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Magnetic Resonance in Dysprosium Metal*

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Magnetic resonance has been observed at 37.7 Gc/sec in a hexagonal platelet of dysprosium metal at temperatures in the range where the spin arrangement is spiral. The resonance behavior is in many respects similar to that observed near the spin-flop field in ordinary antiferromagnets. The temperature dependence of the field for resonance generally follows the temperature dependence of the critical field for the transition from spiral to ferromagnetic spin arrangement. Widths on the order of 1 kOe were observed for the dc field applied along both easy and hard axes of the planar anisotropy. A secondary absorption peak is resolved at a field about 400 Oe higher than the field for the main resonance for temperatures below 106°K with the dc field along an easy axis and below 120°K with the dc field along a hard direction. The planar anisotropy becomes insignificant above the latter temperature. The detailed interpretation of line shapes is complicated by changes in the conductivity occurring at the critical field.

INTRODUCTION

MAGNETIC resonance has been observed at 37.7 Gc/sec in single-crystal hexagonal platelets of dysprosium metal in a temperature range from 94° to 141°K. In the absence of an external magnetic field, dysprosium is ferromagnetic below 87°K and has a spiral spin arrangement[1] from 87° to 179°K. This paper constitutes the first report of the observation of magnetic resonance in any of the heavy rare-earth metals which exhibit complicated periodic magnetic structures.[2] The only previously reported observation of magnetic resonance in a material having a spiral spin arrangement[3,4] involved work on polycrystalline $MnAu_2$. Cooper and Elliott[5] (hereafter referred to as CE) have discussed the expected resonance behavior for a dc magnetic field applied in the plane normal to the *c* axis when there is a large axial anisotropy holding the equilibrium positions of the spins in this plane, as is the case with dysprosium. In the absence of any planar anisotropy, a dc field applied in the plane of the spiral tends to distort the spiral slightly toward the dc field. At a critical field H_c, typically several thousand oersteds, the spin arrangement flops abruptly to a fan structure which closes continuously with increasing field until a ferromagnetic arrangement is reached at $H_f \simeq 2H_c$. The corresponding expected resonance behavior is illustrated in Fig. 1 of CE. The most striking feature of this behavior is a discontinuous change in the resonant frequencies of the spin system at H_c. Thus, for a wide range of system parameters and signal frequencies, one would expect to observe magnetic resonance at the critical field. The general characteristics of the expected resonance behavior are similar to those of antiferromagnetic resonance near the spin-flop field. There are several possible modes of magnetic resonance discussed in CE which depend on the polarization of the rf magnetic field. The introduction of planar anisotropy decreases both H_f and H_c if the dc field is applied along an easy in-plane axis. However, the effect on H_f is much greater than on H_c so that for sufficiently large values of the planar anisotropy, the intermediate fan region disappears and the magnetic structure goes directly from spiral to ferromagnetic. The resonance behavior expected in this case is illustrated in Fig. 2 of CE and, again, is characterized by a large discontinuity in the resonant frequencies of the system at H_c. The situation with the dc field along a hard in-plane direction is more complicated and was not treated in detail by CE. It is possible that in this case an intermediate phase, perhaps of a complicated nature, exists between the spiral and ferromagnetic configurations even when the planar anisotropy is quite large.

EXPERIMENTAL RESULTS

The crystal used in most of these experiments was one of a number provided by Moriarty.[6] These crystals are in the form of *c*-plane platelets and have roughly a hexagonal shape. A sample with an area of approximately 9 mm² was ground parallel to the *c* plane to a thickness of 0.11 mm using Linde B abrasive for the final polish. X-ray examination of the sample both before and after the grinding and polishing operations showed a sharp Laue reflection pattern. The wavelength of the x rays was such that the x-ray penetration depth was on the order of the microwave skin depth at 37 Gc/sec. The platelet was placed at a point of maximum radial rf magnetic field in the mid-

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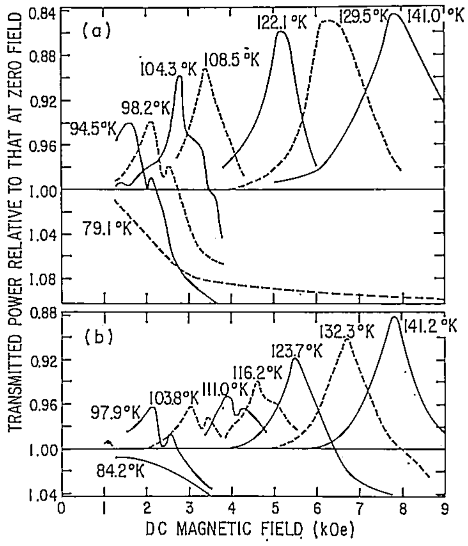

FIG. 1. Transmitted power as a function of dc field relative to the transmitted power at zero field: (a) dc field along an easy in-plane axis; (b) dc field along a hard in-plane axis.

plane of a circular TE_{012} transmission cavity and the power transmitted by the cavity was recorded as a function of dc magnetic field which was continuously swept. In all experiments, the rf field was polarized perpendicular to the dc field and in the plane of the sample. The results for a number of temperatures are shown in Fig. 1(a) for the dc field along an easy axis and in Fig. 1(b) for the field along a hard planar direction. The linewidths are typical of ferromagnetic resonance in metals. The temperature dependence of the field for resonance is in generally good agreement with that of H_c determined from magnetization measurements on a different single-crystal sample.[7] Probably because of the planar anisotropy, the field for resonance is slightly greater with the field along a hard rather than easy planar direction at the lower temperatures. A secondary absorption peak at a field about 400 Oe higher than the field for the main resonance was observed at temperatures below 106°K with the dc field along an easy axis and below 120°K with the field along a hard direction. The fact that the planar anisotropy becomes insignificant at temperatures above 120°K suggests the possibility of an association of the secondary peak with the planar component of anisotropy.

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Conductivity effects, not considered in CE, may be quite important in these measurements. There is an abrupt rise in the dc conductivity as the magnetic structure changes from spiral to ferromagnetic. These conductivity changes have been demonstrated by measurements of the temperature dependence of the dc resistivity of dysprosium,[8] and by measurements of the decrease of resistivity of terbium[9] at H_c. The rf resistivity in Dy might therefore be expected to drop at H_c resulting in reduced absorption at fields well above resonance. The decrease in absorption with field observed at 79.1° and 84.2°K in the ferromagnetic range is consistent with the possibility of both decreasing permeability with field and increasing conductivity arising from less spin-disorder scattering. The sharp rise in conductivity expected at H_c may have an appreciable effect on the resonance line shape. Conductivity effects also influence the line shape by mixing absorption and dispersion and introduce the possibility of excitation of modes other than those considered in CE through the nonuniform rf magnetic field within the skin depth. Hysteresis of several hundred oersteds was noted in the position of the resonance depending on the direction of the dc field sweep. This effect may be associated with the thermal hysteresis in the neutron diffraction data[1] at the transition from ferromagnetic to spiral configuration.

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