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Ultrabroad Ferromagnetic Resonance in Dysprosium Metal*

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An extremely broad ferromagnetic resonance has been observed in single-crystal Dy metal at 37 Gc/sec. Although the large planar anisotropy results in a much higher resonance frequency, the resonance was brought down by applying a high field along a hard direction of the in-plane anisotropy. The temperature dependence of the field for resonance, in the temperature range from 78° to 103°K, was found to follow the behavior of the in-plane anisotropy. Above 87°K the zero field ordering is spiral but ferromagnetic ordering is induced by the applied field. The resonance peak cannot be seen above 103°K because the field for resonance is no longer sufficient to induce ferromagnetic ordering. The absorption was found to be extremely broad in field so that appreciable absorption occurs even where the resonant frequency is far above the experimental frequency. This feature may be interpreted on the basis of either or both of two distinct models. The first relies upon the fact that the spin-wave spectrum decreases to a minimum at a nonzero wave vector k_0 and might thereby provide a number of $k\neq 0$ modes degenerate with the experimental frequency which may be coupled to through various sample inhomogeneities. The second model considers a very large dynamic broadening of the ferromagnetic resonance such as might arise from large magnon–phonon coupling due to the extremely large magnetoelastic interaction in dysprosium. On this model, the shape and width of the absorption curve indicate a relaxation frequency on the order of the resonance frequency.

THE magnetic system of dysprosium metal becomes ordered below 179°K with a large second-order anisotropy confining the atomic moments parallel to the basal plane of the hexagonal close-packed structure. Down to 87°K the atomic moments within each basal plane are ferromagnetically aligned with the direction of alignment spiralling about the *c* axis. Below 87°K the ordering is purely ferromagnetic. A transition from spiral to ferromagnetic ordering in the range from 87° to 179°K is induced by a magnetic field of sufficient strength applied parallel to the hexagonal plane. This model of the magnetic structure is consistent with the results of neutron diffraction experiments[1] and static magnetization measurements on single-crystal samples.[2]

This paper presents results of a series of measurements of microwave absorption at 37.6 Gc/sec by single-crystal samples of dysprosium metal under conditions of ferromagnetic ordering. In a previous paper,[3] we presented measurements of the microwave absorption at the field-induced transition from spiral to ferromagnetic ordering in dysprosium. Calculations of the resonant modes of this type of magnetic system[4,5] show that ordinary ferromagnetic resonance might be expected to occur at frequencies greater than 100 Gc/sec due to the extremely large second-order anisotropy in dysprosium. However, at temperatures below about 110°K, a smaller sixth-order anisotropy becomes effective in the basal plane and the ferromagnetic resonance can be lowered by applying an external magnetic field H along a hard $\langle 10\bar{1}0\rangle$ direction in the plane. In fact, the resonant frequency goes to zero at

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[1] M. K. Wilkinson, W. C. Koehler, E. O. Wollan, and J. W. Cable, J. Appl. Phys. **32**, 48S (1961).
[2] D. R. Behrendt, S. Legvold, and F. H. Spedding, Phys. Rev. **109**, 1544 (1958).
[3] F. C. Rossol, B. R. Cooper, and R. V. Jones, J. Appl. Phys. **36**, 1209 (1965).
[4] B. R. Cooper, R. J. Elliott, S. J. Nettel, and H. Suhl, Phys. Rev. **127**, 57 (1962).
[5] B. R. Cooper and R. J. Elliott, Phys. Rev. **131**, 1043 (1963).

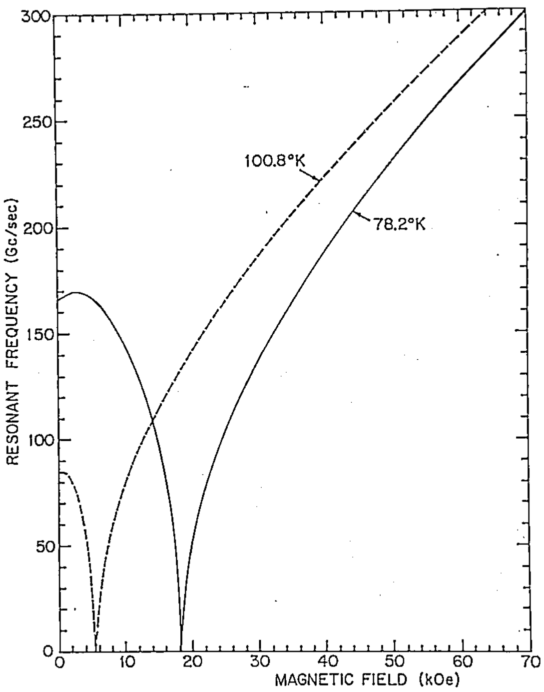

FIG. 1. Calculated field dependence of the ferromagnetic resonance spectrum in dysprosium metal with the field applied parallel to a hard direction in the basal plane.

$H=36H_h$, where H_h is the effective hexagonal anisotropy field.

Figure 1 shows the field dependence of the resonant frequency for two of the temperatures at which absorption measurements were made. These curves were calculated from equations derived in Refs. 4 and 5 using values of H_h and the effective second-order anisotropy field deduced from static magnetization measurements.[2] Typical absorption curves measured at several different temperatures using a transmission cavity spectrometer at 37.6 Gc/sec are shown in Fig. 2. The dc magnetic field was applied along a $\langle 10\bar{1}0\rangle$ direction perpendicular to the rf magnetic field. Bagguley and Liesegang[6] have also reported an absorption peak under these conditions.

The temperature dependence of the field at the absorption peak agrees with that expected from the behavior of the hexagonal anisotropy field H_h as deduced from the magnetization measurements of Behrendt, Legvold, and Spedding[2] and from magnetization measurements on one of our own samples. This agreement confirms our interpretation of these curves as ferromagnetic resonance absorptions. The initial abrupt rise in the curve at 100.8°K occurs at the transition from spiral to ferromagnetic ordering induced by the applied field. At temperatures above about 104°K, the absorption peak is not observed since the field $36H_h$ is no longer adequate to induce ferromagnetic ordering.

[6] D. M. S. Bagguley and J. Liesegang, Phys. Letters 17, 96 (1965).

Perhaps the most striking characteristic of these measurements is that there is appreciable absorption even at zero field while the resonance spectra shown in Fig. 1 suggest that at the experimental frequency, one would expect absorption only at fields in the neighborhood of $36H_h$ as the field passes through the resonance lines. The fact that absorption is observed over such a wide range of fields may be considered from two distinct viewpoints. (I) The spin wave dispersion relation under ferromagnetic ordering as given in the paper by Cooper *et al.*[4] and discussed in more detail in a subsequent paper by Cooper,[7] has a minimum for spin waves propagating along the hexagonal axis of the Brillouin zone at a wave vector $k_0\neq 0$. In fact, the transition from ferromagnetic to fan ordering can be understood in terms of this minimum dropping to zero frequency so that a fan ordering of periodicity determined by k_0 becomes the more favorable static configuration. Such a lowering of the spin-wave spectrum at k_0 could provide states of wave vector $\mathbf{k}\neq 0$ degenerate with the experimental frequency and coupling to these states through inhomogeneities and localized strains might then result in absorption of energy from the incident rf fields. (II) We might also conjecture that the ferromagnetic resonance mode is dynamically broadened to such an extent that there are appreciable spectral components at frequencies as far from the resonant frequency as 37 Gc/sec. In particular such a dynamic broadening might result from large magnon–phonon

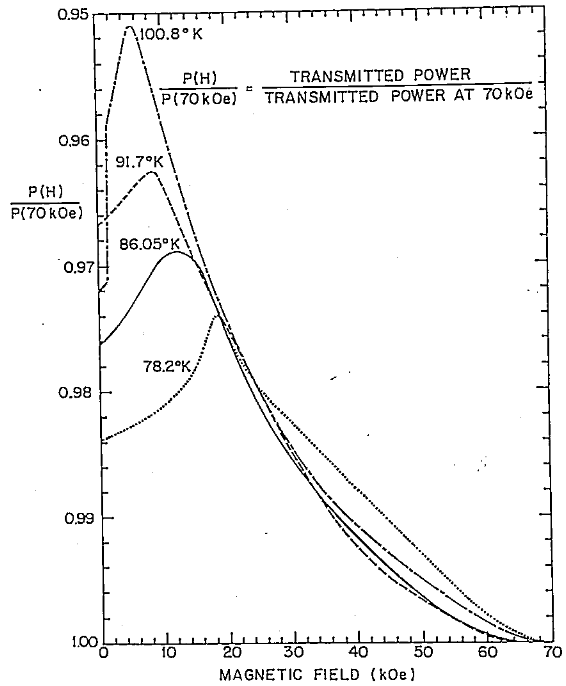

FIG. 2. Field dependence of the power transmitted by the cavity with the field along a hard axis in the basal plane. The curves are normalized at 70 kOe.

[7] B. R. Cooper, Proc. Phys. Soc. (London) 80, 1225 (1962).

couplings due to the extremely large magnetoelastic interaction in dysprosium. A dynamic model including phenomenological damping of the Bloch–Bloembergen form was used to calculate the field dependence of the real part of the surface impedance which was compared with that of the power transmitted by the cavity. This comparison indicates a relaxation time considerably greater than $1/\omega_0$ at fields far from the absorption peak, but decreasing to a minimum on the order of 10^{-12} sec at the absorption peak. Exchange effects arising from the nonuniformity of the magnetization within the skin depth have not been included in the model for the surface impedance, although such effects are believed to be small under the circumstances of these experiments.

There is a peculiar sample inhomogeneity which may be of importance in dysprosium. There are theoretical grounds[8] for the existence of a fan structure in which there is a very small sinusoidally varying deviation of the direction of the moments of a given layer from the direction of the net magnetization. Spatial fluctuations might then arise between fan and purely ferromagnetic ground states. However, the understanding of the phase boundaries between the spiral, fan, and ferromagnetic structures must await further information on the magnetoelastic properties of dysprosium.

[8] T. Nagamiya, K. Nagata, and Y. Kitano, Progr. Theoret. Phys. (Kyoto) 27, 1253 (1962).

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