theories relating the width of the lines, the spin-orbit coupling, and the mean free path of the conduction electrons, can be checked in detail.

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[1]A. M. Portis, Phys. Rev. 91, 1071 (1953).
[2]F. J. Dyson, Phys. Rev. 98, 349 (1955).
[3]W. T. Doyle, Proc. Phys. Soc. (London) (to be published).
[4]F. Bach and K. F. Bonhoffer, Z. physik. Chem. 23B, 256 (1933); W. Rauch, Z. Physik 111, 650 (1938).
[5]H. Bode, Z. physik. Chem. 6B, 251 (1930).
[6]R. W. Wood and C. Lukens, Phys. Rev. 54, 332 (1938).

EFFECTIVE EXCHANGE CONSTANT IN YTTRIUM IRON GARNET*

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We have measured the specific heat of a pure (99.99% yttrium) polycrystalline sample of yttrium iron garnet (YIG) in the temperature range of 1°K to 4°K. We find that the specific heat may be analyzed into a part that depends on temperature as $T^{3/2}$ (the spin-wave contribution) and a part that depends on temperature as T^3 (the contribution from the lattice) as illustrated in Fig. 1.

We thus obtain

$$C_v = 68.9T^{3/2} + 29.3T^3 \text{ erg/cm}^3 \text{ deg K}, \quad (1)$$

where C_v is the specific heat per cm^3 based on the x-ray density[1] of 5.19 g/cm^3.

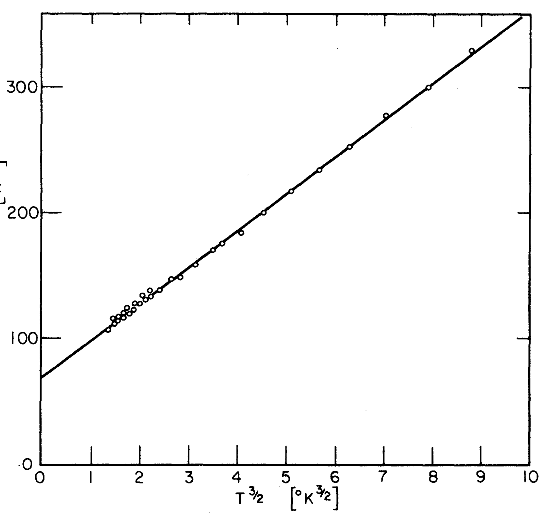

FIG. 1. The specific heat per unit volume of polycrystalline YIG analyzed into its two components by plotting $C_v/T^{3/2}$ against $T^{3/2}$. The points give the results obtained in one experiment. Another experiment performed on the same specimen at the extremes of the temperature range yielded results in agreement with those plotted to within 2%.

Using the equation

$$C_v(\text{lattice}) = (12/5)\,\pi^4 N k_B (T/\theta)^3, \quad (2)$$

where k_B is the Boltzmann constant, we obtain for the Debye temperature $\theta = 454$°K, if we take N to be the total number of atoms of all kinds in unit volume.

Assuming a dispersion relation for the spin waves of

$$\hbar\omega = Dk^2, \quad k = 2\pi/\lambda, \quad (3)$$

one has the standard result for the magnon specific heat per unit volume:

$$C_v(\text{magnons}) = [(15/32)(1.341)\pi^{-3/2}]k_B(k_B T/D)^{3/2}$$
$$= 0.113\,k_B(k_B T/D)^{3/2}. \quad (4)$$

The constant D may be expressed[2] in terms of the Landau-Lifshitz exchange constant A, the saturation magnetization M_s, and the spectroscopic splitting factor g as

$$D = 2Ag(\mu_B/M_s), \quad (5)$$

where μ_B is the Bohr magneton. In this manner we obtain from our measurement of the spin-wave contribution to the specific heat,

$$A(\text{YIG}) = 0.192 \times 10^{-6} \text{ erg/cm}, \quad (6)$$

where we have taken the value[3] $4\pi M_s = 1740$ gauss for YIG. This is to be compared with a value of

$$A(\text{Fe}) \cong 2 \times 10^{-6} \text{ erg/cm}$$

in iron. If we analyze in this manner the results of Kouvel[4] who measured the specific heat of magnetite in the same temperature range, we obtain

$$A(Fe_3O_4) = 0.232\times10^{-6} \text{ erg/cm}.$$

Suhl[5] has shown that in a sphere, z-directed spin waves having a wave number given by k_0 in

$$k_0^2 = 2\pi M_S^2/3A$$

are degenerate in frequency with the uniform precessional mode ($k=0$). We expect[6,7] maximum coupling of the uniform precessional mode to transverse phonons via the z-directed spin waves when the frequency is given by

$$f_c = v_t k_0/2\pi,$$

where v_t is the velocity of transverse phonons. Using our value of A and the value $v_t = 3.87\times10^5$ cm/sec obtained in polycrystalline YIG at 25°C by McSkimin,[8] we find

$$|k_0| = 4.60\times10^5 \text{ cm}^{-1}$$

and

$$f_c = 2.83\times10^{10} \text{ sec}^{-1} \quad \text{or} \quad \lambda_c = 1.05 \text{ cm}.$$

It is our pleasure here to record our debt to Professor C. Kittel who suggested the investigation and to M. K. Jack of Hughes Research Laboratories who kindly supplied us with the specimen of YIG.

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[1]F. Bertaut and F. Forrat, Compt. rend. 242, 382 (1956).
[2]C. Herring and C. Kittel, Phys. Rev. 81, 869 (1951).
[3]W. P. Wolf and G. P. Rodrigue, J. Appl. Phys. 29, 105 (1958).
[4]J. S. Kouvel, Phys. Rev. 102, 1489 (1956).
[5]H. Suhl, Proc. Inst. Radio Engrs. 44, 1270 (1956); J. Chem. Phys. Solids 1, 1 (1957).
[6]C. Kittel, Phys. Rev. 110, 836 (1958).
[7]Akhiezer, Bar'iakhtar, and Peletminskii, J. Exptl. Theoret. Phys. U.S.S.R. 35, 228 (1958)[translation: Soviet Phys. JETP 8, 157 (1959)].
[8]H. J. McSkimin (private communication).

SUPERCONDUCTIVITY VERSUS FERROMAGNETISM IN LANTHANUM-GADOLINIUM ALLOYS

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The differential paramagnetic susceptibility of samples of LaGd alloys containing from 0.60 to 5.00% Gd has been measured in the temperature range from 4.22 to 0.10°K. Matthias et al.[1] have shown that the addition of small amounts of Gd to La produces solid solutions with unusual magnetic properties. Alloys containing up to 0.90% Gd are superconductors with transition temperatures (T_c) which decrease linearly with increasing Gd content. Alloys containing 3.0 or more percent Gd are ferromagnetic with Curie temperatures which increase with increasing Gd content. The alloy containing 3.0% Gd becomes ferromagnetic at 1.3°K, the lowest temperature they could attain. Extrapolation of these data suggests that the T_c vs percent Gd curve and the Curie temperature vs percent Gd curve would intersect for an alloy of 1.25% at a temperature of 0.5°K. Thus two possibilities are suggested: (1) the curves meet and terminate, indicating the possibility of a ferromagnetic superconductor for one specific composition, or (2) they intersect in such a way that there would exist a range of compositions for which a given alloy would exhibit (in zero magnetic field) both superconductivity and ferromagnetism, but at different temperatures. The primary purpose of the work reported here was to investigate the validity of these extrapolations.

Temperatures below 1°K were produced by the magnetic cooling method. The sample to be investigated was cemented in a copper holder which was in thermal contact with the paramagnetic salt via a copper rod 12 cm long and 3 mm in diameter. A carbon resistor cemented directly on the sample indicated that it was in intimate