$\langle\Delta E\rangle \approx -(\Delta m)^2(\mu H_{ex}\Delta\theta)^2/kT, \tag{2}$$

within a factor of the order of unity. Thus the anomalous anisotropy field is given by

$$H_a \approx (\Delta m)^2(\mu H_{ex}{}^2)f/kT \approx 10^4/T \text{ oersteds}, \tag{3}$$

where T is in deg K. The anomaly has an angular width

$$\Delta\theta \approx kT/\mu H_{\mathrm{ex}} \Delta m \approx 0.03T \text{ radian.} \qquad (4)$$

These estimates are reasonable agreement with the observations. The order of magnitude of height and width are correct, and the directions of the temperature dependences are correct. It should be noted that our mechanism predicts the anomaly should always be an increase in resonance field, as seems to be observed. Different ion sites will give crossovers at different angles.

The model makes one important nontrivial assumption—that at the crossover point the rare earth ions relax rapidly so that even at microwave frequencies the ions stay in thermal equilibrium. Otherwise we would lose the anomaly. A phase lag will lead to a line broadening at the anomaly. The lines are indeed considerably broadened at the anomaly, but further experiments are required to determine the actual magnitude of this possible contribution to the width. If, however, the levels do not actually cross over, but are split by perturbations at the nominal crossover, then Eqs. (3) and (4) are valid only for $T > T_S \approx \Delta/k$, where Δ is the splitting. Now relaxation processes are not essential. Exchange interactions among the rare earth ions and indirectly via the ferric ions will also limit the temperature to which our results apply. These systems may have important applications to magnetic cooling by turning the external field to a crossover point.

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[2] J. F. Dillon, Jr., and J. W. Nielsen, Phys. Rev. Letters 3, 30 (1959).

[3] W. P. Wolf, Proc. Phys. Soc. (London) (to be published).

[4] Detailed calculations on this basis for cubic fields are given by R. L. White and J. P. Andelin, Jr., Phys. Rev. (to be published).

[5] The order of the levels in Tb ethyl sulphate found by J. M. Baker and B. Bleaney, Proc. Roy. Soc. (London) A245, 156 (1958), will not give an anomaly.

[6] R. Pauthenet, Ann. phys. 3, 424 (1958); see also de Gennes, Kittel, and Portis, Phys. Rev. (to be published).

CONSIDERATIONS ON THE INTERACTIONS BETWEEN THERMAL VACANCIES AND DISLOCATIONS*

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In previous experiments originally undeformed, electron-transparent aluminum foils have been mechanically strained while under observation in the electron microscope.[1] Among the interesting results, published elsewhere,[2] was the observation that the dislocation lines introduced during the straining are mostly smooth and move without drastically changing their shape. From other work it is known that rapidly quenched aluminum contains a high concentration of prismatic dislocation loops, due to the condensation of thermal vacancies,[3] as had been predicted previously.[4,5]

Recently a study was made of the behavior of thin aluminum foils, containing quenched-in dislocation loops, while being strained in the electron microscope. It was found that in them the typical smooth dislocation lines arose which often moved quite closely past loops without obviously affecting them. In other cases loops moved out of the specimens, either spontaneously, or under the influence of an approaching glide dislocation; and occasionally small loops were observed to emit glide dislocations when a dislocation moved past them at a close distance, an effect which was predicted in an earlier paper.[6]

In an effort to determine what influence, if any, specimen size has on these phenomena,