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Magnetoresistance studies in the ternary spin glass $(Au_xCu_{1-x})_{0.99}Mn_{0.01}$

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Longitudinal magnetoresistance measurements have been made on ternary spin-glass alloys $(Au_xCu_{1-x})_{0.99}Mn_{0.01}$ for $0.05 \leq x \leq 0.60$ in the temperature range 4.2–40 K in magnetic fields up to 45 kG. The procedure adopted by us to fit the results to theory has yielded values for the s-d exchange interaction constant $|J|$ and the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction strength V_0 which are in reasonable agreement with values obtained through other studies such as magnetization measurements. Unlike earlier attempts to fit the magnetoresistance data with theory, we obtain acceptable values of $|J|/V$, the ratio of the exchange coupling to the Coulomb potential. The values of V_0 obtained are consistent with an RKKY interaction which has been damped due to a reduction in the electron mean free path.

I. INTRODUCTION

Magnetoresistance measurements in noble-metal-host transition-metal-impurity (NM-TM) spin glasses have recently been analyzed by several authors.[1,2] Although these calculations qualitatively agree with experiment, it has been found that there are several discrepancies. For example, the computed values for the ratio of the s-d coupling to the potential fluctuations, $|J|/V$, are too large compared to what can be expected in these alloys. Moreover, the magnitude of the s-d exchange coupling is found to vary with the field and temperature at which the calculations are made, indicating that the field and temperature variation of the magnetoresistance have not been properly accounted for.

We have attempted to examine the reasons for the disagreement between theory and experiment. Longitudinal magnetoresistance measurements have been made by us on the ternary spin-glass alloys $(Au_xCu_{1-x})_{1-y}Mn_y$ for $0.05 \leq x \leq 0.60$ and $y = 0.01$. We have shown that by comparing the theoretical expressions with the appropriate measured quantities in determining $|J|$, a consistent set of $|J|$ and $|J|/V$ values which are physically admissible are obtained.

It has now been fairly well established that the dominant interaction responsible for spin-glass behavior in NM-TM alloys is the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction.[3] However, the true nature of the spin-freezing process is yet to be understood. Several attempts to investigate the role of other interaction mechanisms, including the effect of a reduction in the mean free path, have been reported in the literature.[4,5] In our study, we have chosen the ternary $(Au_xCu_{1-x})_{1-y}Mn_y$ system, where the electron mean free path λ has been varied by changing x, keeping y constant. Through magnetoresistance measurements, we have determined the value of the RKKY interaction strength V_0, and investigated the effect of a reduction in λ on V_0.

It was pointed out by de Gennes[6] that the damping of the RKKY interaction due to mean-free-path effects has an exponential form, and that the RKKY interaction strength V_0 decreases with λ as

$$V_0(\lambda) = V_0(\lambda = \infty)\exp(-\langle r \rangle/\lambda) \quad , \tag{1}$$

where $\langle r \rangle$ is the average interimpurity distance. As has been discussed by de Chatel,[7] this expression is valid for $\lambda >> a_0$, the lattice constant. The behavior of V_0 obtained through our magnetoresistance measurements, as a function of the Au concentration x, supports the theoretical prediction of an exponential damping of the RKKY interaction.

II. EXPERIMENTAL ASPECTS

The samples were prepared from 99.999%-pure Au and Cu, and 99.99%-pure Mn by arc melting the constituents in an argon atmosphere. The samples were alternately cold rolled and annealed several times, and finally annealed in vacuum at 750 °C for 24 h, quenched in cold water, and stored in liquid nitrogen until measurements were made.

Longitudinal magnetoresistance measurements have been made in fields up to 45 kG for 4.2 K $< T \leq 40$ K using the four-probe dc technique on rectangular sample strips $20 \times 2 \times 0.8$ mm^3 in size. Zero-field dc resistivity measurements using the four-probe method were also made on the same samples from 4.2 to 300 K. These measurements were required to estimate the mean free path of the conduction electrons for these alloys. For all the samples, the resistivity of the corresponding noble-metal-host alloys were also determined in the same temperature range. Further, low-field ac susceptibility measurements at a fixed frequency of 23 Hz were made on these samples to determine the spin-glass freezing temperature, T_f. The T_f values were required in the analysis of the magnetoresistance data.

III. RESULTS AND DISCUSSION

Figure 1 shows a plot of the measured magnetoresistance for all the samples at 4.4 K as a function of the magnetic field H. We observe that magnetoresistance decreases in magnitude up to about 40% Au, and increases for higher concentrations of Au.

The magnetoresistance measurements have been analyzed in terms of an appropriate interpretation of the expression obtained through Mookerjee's theory.[8] The theory, based on the Edwards-Anderson model,[9] predicts that the change in the resistivity due to a magnetic field H at temperature T is given by

$$\Delta\rho_H = \rho(H) - \rho(0)$$
$$= yR_0J^2\left[M(H)\tanh\left(\frac{g\mu_B H}{2k_B T}\right) + 2[Q(H)-Q(0)]\left(1-\frac{J^2}{V^2}S(S+1)\right) + 2\frac{J^2}{V^2}Q(H)M(H)\tanh\left(\frac{g\mu_B H}{2k_B T}\right)\right] , \quad (2)$$

where V and J are the Coulomb and the s-d exchange potentials, respectively, and S is the impurity spin. $M(H)$ and $Q(H)$ are the Edwards-Anderson order parameters given by the transcendental equations

$$M(H) = (2\pi)^{-1/2}\int_{-\infty}^{\infty} e^{-z^2/2}\tanh\left(\alpha + \frac{\Theta M(H)}{T} + \frac{T_f Q^{1/2}(H)}{T}z\right)dz , \quad (3a)$$

$$Q(H) = (2\pi)^{-1/2}\int_{-\infty}^{\infty} e^{-z^2/2}\tanh^2\left(\alpha + \frac{\Theta M(H)}{T} + \frac{T_f Q^{1/2}(H)}{T}z\right)dz , \quad (3b)$$

where Θ is the Curie-Weiss temperature and $\alpha = \mu H/k_B T$, where μ is the magnetic moment of the Mn atoms. R_0 is defined as

$$R_0 = \frac{3\pi m}{4\hbar e^2}\frac{1}{nE_F} ,$$

where n is the number of conduction electrons per unit volume.

Contrary to calculations reported in the literature,[1,2] we find that although $|J|/V$ is small, it is necessary to include the second-order terms in J/V in the expression. This is because the value of Q is significant at low temperatures, and hence the contribution from the $(J/V)^2$ term is comparable to that from the terms independent of V. We estimate the value of $|J|/V$ from an expression for the contribution to the magnetoresistance from the magnetic impurities, which we define as

$$\frac{[\rho_s(H)-\rho_h(H)]-[\rho_s(0)-\rho_h(0)]}{\rho_s(0)-\rho_h(0)} =$$
$$\frac{M(H)\tanh(g\mu_B H/2k_B T) + 2[Q(H)-Q(0)] + J^2/V^2\{2Q(H)M(H)\tanh(g\mu_B H/2k_B T) - 2[Q(H)-Q(0)]S(S+1)\}}{V^2/J^2 + S(S+1) - 2Q(0) + J^2/V^2[2Q(0)S(S+1)]} , \quad (4)$$

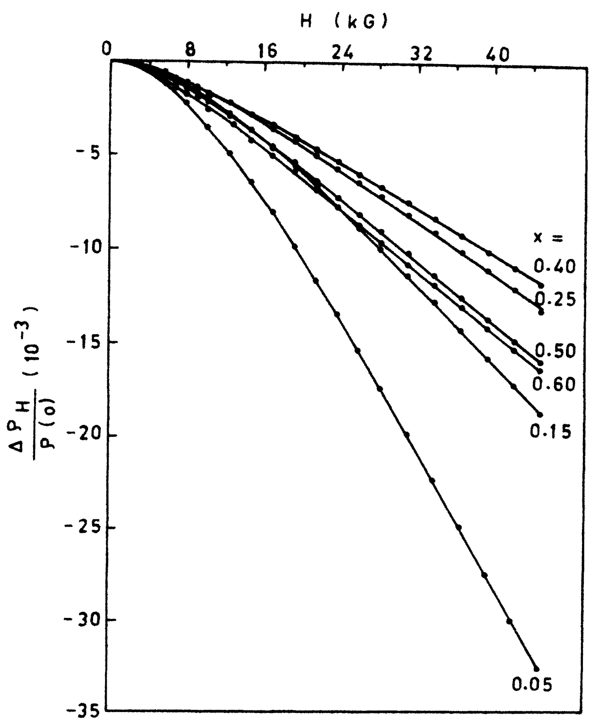

FIG. 1. Longitudinal magnetoresistance $\Delta\rho_H/\rho(0)$ vs external magnetic field H for $(Au_xCu_{1-x})_{0.99}Mn_{0.01}$ alloys at 4.4 K.

where ρ_s and ρ_h are the resistivities of the spin-glass alloy and the nonmagnetic host, respectively. We assume in our calculations that $\rho_h(H) \cong \rho_h(0)$ and hence equate the left-hand side of Eq. (4) to $[\rho_s(H)-\rho_s(0)]/[\rho_s(0)-\rho_h(0)]$. This is justified since we expect the positive contribution to the magnetoresistance to be negligible in comparison to the negative contribution, as has been established by Rohrer.[10] With this approach, we obtain values of J^2/V^2 and $|J|$ which show no field or temperature dependence up to 45 kG and 36 K for all the samples.

We have obtained the value of M and Q by an iterative process, solving for them self-consistently at fixed H, with T going up successively from $T=0$. The values of the Curie-Weiss temperature Θ and P_{eff} have been taken from high-temperature susceptibility data[11] on *Cu*Mn. The values of the spin-glass freezing temperature T_f were determined through ac susceptibility measurements. The T_f values were found to vary from 10.3 K for $x=0.05$ to 5.75 K for $x=0.6$. Figures 2(a) and 2(b) show the plots for M and Q as a function of T for fixed H for one of the samples.

The value of $|J|/V$ obtained varied from 0.22 for $x=0.05$ to 0.14 for $x=0.6$, which may be compared with 0.16 for *Cu*Mn.[12] This is a marked improvement over the high value of 0.68 obtained by Das, Tripathi, and Joshi[2] through calculations based on transverse magnetoresistance measurements.

We have determined the value of the RKKY interaction

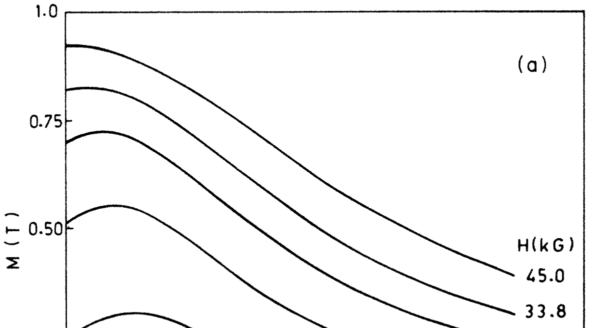

FIG. 2. The Edwards-Anderson order parameters M and Q vs temperature T calculated using Eqs. (3a) and (3b) at several values of external field H for $(Au_{0.05}Cu_{0.95})_{0.99}Mn_{0.01}$.

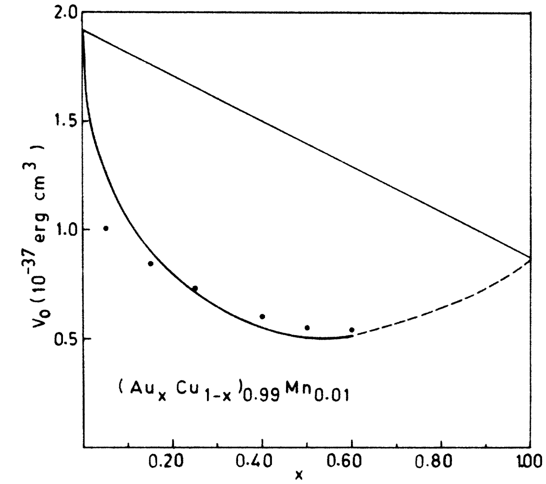

FIG. 3. Calculated and experimental values of the RKKY interaction strength V_0 vs the Au concentration x for $(Au_xCu_{1-x})_{0.99}Mn_{0.01}$ spin-glass alloys, showing mean-free-path effects. The straight line indicates the linearly interpolated values of $V_0(\lambda=\infty)$ between $CuMn$ and $AuMn$ values.

strength V_0 using the expression[3]

$$V_0=\frac{3z^2J^2}{16\pi nE_F} , \tag{5}$$

where z is the valence of the host and n is the number of conduction electrons per unit volume.

To compare the measured value of V_0 with the value expected from Eq. (1) we need the value of the mean free path λ and $V_0(\lambda=\infty)$. The value of λ is calculated using Larsen's expression[13]

$$\lambda=\frac{a_0^2h(3/16\pi)^{1/3}}{2\beta e^2\rho} , \tag{6}$$

where a_0 is the lattice constant, ρ is the total resistivity, and β is an adjustable parameter[13] taken to be 3.5. As pointed out by Waldstedt and Walker,[14] the damping of the RKKY interaction can be due to the host, in which case $\langle r\rangle/\lambda \sim \rho y^{-1/3}$ and $\langle r\rangle \sim y^{-1/3}$, or due to the magnetic impurities themselves, when $\langle r\rangle/\lambda \sim y^{2/3}$. Since we are introducing a large compositional disorder in the sample through the use of a binary host, and since the magnetic impurity concentration is reasonably small, we expect that the damping is largely due to the disorder of the host, and take $\langle r\rangle = n_I^{-1/3}$, where n_I is the number of magnetic impurities per unit volume. Values of $V_0(\lambda=\infty)$ needed in Eq. (1) have been obtained by linear interpolation between the values of V_0 for $CuMn$ and $AuMn$. The values of $V_0(CuMn)=1.95\times10^{-37}$ erg cm^3 and $V_0(AuMn)=0.92\times10^{-37}$ erg cm^3 used in the interpolation are in reasonable agreement with values obtained from magnetization studies[15], and the relative value $V_0(CuMn)/V_0(AuMn)=2.1$ obtained by us is consistent with that expected from several estimates of V_0 through various studies.[15,16]

Figure 3 shows the prediction of Eq. (1) and the experimental values of V_0 obtained through our magnetoresistance studies. We find fairly good agreement with experiment for the $(Au_xCu_{1-x})_{0.99}Mn_{0.01}$ alloys.

IV. CONCLUSIONS

Longitudinal magnetoresistance, dc resistivity, and low-field ac susceptibility measurements were made on the same set of samples, so as to be able to analyze the data consistently using the procedure outlined in the paper. We have obtained field-independent and temperature-independent values of $|J|/V$ and $|J|$ over the entire range of field and temperature studied. These values are in close agreement with the values obtained by several authors using other techniques. From the variation of the RKKY interaction strength V_0 with the mean free path λ, we conclude that an exponential damping factor adequately describes the effect of the reduction in the mean free path in these alloys.

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