tifying the orbit giving rise to the resonance, and in this instance allows us to identify the $m^* \approx 0.6 m_e$ orbit to be one such as B. The oscillations of low m^* are of type A.

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CYCLOTRON RESONANCE IN TUNGSTEN

E. Fawcett and W. M. Walsh, Jr.

Bell Telephone Laboratories, Murray Hill, New Jersey

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We have observed cyclotron resonance in tungsten, this being the first observation of the effect in a transition metal. The single crystal used in these experiments was supplied by the Lamp Division of the Westinghouse Corporation and has a residual resistivity ratio, $\rho_{295°K}/\rho_{1.6°K}$, of 7250. Two samples were cut and electropolished with their principal surfaces in the (001) and (110) planes, respectively. Each sample was mounted as part of the end wall of a 35-kMc/sec cavity in which the microwave current lines were essentially parallel over the exposed surface area (~0.2 cm^2). The derivative with respect to field of the sample's power absorption coefficient was recorded for several orientations of the applied magnetic field, which could be rotated in a plane approximately parallel to that of the sample. While some degree of resonance absorption could be seen at a temperature of 11°K, the results described in the following were obtained at 1.6°K.

With this experimental geometry, the theory of Azbel' and Kaner[1] predicts an oscillatory variation of the surface resistance with magnetic field H having the following characteristics: (1) carriers for which the effective mass m^* is extremal (i.e., $\partial m^*/\partial k_H = 0$, where k_H is the component of the wave vector parallel to the field) dominate the behavior; (2) each such class of carriers produces a damped oscillation periodic in H^{-1} with about $\omega\tau$ resolved peaks, ω being the microwave angular velocity and τ the carrier relaxation or scattering time; (3) for $\omega\tau \gg 1$ the positions H_n of the peaks of the field derivative of the resistance are given to high accuracy[2] by the equation,

$$H_n^{-1} = (e/\omega c)(n/m^*), \qquad (1)$$

n being an integer denoting the order of the subharmonic.

Recorder traces for one orientation of the field near the ⟨110⟩ axis of the (001)-plane sample are shown in Fig. 1. The derivative peaks associated with three distinct carriers are indicated and the corresponding reciprocal field versus integer plots are shown in Fig. 2. As the magnetic field is rotated in the (001) plane, the carriers with nominal mass ratios $m^*/m_0 = 0.25$ and 0.58 exhibit little anisotropy and are seen for most field directions, though the intensities of the signals vary widely. The carrier with nominal mass ratio 1.24 is not seen farther than ±20° from the ⟨110⟩ axis, and as this signal fades in intensity the mass ratio is increasing rapidly.

In the (110)-plane sample a carrier with nearly isotropic mass ratio ~0.6 is seen over most of the angular range, and presumably corresponds to the carrier with nominal mass ratio 0.58 seen in the (001) plane. The lightest carrier (0.25) has not been seen in this sample. A heavier carrier is clearly resolved, however, its mass ratio having a broad minimum of 0.84 near the $\langle 1\bar{1}1 \rangle$ axis and increasing as the orientation of the applied field approaches the $\langle 1\bar{1}0 \rangle$ and ⟨001⟩ axes. The resonance intensity decreases rapidly and may go to zero near these axes, which might suggest the existence of open orbits on a multiply-connected

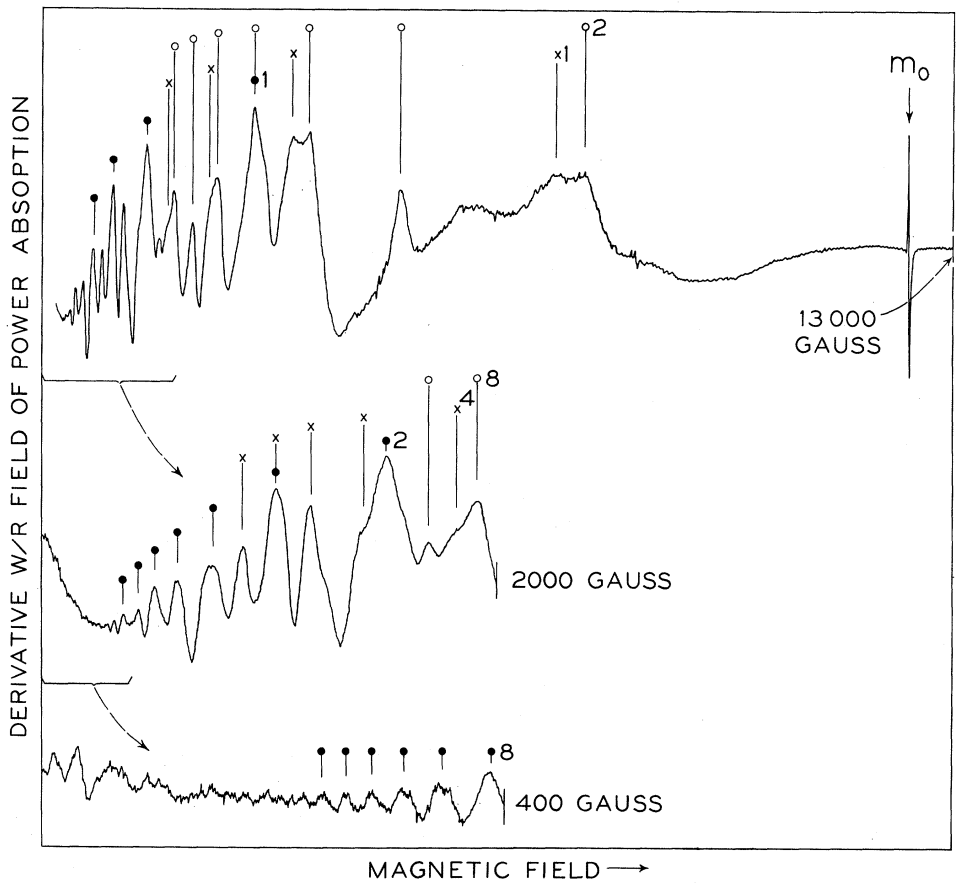

FIG. 1. Cyclotron resonance in tungsten. The magnetic field is 9° from ⟨110⟩, 48° from the microwave current direction, and is approximately parallel to the (001) plane of the sample surface; temperature = 1.6°K and frequency = 34.78 kMc/sec.

sheet of the Fermi surface. The dc magnetoresistance measurements[3] indicate, however, that no such open orbits exist in tungsten. This heavy carrier may correspond to the heaviest carrier seen in the (001) plane in that the line shapes are rather distinctive and similar in the two cases and the extrapolated mass ratio near the $\langle 1\bar{1}0\rangle$ axis in the (110) plane could correspond to the value 1.20 observed at that axis in the (001) plane.

It should be emphasized that not all features of these experimental data are accounted for by the mass ratio assignments indicated above. In particular, the oscillations at fields less than 50 gauss shown in Fig. 1 do not appear to be a cyclotron resonance, but are reminiscent of similar signals observed by Khaikin[4] at very low fields in tin.

The recent preparation of tungsten sufficiently pure to exhibit well-resolved magnetoacoustic[5] and cyclotron resonance oscillations leads one to expect that the electronic band structure of this

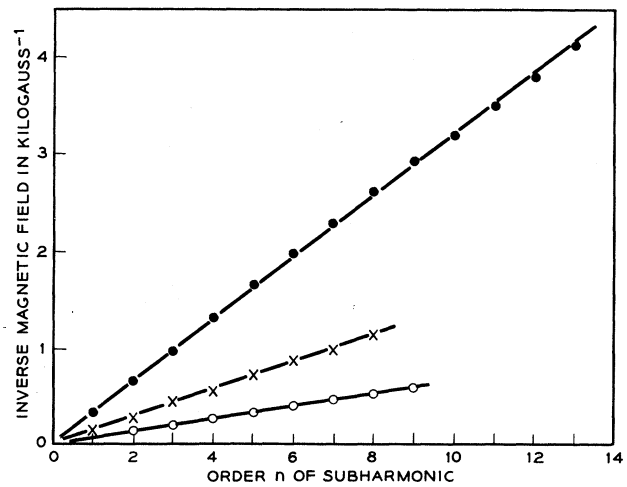

FIG. 2. The reciprocal field plots of the derivative maxima of Fig. 1. Equation (1) gives the effective mass ratios: ●−0.25, ×−0.58, o−1.24.

material can be deduced in as much detail as it is now known for several nontransition metals.

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SPIN-LATTICE RELAXATION IN MULTILEVEL SPIN SYSTEMS

R. Orbach*

Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts

and

M. Blume†

Theoretical Physics Division, Atomic Energy Research Establishment, Harwell, Berkshire, England

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We wish to report the possibility of a new temperature dependence for the spin-lattice relaxation time due to two-phonon Raman processes in multilevel spin systems. The process is simply an extension of the Van Vleck[1] "cancellation" argument for a Kramers doublet lowest to the case when there is a multilevel Kramers state lowest in energy. In the former case Van Vleck found $T_1 \propto T^{-9}$ in the Raman region. We find for the latter case, in addition to the T^{-7} dependence of T_1 found by Van Vleck, a T^{-5} dependence of T_1 in the low-temperature part of the Raman region. The T^{-5} law competes with the T^{-7} term, but should be relatively more important in the rare-earth group and third transition group than in the first and second transition groups. A very rough order-of-magnitude argument gives the criterion,

$$\lambda(\lambda/\Delta) > kT,$$

for the dominance of the T^{-5} term over the T^{-7} term in the first two transition groups. Here, λ is the spin-orbit coupling constant, and Δ is an appropriate crystalline field splitting. In the rare-earth group, however, where the crystalline field splittings are small compared to the spin-orbit splittings, the criterion for the appearance of the T^{-5} law is simply:

$$\Delta > kT.$$

To be specific, let us examine a situation where the T^{-5} law is sure to dominate over at least a portion of the Raman region. Consider a rare-earth ion in a cubic environment such that a Γ_8 quartet is lowest in energy. Such would definitely be the case[2] for Ce^{3+}, Nd^{3+}, and Sm^{3+} in a cubal environment (eightfold coordination) and, depending on the relative size of the fourth and sixth order crystalline field terms, for Dy^{3+} in a cubal environment and for Nd^{3+}, Dy^{3+}, and Er^{3+} in an octahedral environment. Consider the case of Sm^{3+} in a cubal environment. The wave functions are[3]

$$|\Gamma_8, M_J = \tfrac{3}{2}\rangle = -(\tfrac{1}{6})^{1/2}|J = \tfrac{5}{2}, M_J = \tfrac{3}{2}\rangle - (\tfrac{5}{6})^{1/2}|J = \tfrac{5}{2}, M_J = -\tfrac{5}{2}\rangle;$$

$$|\Gamma_8, M_J = \tfrac{1}{2}\rangle = |J = \tfrac{5}{2}, M_J = \tfrac{1}{2}\rangle;$$

$$|\Gamma_8, M_J = -\tfrac{1}{2}\rangle = -|J = \tfrac{5}{2}, M_J = -\tfrac{1}{2}\rangle;$$

$$|\Gamma_8, M_J = -\tfrac{3}{2}\rangle = (\tfrac{5}{6})^{1/2}|J = \tfrac{5}{2}, M_J = \tfrac{5}{2}\rangle + (\tfrac{1}{6})^{1/2}|J = \tfrac{5}{2}, M_J = -\tfrac{3}{2}\rangle. \quad (1)$$

The wave functions for Nd^{3+}, Dy^{3+}, and Er^{3+} are not so simple because there is more than one Γ_8 quartet in the ground multiplet, and the detailed nature of the wave functions will depend on the ratio of the fourth to sixth order crystalline field