

ANISOTROPY IN THE KONDO EFFECT OCCURRING IN Zn-Mn SINGLE CRYSTALS*

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Studies of the low-temperature resistivity of single crystals of pure Zn and pure Zn doped with a small quantity of Mn (64 ppm) indicate that the anisotropy of the band structure is not sufficient to explain the observed anisotropy in the Kondo effect occurring in the Zn-Mn system, and that a small anisotropy in the s - d exchange constant is required.

Miwa and Nagaoka¹ have pointed out the importance of studying the effect of an anisotropic exchange interaction in the Kondo effect. These authors predict that for the case of an axially symmetric crystal there should be two principal values of the exchange constant J_{\perp} and J_{\parallel} , where the subscripts refer to directions perpendicular and parallel to the axis of axial symmetry. Nagasawa² in some recent experiments on the de Haas-van Alphen effect in Zn-Mn alloys suggests that the apparent anisotropy in the Dingle temperature may result from an anisotropy in the exchange scattering. We wish to report measurements on the low-temperature resistivity of single crystals of Zn and Zn-Mn measured parallel and perpendicular to the c axis. The Zn and Zn-Mn crystals were grown by the Bridgman technique from 99.999% pure zinc and an alloy made from the same pure-zinc stock but containing 64 ppm Mn. After growth, samples were cleaved from each end of the crystal and the resistance ratio measured to determine the concentration gradient. A homogenizing anneal was given at 400°C until the concentration gradient was less than 1 ppm over the length of the 2-cm crystal. The 64-ppm concentration of Mn in the Zn-Mn crystal was determined by resistance-ratio measurements using the published data.^{3,4} Resistance measurements on pure Zn and the Zn-Mn alloy were made on two crystals spark cut from each ingot. The current leads were attached with 50-50 Pb-Sn solder such that the current flow was in one case parallel to, and in the other case perpendicular to, the c axis of the crystal. On using currents of 1-10 mA the resulting voltages were of the order of 10^{-11} V for the pure zinc crystals and 10^{-10} V for the Zn-Mn crystals. The voltages were measured using a superconducting Josephson device or superconducting, low-impedance, undulatory galvanometer similar to that described by McWane, Neighbor, and Newbower.⁵

Shown in Figs. 1(a) and 1(b) are the two components of resistivity as a function of temperature for pure zinc and for the Zn-Mn alloy, re-

spectively. The value of $\rho_{\perp}/\rho_{\parallel}$ for the pure zinc crystal is 0.96 which is in good agreement with the estimated value 0.97 reported by Aleksandrov and D'Yakov.⁶ The solid lines shown in Fig. 1(b) are a least-squares fit to the data and yield

$$\frac{(\partial\rho/\partial\ln T)_{\perp}}{(\partial\rho/\partial\ln T)_{\parallel}} = 1.13 \pm 0.08.$$

The total resistivity $\rho(T)$ for a dilute magnetic

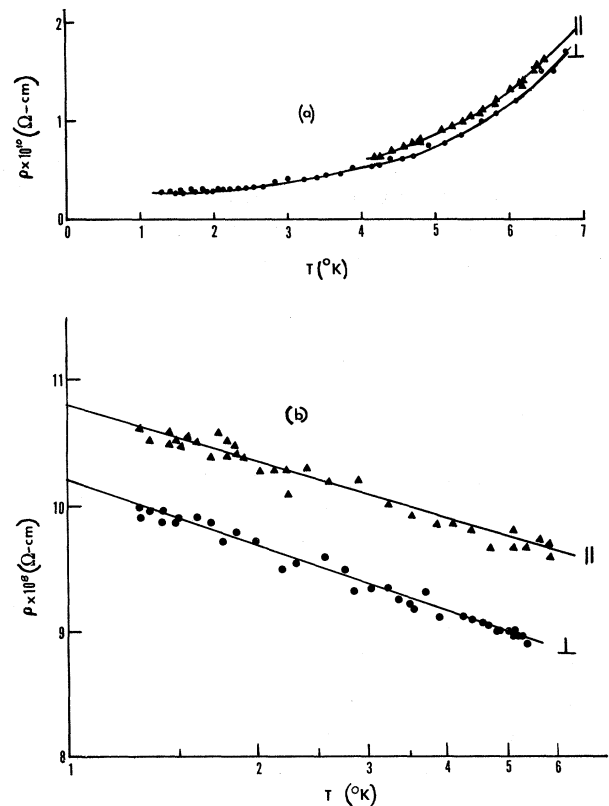


FIG. 1. (a) Temperature variation of resistivity of pure zinc parallel (closed triangles) and perpendicular (closed circles) to the c axis. Because of mechanical damage done to the crystal upon thermal cycling the measurements parallel to the c axis were not continued below 4.2°K. (b) Temperature variation of resistivity of the Zn-Mn alloy (64 ppm) parallel (closed triangles) and perpendicular (closed circles) to the c axis.

alloy can be written⁷ as

$$\rho(T) = \rho_L + c\rho_A + cKm^*J^2[A + N(0)J \ln T], \quad (1)$$

where ρ_L is the host lattice resistivity; $c\rho_A$ results from Coulomb scattering due to the presence of the paramagnetic impurity; c is the concentration of paramagnetic impurity; K is a proportionality constant involving atomic volume, Fermi energy, etc., which will be a constant for any particular solvent; $A = [1 - JN(0) \ln 0.77D]$, where D is the conduction-electron bandwidth of the solvent; J is the s - d exchange parameter; $N(0)$ is the density of states per atom for one direction of spin at the Fermi energy; m^* is the appropriate effective mass; and T is the temperature in $^\circ\text{K}$.

Assuming that at temperatures below 5°K ρ_L and ρ_A are independent of temperature, then upon differentiating Eq. (1) with respect to $\ln T$ we obtain

$$(\partial\rho/\partial \ln T) = cKm^*J^2[N(0)J]. \quad (2)$$

At the present time s - d conduction-electron scattering has not been generalized to include a nonspherical Fermi surface; so no theoretical expression exists describing the anisotropy in the anticipated logarithmic divergence in the resistivity. Intuitively one could suggest that Eqs. (1) and (2) could be generalized by defining a J_\perp^2 , J_\parallel^2 , $[N(0)J]_\perp$, and $[N(0)J]_\parallel$. We would then have from Eq. (2)

$$\frac{(\partial\rho/\partial \ln T)_\perp}{(\partial\rho/\partial \ln T)_\parallel} = \frac{m_\perp^*}{m_\parallel^*} \left(\frac{J_\perp}{J_\parallel}\right)^2 \frac{[N(0)J]_\perp}{[N(0)J]_\parallel}. \quad (3)$$

Assuming a parabolic band we suggest a further extension of the above assumptions, i.e., $[N(0)J]_\perp \propto J_\perp(m_\perp^*)^{3/2}$, so that

$$\frac{(\partial\rho/\partial \ln T)_\perp}{(\partial\rho/\partial \ln T)_\parallel} = \left(\frac{J_\perp}{J_\parallel}\right)^3 \left(\frac{m_\perp^*}{m_\parallel^*}\right)^{5/2}. \quad (4)$$

Assuming an isotropic relaxation time and a single-band effective-mass approximation for the resistivity of pure zinc the value of m_\perp^*/m_\parallel^* is given by

$$(m_\perp^*/m_\parallel^*)_{\text{zinc}} = (\rho_\perp/\rho_\parallel)_{\text{zinc}} = 0.96.$$

Assuming that the effective masses are unchanged in the 64-ppm alloy Eq. (4) can be solved for $J_\perp/$

J_\parallel using the above value of m_\perp^*/m_\parallel^* . We find

$$J_\perp/J_\parallel = 1.08 \pm 0.04.$$

Further, from Eq. (3) we notice that

$$\frac{[N(0)J]_\perp}{[N(0)J]_\parallel} = \frac{(\partial\rho/\partial \ln T)_\perp}{(\partial\rho/\partial \ln T)_\parallel} \left(\frac{J_\parallel}{J_\perp}\right)^2 \frac{m_\parallel^*}{m_\perp^*}. \quad (5)$$

Solving for the right-hand side of Eq. (5) we find it equal to 0.99 ± 0.05 . From this we can conclude that within the experimental error $N(0)J$ is a constant, and hence any parameter involving this product, viz., the Kondo temperature, will be isotropic.

If we assume, as suggested by Kondo, that the Coulomb and spin scattering are equal, then solving Eq. (1) for J using an average value for the slope of $\partial\rho/\partial \ln T$ and for $\rho(1^\circ\text{K})$ appropriate for a polycrystalline sample⁸ we obtain $J = -0.23$ eV.

In the absence of a theoretical extension of the Kondo theory to include nonspherical Fermi surfaces, we have improvised a semiphenomenological expression, from which we suggest that the anisotropy of the band structure is not sufficient to explain the observed anisotropy in the Kondo effect occurring in the Zn-Mn system and that a small anisotropy in the s - d exchange constant is indicated.

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⁸The average values of $\rho(1^\circ\text{K})/c$ and $(\partial\rho/\partial \ln T)c^{-1}$ agree closely with the experimental values obtained by F. T. Hedgcock and C. Rizzuto (Ref. 4) for polycrystalline material.