PHYSICAL REVIEW B VOLUME 4, NUMBER 7 1 OCTOBER 1971

Magneto-Elastic Effects and 3-mm Microwave Resonance in Single-Crystal $Tb_{85}Y_{15}$[†]

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(Received 25 February 1971)

Ferromagnetic resonance at 102.5 GHz has been observed in the rare-earth intermetallic alloy $Tb_{85}Y_{15}$ and the data have been compared with the theory of Cooper, including the magneto-elastic effects in the frozen-strain model. Based on a Néel temperature of 204 °K, parameters which give the best fit to the data are: axial anisotropy $P_2S = 15.5$ °K/atom and magneto-elastic constant $D^\gamma = 1.7$ °K/atom. These compare to the values for pure Tb: $P_2S = 18.2$ °K/atom and $D^\gamma = 1.7$ °K/atom. A physical explanation for the observed dependence of P_2S on the concentration of a nonmagnetic diluent (Y) is given.

INTRODUCTION

The magnetic properties of the alloy system $Tb_{1-x}Y_x$ have been studied[1] by elastic neutron diffraction, and the Curie and Néel temperatures determined as a function of x. The addition of Y to Tb reduces the magnetic coupling between Tb atoms (since Y has no $4f$ electrons) and at the same time increases the temperature range over which the helical magnetic ordering exists. Since ferromagnetic resonance studies have been made in detail on pure Tb,[2,3] it seemed of interest to investigate the effect of the addition of Y on the long-wavelength spin-wave spectrum of Tb.

An arc-melted button of $Tb_{85}Y_{15}$ was prepared, rolled, and remelted several times to improve homogeneity. A single crystal was grown by the strain-anneal process, oriented by x-ray techniques and a slice approximately perpendicular to ⟨0001⟩ was cut out. The slice was then mounted with beeswax on a specially designed adjustable jig. The jig was used to grind down mechanically the sample thickness with No. 600 grit paper. The jig also allowed precise alignment of the normal of the sample faces with ⟨0001⟩. Finally, a circular disc-shaped sample of diameter 6.4 mm was cut from the slice. The final alignment of the disc faces was perpendicular to ⟨0001⟩ to within ± 0.2°. The disc was then electropolished. The final disc thickness was 1.3 mm.

To obtain magnetization data for this composition alloy, the saturation magnetization was scaled by the at.% Tb (Y and Tb have almost the same lattice parameter), and the temperature was scaled according to the Néel temperature for $Tb_{85}Y_{15}$ (204 °K). This approach would be correct in the molecular field case. In other words, it was assumed that $\sigma(T,H)/\sigma_{\text{sat}}$ vs T/T_N is the same for $Tb_{85}Y_{15}$ as for pure Tb.

The microwave apparatus is identical to that used before (Ref. 2). The microwave absorption vs applied field showed a peak similar to those seen in pure Tb. The position of the resonance field vs reduced temperature (T/T_N) is shown in Fig. 1. The data have been fitted to the expression derived by Cooper[4] for the ferromagnetic resonance including magneto-elastic effects in the frozen-strain model, i.e.,

$$\hbar\omega(0) = \{[-2P_2S\hat{I}_{5/2}/\sigma + 6P_6^6S^5\hat{I}_{13/2}/\sigma + g\mu_BH + D^\gamma(\hat{I}_{5/2})^2/\sigma] \times [36P_6^6S^5\hat{I}_{13/2}/\sigma + g\mu_BH + 2D^\gamma(\hat{I}_{5/2})^2/\sigma]\}^{1/2} . \quad (1)$$

Here $I_{l+1/2}$ is the ratio of the hyperbolic Bessel function of order $l+\frac{1}{2}$ to that of order $\frac{1}{2}$, $\sigma(T)$ is the ratio of the magnetization at temperature T to that at $T=0$, P_2S and $P_6^6S^5$ are two- and sixfold

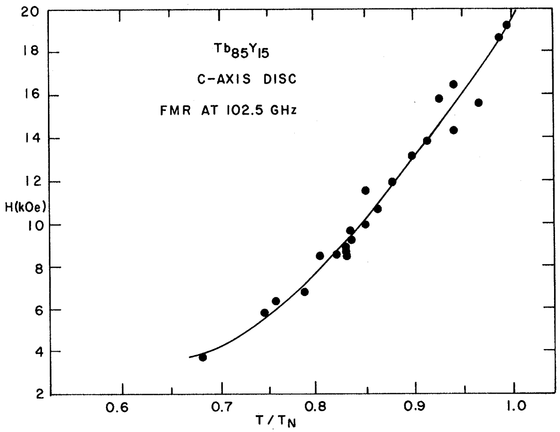

FIG. 1. Plot of ferromagnetic resonance field for $Tb_{85}Y_{15}$ vs reduced temperature T/T_N. $\vec{H}$ was along a hard basal plane axis and $\omega/2\pi = 102.5$ GHz. The solid line is a theoretical fit discussed in the text.

crystal-field anisotropy constants, and D^{γ} is the relevant magneto-elastic constant. The argument of the hyperbolic Bessel functions involved in the $I_{l+1/2}$ is the inverse Langevin function of $\sigma(T)$. Equation (1) is valid for H applied along a hard basal plane axis with magnitude large enough to pull all of the spins parallel to that hard axis. The demagnetizing effect of the finite diameter-to-thickness ratio of the sample was taken into account. The solid line in Fig. 1 is a fit of Eq. (1) with parameters $P_2S = 15.5$ °K/atom, $D^{\gamma} = 1.7$ °K/atom. The parameters for pure[2] Tb were found to be $P_2S = 18.2$ °K/atom, $D^{\gamma} = 1.7$ °K/atom.

DISCUSSION

The fitting of our data using Eq. (1) is fairly sensitive to the value of P_2S but not as sensitive to D^{γ}. The main effect of the addition of a sizable amount of magnetic diluent (15-at.%Y) to Tb apparently is to decrease the twofold magnetic anisotropy P_2S (by 15%). P_2S is thought to arise physically from the combined effects of the anisotropy crystalline electric field seen by $4f$ electrons at a lattice site, and spin-orbit interactions which couple the $4f$ magnetic moments to their spacial orientation. To first order, one expects the crystalline electric fields to be unchanged by the replacement of Tb atoms by Y atoms, since they are similar except for their inner $4f$ electrons. The spin-orbit interaction, however, should decrease with increasing concentration x of Y in Tb, because the average spin S of an atom is proportional to the average magnetization in the crystal through the exchange interaction. The average magnetization varies as $1 - x$. The energy term in the Hamiltonian due to spin-orbit interaction must then vary as $(1-x)^2$. In Cooper's formalism,[4] the latter energy term is proportional to P_2S^2. Thus, the axial anisotropy constant defined as P_2S should be proportional to $(1-x)^2/(1-x) = 1-x$. We conclude that the concept of a statistical average of atomic magnetic properties in a partially diluted disordered magnetic alloy yields a reasonable explanation of the observed dependence of axial magnetic anisotropy on alloy concentration.

Although Eq. (1) is not strongly sensitive to D^{γ}, it appears that a large change does not occur in the magneto-elastic parameter.[5]

The ferromagnetic resonance linewidths in $Tb_{85}Y_{15}$ were approximately the same as those found in pure Tb ($\Delta H/H \sim 1$).[2] It is interesting that the mechanism for the spin-wave linewidths is so strong that the addition of considerable magnetic disorder to the crystal does not appreciably decrease the long-wavelength magnon lifetimes. A convincing explanation of this effect is lacking at present.

ACKNOWLEDGMENTS

We are grateful to Professor F. H. Spedding for the loan of the rare-earth metals used in this investigation, and to Professor S. H. Liu for an enlightening conversation. We also want to thank Dr. F. C. Rossol for taking the time to suggest a number of changes which have improved the clarity of the presentation.

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†Work performed in the Ames Laboratory of the U. S. Atomic Energy Commission. Contribution No. 2949.

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[5] The uncertainty of D^{γ} from the fit to our data is approximately ± 0.2 °K/atom.