GYROMAGNETIC EFFECT IN VANADIUM

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Before Kubo and Obata[1] in 1956 pointed out that interstate mixing could lead to appreciable orbital paramagnetism in the transition metals, it had been generally assumed that the orbital magnetic moment was effectively quenched in these materials as in ferromagnetic metals, so that the only contribution to the susceptibility was due to the electronic spin; the gyromagnetic ratio g' would therefore be approximately 2 (neglecting diamagnetism). Clogston et al.[2] and later Butterworth[3] showed the importance of orbital paramagnetism from Knight-shift studies; these results were confirmed by theoretical calculations by Denbigh and Lomer[4] and recently by Mori.[5] But it appears that gyromagnetic experiments are the only direct source of information on the relative electronic contributions to the paramagnetism. For if spin-orbit interaction is neglected, then $g' = (\chi_S + \chi_O)/(\frac{1}{2}\chi_S + \chi_O)$ (see Kubo and Obata),[1] and therefore the spin and orbital susceptibilities χ_S and χ_O can be obtained from a knowledge of g' and the total susceptibility.

Although gyromagnetic effects in ferromagnetic materials have been extensively studied for many years and measurements have been made, by Sucksmith,[6] in strongly paramagnetic salts, this Letter reports what is believed to be the first determination of the gyromagnetic ratio of a paramagnetic metal. The measurement of g' for these metals presents considerable problems because of their very low susceptibility—rotations of the order of 10^{-5} rad have to be measured, compared with 10^{-3} rad in Sucksmith's experiments. The Einstein–de Haas resonance method,[7] later improved by Sucksmith,[6] Coeterier and Scherrer,[8] Scott,[9] Doll,[10] etc., appears to be the only one capable of sufficient sensitivity while also allowing for the elimination of disturbing effects which can be very large compared with the signal.

In our experiment the cylindrical specimen, suspended axially by a quartz filament, is set into oscillation by an alternating magnetic field H, parallel to its axis. H is controlled by the rotational displacement θ of the sample through a positive feedback system. With a phase difference of δ between θ and H, and a decay time of free oscillations of τ, the resonance amplitude is given by

$$\theta_0 = \frac{2m_0}{e}\frac{\chi m}{Ig'}\frac{\tau}{2}H_0\cos\delta + a_1 H_0 \sin\delta + a_2 H_0 \cos\delta, \quad (1)$$

where m_0 = electron mass, e = electron charge, χ = mass susceptibility, m = mass of paramagnetic system, I = moment of inertia of the system, and H_0 = amplitude of magnetizing field. The first term on the right-hand side of Eq. (1) is the amplitude due to the gyromagnetic torque; the last terms are due to the interactions between steady magnetic fields (e.g., earth's field) and moments induced in the specimen by the alternating field. These latter can be eliminated by reducing δ to zero, and by aligning the alternating field with the vertical axis of the specimen (experimental details will be published later).

An essential part of the apparatus, which is illustrated schematically in Fig. 1, is the optical lever designed and made for us by Jones,[11] which detects the displacement of the light beam deflected by the mirror M. The signal from a differential pair of silicon photocells is compared with the signal from a pickup coil measuring the field. The phases of the signals are compared using a phase-sensitive detector.

The two specimens used consisted of 5-cm straightened lengths of zone-refined pure vanadium wire of 0.5 mm diam supplied by Materials Research Corporation. Each was suspended by a quartz fiber in a vacuum chamber to give a frequency of oscillation of 16 cps for one sample and 18.5 cps for the other. The characteristic decay time of free oscillations was between 50 and 450 sec.

As a test of the apparatus, we measured the gyromagnetic ratio of gadolinium oxide. The value obtained was 1.95 ± 0.10, which is in good agreement with the theoretical value of 2 and the previous experimental determination by Sucksmith. The results for vanadium were as follows: sample I, 50 measurements, $g' = 1.20 \pm 0.10$; sample II, 20 measurements, $g' = 1.16 \pm 0.07$. The errors quoted represent the maximum spread of the measurements.

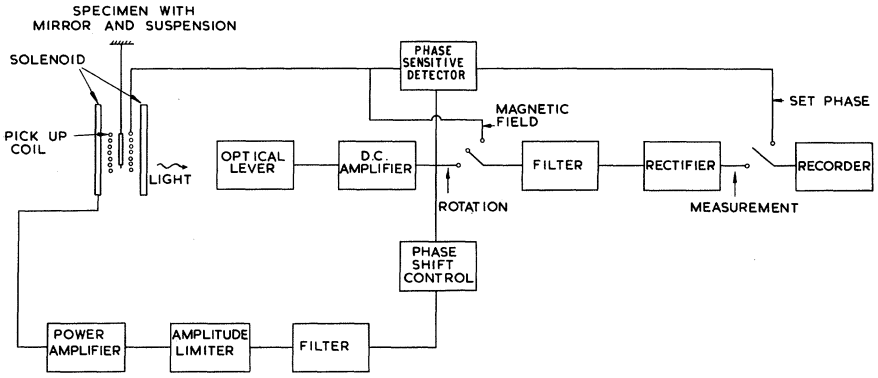

FIG. 1. Block diagram for g' measurement.

Using the formula

$$\chi_s = (2/g')(g'-1)(\chi_{meas}-\chi_{dia}),$$

the susceptibility of 5.7×10^{-6} emu/g measure for our samples leads to the following spin and orbital susceptibilities in units of 10^{-6} emu/g at., calculated from the sample-I result ($g' = 1.20$):

$\chi_{measured}$	291 ± 3
χ_{dia} (estimated diamagnetic term)	-15
χ_s	102 ± 42
χ_o	204 ∓ 42
(χ_{spin} from electronic specific heat	122)

The errors quoted in χ_s and χ_o neglect the smaller errors on χ_{meas} and χ_{dia}; the upper and lower signs have to be taken together in both quantities.

Our value of χ_s is smaller than the value derived from electronic specific heat and so supports Clogston et al.'s suggestion of a diminution of $\chi_{sp.\ heat}$ in superconductors due to the attractive potential between the electrons.[12,2] But the accuracy of our measurement is not sufficient to draw a definite conclusion.

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[1]R. Kubo and Y. Obata, J. Phys. Soc. Japan 11, 547 (1956).

[2]A. M. Clogston, A. C. Gossard, V. Jaccarino, and Y. Yafet, Phys. Rev. Letters 2, 262 (1962).

[3]J. Butterworth, Proc. Phys. Soc. (London) 83, 71 (1964).

[4]T. S. Denbigh and W. M. Lomer, Proc. Phys. Soc. (London) 82, 156 (1963).

[5]N. Mori, J. Phys. Soc. Japan 20, 1383 (1965).

[6]W. Sucksmith, Proc. Roy. Soc. (London) 128, 276 (1930); 133, 179 (1931); 135, 276 (1932).

[7]A. Einstein and W. de Haas, Verhandl. deut. physik. Ges. 17, 152 (1915).

[8]F. Coeterier and P. Scherrer, Helv. Phys. Acta 5, 217 (1932).

[9]G. C. Scott, Rev. Mod. Phys. 34, 102 (1962).

[10]R. Doll, Z. Physik 153, 207 (1958).

[11]R. V. Jones, J. Sci. Instr. 38, 37 (1961).

[12]A. M. Clogston, V. Jaccarino, and Y. Yafet, Phys. Rev. 134, A650 (1964).