SPIN-WAVE RESONANCE IN NICKEL FILMS: TEMPERATURE DEPENDENCE

T. G. Phillips and H. M. Rosenberg
The Clarendon Laboratory, Oxford University, Oxford, England

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Experiments have been made to determine how the resonance conditions change for the excitation of spin waves in thin films of pure Ni for the temperature range 15 to 300°K. These have shown a much larger effect than was expected, and the temperature dependence does not appear to be in agreement with the present theoretical predictions.

The films were evaporated onto substrates of optically polished, single-crystal sapphire and quartz. Their thickness was measured using multiple-beam interferometry, and was between 2000 and 6000 Å for the various specimens. They were mounted in a conventional microwave resonance cavity, tuned to a fixed frequency of 9.2 kMc/sec, and a dc magnetic field, perpendicular to the plane of the film, was swept from zero to 10 kOe. In this range the ordinary ferromagnetic resonance signal (spin waves with wave number $k = 0$) was observed, and at lower fields up to 10 other resonances were found corresponding to spin waves of higher modes. The main object of the experiment was to measure the dc-field separation between the resonances of the various modes and to determine how this varied with temperature.

On the simplest model, the energy of a spin wave in an effective field H is

$$g\beta H + Dk^2, \tag{1}$$

where D is the dispersion parameter which depends on the exchange interaction between the spins (e.g., see Kittel[1]). For resonance at an angular frequency ω, we must therefore have

$$\hbar\omega = g\beta H + Dk^2 \tag{2}$$

or

$$\hbar\omega = g\beta(H_0 - 4\pi M_S + Dk^2/g\beta), \tag{3}$$

where H_0 is the external field and M_S is the saturation magnetization. [This simple expression should be modified to take account of magnetic anisotropy and mechanical strains (Nosé[2]).] Hence at constant frequency the field separation ΔH between resonances corresponding to wave numbers k_1 and k_2 is

$$\Delta H = (k_1^2 - k_2^2)D/g\beta. \tag{4}$$

The surface spins can be pinned by surface anisotropy, antiferromagnetic surface layers, or eddy currents (see Kittel[3] and Pincus[4]), and hence for standing waves in a film of thickness L, $k = p\pi/L$ where p is an integer. From (4) it is usually possible to identify the various modes which are excited, and hence the interaction parameter D can be determined.[5]

It is found that D is not constant, but that it decreases with increasing temperature. A typical logarithmic plot of $(D_0 - D)/D_0$, where D_0 is the limiting value of D at the lowest temperatures, is shown in Fig. 1. Below 80°K each of the points plotted is the average of about 10 separate resonance measurements. Figure 1 indicates that at temperatures down to at least 50°K, $(D_0 - D)/D_0$ varies approximately as $T^{3/2}$ with a constant of proportionality which varied from 2.8 to 5.5×10^{-5} over eight specimens.

The log-log plot is very sensitive in the low-

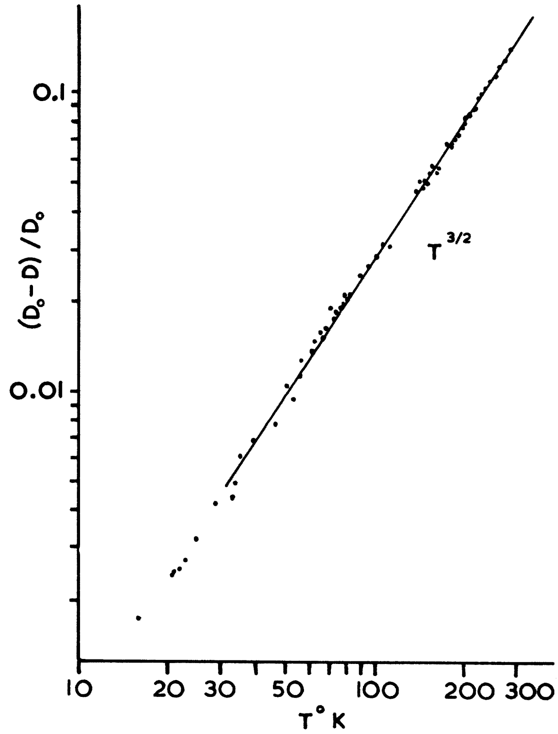

FIG. 1. A typical logarithmic plot of $(D_0 - D)/D_0$ against T.

temperature region to the extrapolation to 0°K which is necessary in order to determine D_0, and the scatter is such that the slope cannot be trusted below about 40°K. Nevertheless, an error of 0.1% in D_0 would be necessary in order that the temperature dependence should be $T^{5/2}$ at low temperatures. The experimental accuracy in measuring the mode separation is limited by the resonance linewidth which is about 100 Oe in these films. However, the plot of D versus $T^{3/2}$ does not show any large deviations (Fig. 2). The theory (see Dyson,[6] Oguchi,[7] and Keffer and Loudon[8]) predicts that if the spin-wave energy is written as Dk^2, the spin-wave interaction gives rise to a temperature dependence of D of the form $(D_0 - D)/D_0 = bT^{5/2}$ at low temperatures. The order of magnitude of $(D_0 - D)/D_0$ is much larger than the theory predicts. Between 0 and 300°K, D should change by about 0.1%, whereas we observe a change of about 15%. Tannenwald[9] has also observed anomalously large changes in D for permalloy films, although he and Weber have found a $T^{5/2}$ dependence at low temperature.

It should be pointed out that a $T^{3/2}$ dependence for $(D_0 - D)$, such as we observe, can be obtained if a constant (energy-gap) term is included in the spin-wave dispersion relation (1), but this would have to be unrealistically large in order to account for our results.

It is possible that the conduction electron theory of exchange might give rise to a $T^{3/2}$ term at low, but nonzero, temperatures (e.g., see Horwitz and Mattis[10]).

Attempts to extend these measurements to higher frequencies (24 and 36 kMc/sec) have so far not been very successful. The ordinary ferromagnetic resonance signal has been observed at fields which correspond to that found at 9.2 kMc/sec, but the spin-wave spectrum could not be resolved.

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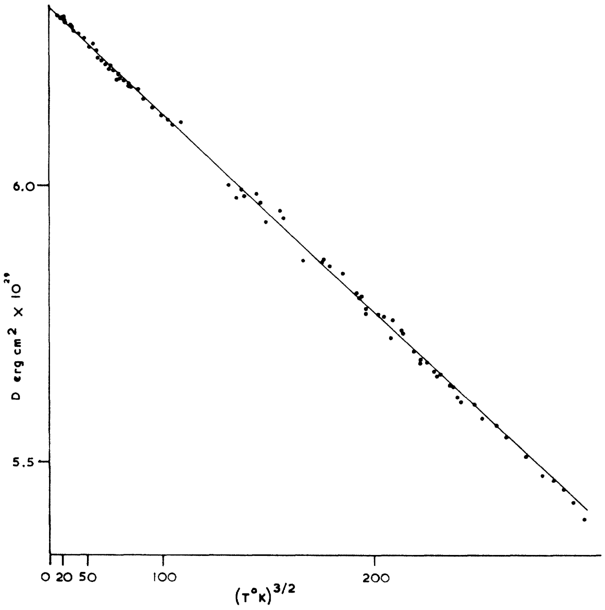

FIG. 2. A plot of D against $T^{3/2}$.

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