[1]J. D. Cashion, A. H. Cooke, L. A. Hoel, D. M. Martin, and M. R. Wells, Proc. Colloq. Intern. CNRS Eléments Terres Rares 180, 417 (1970).
[2]R. W. G. Wyckoff, *Crystal Structures*, 2nd. ed. (Interscience, New York, 1965), Chap. VIII.
[3]R. S. Feigelson, J. Am. Ceram. Soc. 47, 257 (1964).
[4]J. C. Wright, H. W. Moos, J. H. Colwell, B. W. Mangum, and D. D. Thornton, Phys. Rev. B3, 843 (1971).
[5]J. H. Colwell, Rev. Sci. Instr. 40, 1182 (1969).
[6]This temperature is based on the NBS Provisional Temperature Scale 2–20 (1965); H. Plumb and G. Cataland, Metrologia 2, 127 (1966).
[7]J. W. Stout and E. Catalano, J. Chem. Phys. 23, 2013 (1955).
[8]A. R. Miedema, R. F. Wielinga, and W. J. Huiskamp, Physica 31, 835 (1965).
[9]J. D. Cashion, A. H. Cooke, T. L. Thorp, and M. R. Wells, Proc. Roy. Soc. (London) A318, 473 (1970).
[10]J. H. Van Vleck, J. Chem. Phys. 9, 85 (1941).
[11]J. W. Essam and M. F. Sykes, Physica 29, 378 (1963).
[12]C. Domb and M. K. Sykes, Phys. Rev. 128, 168 (1962).
[13]See, for example, C. Domb and A. R. Miedema, in *Progress in Low-Temperature Physics*, edited by C. J. Gorter (North-Holland, Amsterdam, 1964), Vol. IV, Chap. 4; M. E. Fisher, Rept. Progr. Phys. 30, 615 (1967).
[14]B. W. Mangum and D. D. Thornton, in *Proceedings of the Twelfth International Conference on Low Temperature Physics, Kyoto, Japan*, 1970 (Keigaku Publishing, Tokyo, Japan, 1971).
[15]B. W. Mangum and D. D. Thornton (unpublished).
[16]F. Keffer, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1966), Vol. 18, Part 2, p. 1.
[17]M. E. Lines, Phys. Rev. 135, A1336 (1964).
[18]M. E. Lines, Phys. Rev. 156, 543 (1967).
[19]G. S. Rushbrooke and P. J. Wood, J. Mol. Phys. 1, 257 (1958); 6, 409 (1963).
[20]J. H. Van Vleck, J. Chem. Phys. 5, 320 (1937).
[21]R. Kubo, Phys. Rev. 87, 568 (1952).
[22]N. W. Dalton and D. W. Wood, Phys. Rev. 138, A779 (1965); 159, 384 (1967); J. Math. Phys. 10, 1271 (1969).

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Spin Reorientation in $ErFeO_3$ Single Crystals Observed by Neutron Diffraction

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Neutron diffraction from a single crystal of $ErFeO_3$ confirms that the spin reorientation at about 95 °K does not occur by a first-order transition, but is a gradual rotation.

The spin reorientations which occur in many of the rare-earth orthoferrites have been investigated by various techniques.[1-5] Mössbauer measurements recently performed[4,5] on $ErFeO_3$ showed that spin reorientation proceeds by a gradual and uniform spin rotation and not by a first-order transition (discontinuous 90° spin flip) occurring in different regions of the sample at different temperatures.

In the present communication we confirm the Mössbauer results by directly monitoring the orientation of the spins as they change their direction as a function of temperature. This technique is based upon the fact that the neutron-scattering cross section from a magnetic reflection is proportional to the quantity $\sin^2\phi$, where ϕ is the angle between the scattering vector and a vector parallel to the spin direction.[6] If a reflection is chosen whose scattering vector is parallel to the reorientation plane and if the spin reorients continuously with temperature, the neutron intensity may go through a maximum or a minimum depending on the angle and sense of the rotation. On the other hand, if the rotation is a discontinuous spin flip (but at different temperatures in different parts of the crystal), then the neutron intensity will change monotonically. It is also necessary that all spins rotate in the same direction (clockwise or counterclockwise). Otherwise the maximum or minimum may be averaged out. In the case of the rare-earth orthoferrites, a magnetic field is used to act on the weak ferromagnetic moment associated with the dominant antiferromagnetism in order to satisfy this condition.

We have applied this technique to a single crystal of $ErFeO_3$. The crystal structure of this compound belongs to the orthorhombic space group *Pbnm*.[7] In the reorientation range ~ 90–100 °K, upon heat-

ing, the weak ferromagnetic moment (WFM) rotates from the x to the z direction while the antiferromagnetic axis (AFA) rotates from the z to the x direction.[1-5] The WFM is[1] less than $0.1\mu_B$, so its contribution to the reflected neutron intensities is negligible compared to the contribution from the $5\mu_B$ of the AFA.

The crystal (about $2\times3\times4$ mm) was mounted with its b axis parallel to the diffractometer axis. The measurements were performed on the (101) and $(\bar{1}01)$ reflections, which are mainly of magnetic origin, with incident neutrons of wavelength 0.6 Å. In the reorientation range, the intensity should reach a maximum when the AFA is perpendicular to the scattering vector and a minimum when it is parallel to the scattering vector. The angle between the projection of the applied field on the reorientation plane (ac) and the scattering vector determines whether a maximum or a minimum will occur. In the case of a discontinuous 90° spin flip, neither a maximum nor a minimum should occur. In the experiment described in Fig. 1(a), a magnetic field $H\sim400$ G was applied in the ac plane, forming an angle of 45° with the $+x$ direction, that is, in a direction approximately parallel to the scattering vector. The orientation proceeds so that the AFA passes a direction in which it is perpendicular to the scattering vector. At this direction, the observed intensity should pass a maximum, in full accord with Fig. 1(a). In the experiment described in Fig. 1(c), H was applied in the ac plane forming an angle of 135° with the $+x$ direction, that is, in a direction approximately perpendicular to the scattering vector. In this case, in the course of reorientation the AFA passes a direction parallel to the scattering vector and a minimum is observed, as expected. In the absence of an external field [Fig. 1(b)], rotations in either direction occur and an average curve is obtained.

As is to be expected from geometrical considerations, the maximum in Fig. 1(a) is observed at a lower temperature than that corresponding to the minimum in Fig. 1(c). The observed temperature for the maximum in Fig. 1(a) is in good agreement with calculations based on Fig. 1(c). Heating and cooling experiments led to the same temperature dependence within 0.5 °K. We found that the reorientation occurs over a range of ~11 °K, in agreement with Grant and Geller.[5] However, the actual temperatures reported here are lower by 2–3 °K than those reported by Grant and Geller.

Results similar to those presented in Figs. 1(a) and 1(c) were obtained by programming the counter to measure alternately the (101) and $(\bar{1}01)$ reflections during a very slow cooling (or heating) of the crystal in which the magnetic field was held fixed. In that way the two curves were measured simultaneously.

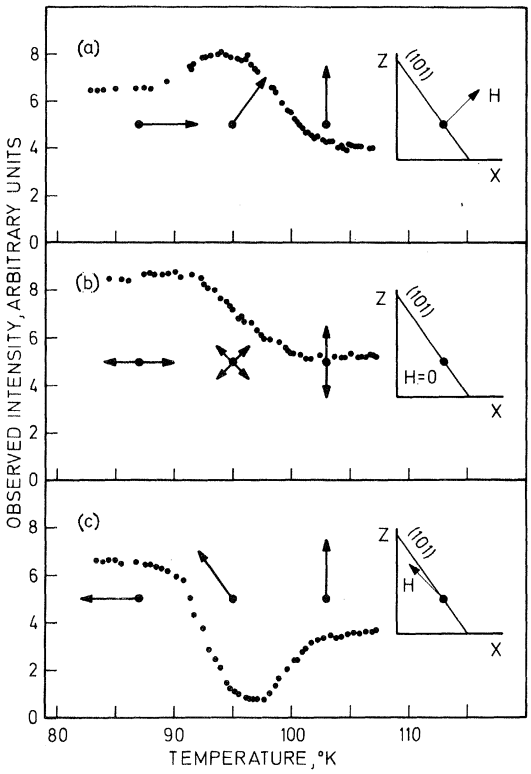

FIG. 1. Temperature dependence of the intensity of the (101) reflection of neutrons ($\lambda\sim0.6$ Å) from a single crystal of $ErFeO_3$. A projection of the (101) plane on the ac plane and the direction of the externally applied field H are schematically indicated on the right. The bold arrows indicate the direction of the weak ferromagnetic moment at the various stages of the experiments relative to the axes shown on the right. The lengths of these arrows are proportional to the number of domains in the stages indicated by the arrows.

For 0.6-Å neutrons, $[I^-/I^+]_{obs}$, the ratio of the observed intensities below and above the reorientation range, was found (Fig. 1) to be about 1.9, and to decrease monotonically with wavelength down to ~1.4 for 2.6-Å neutrons. The calculated ratio on the other hand is given by

$$[I^-/I^+]_{calc}\sim\sin^2([101],[001])/\sin^2([101],[100])\ .$$

The ratio is independent of wavelength and for the orthoferrites (where $c\sim a\sqrt{2}$) is equal to 2. This discrepancy is attributed to the existence of extinctions[8] which are probably responsible also for the fact that the maximum observed in Fig. 1(a) is lower than expected.

In conclusion we note that the occurrence of a maximum in Fig. 1(a) and a minimum in Fig. 1(c) proves that, upon heating the crystal through the reorientation region, the spins (AFA) rotate gradually from the c to the a axis in agreement with the conclusion of the Mössbauer studies.[4,5] We have so

far applied the technique only to single crystals. It should be applicable to powder samples as well.

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[1]R. M. Bozorth, V. Kramer, and J. P. Remeika, Phys. Rev. Letters 1, 3 (1958).
[2]E. M. Gyorgy, J. P. Remeika, and F. B. Hegedorn, J. Appl. Phys. 39, 1369 (1968).
[3]G. Gorodetsky and L. M. Levinson, Solid State Commun. 7, 67 (1969).
[4]G. Gorodetsky, L. M. Levinson, S. Shtrikman, D. Treves, and B. M. Wanklyn, Phys. Rev. 187, 637 (1969).
[5]R. W. Grant and S. Geller, Solid State Commun. 7, 1291 (1969).
[6]G. E. Bacon, *Neutron Diffraction* (Oxford U. P., Oxford, England, 1962), p. 163.
[7]S. Geller, J. Chem. Phys. 24, 1236 (1956).
[8]V. W. Arndt and B. T. M. Willis, *Single Crystal Diffractometry* (Cambridge U. P., Cambridge, England, 1968), p. 247.

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Magnetoresistance Measurements on Ferromagnetic *Pd*Fe and *Pd*Co Alloys*

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The temperature dependence of the resistivity of a Pd-0.78-at.% Fe alloy and a Pd-0.73-at.% Co alloy has been measured in the temperature region 1.4–20 K, and in applied fields up to 60 kOe. These data can be fitted simply by including the effects of the applied field in a model due to Long and Turner; this model, based on s-electron scattering from collective excitations in the coupled impurity-moment d-band system of the alloy, satisfactorily accounts for the majority of the zero-field properties of this class of alloy. Analysis of the *Pd*Fe data yields $g=2$, while the acoustic spin-wave stiffness D is found to be field dependent. Various origins of this field dependence are discussed. For the *Pd*Co system this scheme of analysis requires the splitting factor g to be significantly less than 2. The D is again found to be field dependent.

I. INTRODUCTION

The properties of alloys of Pd with the transition metals Fe and Co exhibit many anomalous features, of which (i) the giant moment phenomenon[1–4] and (ii) the rapidly increasing magnetic-ordering temperature T_c with relatively low impurity concentration[5] c have received the most experimental and theoretical attention. The origin of both (i) and (ii) lies in the nearly ferromagnetic, itinerant character of the Pd d band. The conventional Ruderman-Kittel-Kasuya-Yosida (RKKY) oscillations[6] induced in the host conduction band via an exchange coupling of the form $-2J\vec{S}\cdot\vec{\sigma}$ between the impurity spin ($\vec{S}$) and the conduction-electron spin ($\vec{\sigma}$) are, in this case,[7] suppressed to relatively large distances by the effects of exchange enhancement.[8,9] Consequently, there is an enhancement in the *range* of the induced polarization, as evidenced by neutron diffraction[10] and Mössbauer data.[11,12]

Clogston *et al.*[3] used the concept of a magnetized virtual bound state to discuss the static magnetic properties of these alloys, while Rhodes and Wohlfarth[13] have used a rigid-band model in their theoretical discussion. More recently Moriya[14] has given careful consideration to these static properties on the basis of the Anderson model.[15]

The dynamic properties of these alloys in the ferromagnetic state were first investigated by Doniach and Wohlfarth[16]; this work was later extended by Cole and Turner,[17] who concluded that the dynamical spin states could, at temperatures well below the magnetic-ordering temperature T_c be approximately described by spin waves. In a recent publication by Long and Turner[18] the resistivity of this class of alloy has been calculated on the basis of this dynamical model; the conductivity is regarded as being dominated by s electrons (in view of their relatively low effective mass[19,20]) which scatter from the collective excitations in two