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Strength of the Ruderman-Kittel-Kasuya-Yosida interaction in dilute AgMn alloys*

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From measurements of the magnetic properties of some dilute AgMn alloys we have determined the strength of the Ruderman-Kittel-Kasuya-Yosida interaction, $V(r) = (V_0 \cos 2k_F r)/r^3$, to be $V_0 = 3.5 \times 10^{-37}$ erg cm^3. The corresponding value of the s-d exchange parameter is $|J| = 1.1$ eV.

I. INTRODUCTION

Recently the dilute magnetic alloy system AgMn has been the subject of experimental and theoretical work whose aim has been to extract the value of the s-d exchange parameter J primarily from measurements of host NMR line broadening[1] and EPR linewidth.[2] The indirect Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction[3] between pairs of Mn impurities in Ag via the host conduction electrons is an additional manifestation of the s-d exchange. We report here measurements of the magnetic properties of a series of dilute AgMn alloys and, from these measurements, a determination of the strength V_0 of the RKKY interaction, given by $V(r) = (V_0 \cos 2k_F r)/r^3$. We have also been able to determine $|J|$ for AgMn from our measured value of V_0 using $V_0 = 3z^2 J^2/16\pi n E_F$, where z is the host valence, n is the concentration of conduction electrons, and E_F is the Fermi energy.[3]

II. EXPERIMENT

Magnetization measurements from 0 to 50 kG and from 1.2 to about 100 K have been made on three AgMn alloys (203, 565, and 1180 ppm Mn). The samples were prepared by melting the constituents (Asarco 99.999% Ag and Johnson Matthey 99.99% Mn) under an argon atmosphere in an arc furnace. The polycrystalline samples, whose masses were 0.5–1 g, were not annealed prior to measurement.

The Mn concentrations in the samples were determined both from measurements of the residual resistance ratios $\rho = R(4.2)/[R(273) - R(4.2)]$ and the magnetic properties of the samples. In Table I we list the nominal concentrations n_0 for these samples, along with concentrations n_1 and n_2 determined as follows. n_1 is found from the measured values of ρ, using[4,5] $n_1 = 9.05 \times 10^3 \rho$. n_2 is determined from measured values of the Curie constant $C = n_2 g^2 \mu_B^2 S(S+1)/3k_B$ and the saturation magnetization $M_{\text{sat}} = n_2 g \mu_B S$. Eliminating the spin S and solving for n_2, we have $n_2 = M_{\text{sat}}^2/(3k_B C - g\mu_B M_{\text{sat}})$. Throughout this work we have assumed $g = 2$ for Mn impurities in Ag. The values of C and M_{sat} measured for these samples and used in determining n_2 are listed in Table II. The Mn concentrations which we have chosen to use in the analysis of the data are listed in the last column of Table I and are obtained by averaging n_1 and n_2.

The magnetization has been measured by the Faraday method using a Cahn RH electrobalance (resolution 2 μg) and a Westinghouse superconducting solenoid (0–50 kG). Magnetization curves for these alloys were obtained by plotting the off-balance signal of the Cahn RH electrobalance as a function of applied magnetic field on an X-Y recorder. For all the samples, the magnetization was corrected for the contribution from the diamagnetic susceptibility of pure Ag, which was assumed to be $(-0.1826) \times 10^{-6}$ emu/g.[6]

III. RESULTS AND DISCUSSION

Our results for the magnetic susceptibility $\chi(T)$, determined graphically from the slope of M vs H as $H \to 0$, have been fitted for each alloy to a Curie-Weiss law, $\chi(T) = C/(T + \Theta)$. The resulting values of C are listed in Table II. To within experimental error, $\Theta = 0 \pm 0.1$ K for all three alloys. The only significant deviations from Curie-Weiss behavior occur below 2 K for $n = 1180$ ppm Mn.

From the measured Curie constants C, saturation magnetizations M_{sat}, and concentrations n listed in Table II we have calculated values for the impurity spin S, assuming $g = 2$. The values of S so obtained (Table II) increase slightly with

TABLE I. Mn concentrations of AgMn alloys studied.

n_0 (ppm Mn nominal)	n_1[a] (ppm Mn)	n_2[b] (ppm Mn)	n[c] (ppm Mn)
200	209	197	203 ± 6
600	560	570	565 ± 5
1000	1154	1205	1180 ± 25

[a] Concentrations determined from residual resistance ratios ρ (see text).

[b] Concentrations determined from measured values of the Curie constant C and saturation magnetization M_{sat}, listed in Table II (see text).

[c] Concentrations determined by averaging the values of n_1 and n_2 from this table, and used in the analysis of the data.

TABLE II. Magnetic properties of AgMn alloys studied.

n (ppm Mn)	C^a (10^{-6} emu K/g)	M_{sat} ^{b} (10^{-3} emu G/g)	S^c	S^d
203	5.1 ± 0.2	38.8 ± 1	1.86 ± 0.08	1.87 ± 0.09
565	15.6 ± 0.5	117 ± 3	1.95 ± 0.08	1.95 ± 0.08
1180	35 ± 1	256 ± 5	2.03 ± 0.08	2.05 ± 0.08

[a] Measured Curie constant C.

[b] Measured saturation magnetization M_{sat}.

[c] Spin S per Mn atom determined from the measured Curie constant C.

[d] Spin S per Mn atom determined from the measured saturation magnetization M_{sat}.

Mn concentration, and yield an average spin $S = 1.95 \pm 0.1$. This value is in good agreement with the results of Hurd,[6] but is slightly lower than other results on dilute AgMn.[7] In Fig. 1 $\chi(n, T)/S(S+1)$ is plotted as a function of T/n to test the scaling prediction[8] for the susceptibility (modified to account for the observed dependence of spin S on n). The susceptibility data for the three alloys fall quite well on a universal curve, to within experimental error.

To obtain the strength V_0 of the RKKY interaction we compare our magnetization data with the prediction of Larkin *et al.*[9] for the approach to saturation of the magnetization

$$M = g\mu_B S n[1 - 2(2S+1)nV_0/3g\mu_B H]. \tag{1}$$

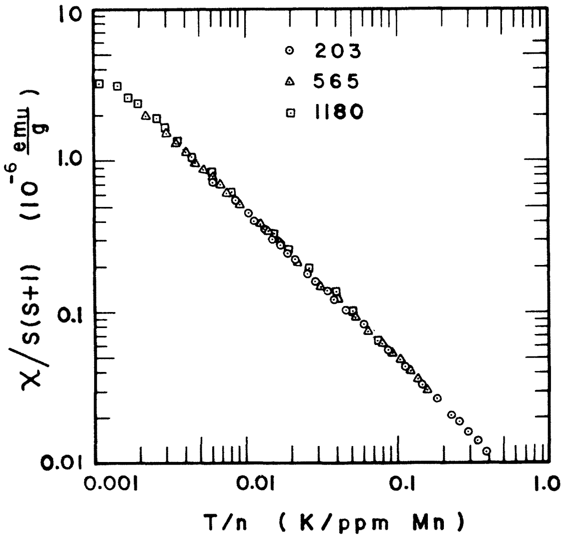

FIG. 1. Magnetic susceptibility $\chi/S(S+1)$ for three AgMn alloys (203, 565, and 1180 ppm Mn) as a function of "reduced temperature" T/n. For each alloy, we use the appropriate spin S listed in Table II.

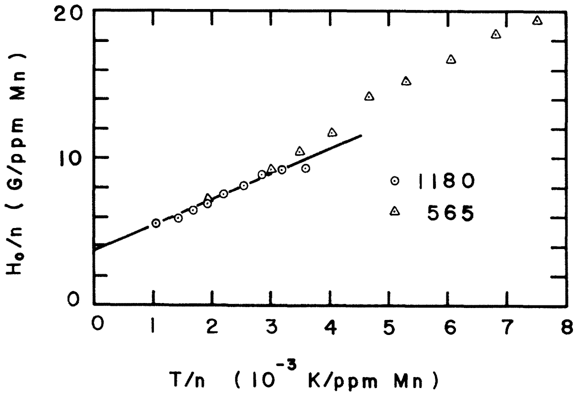

FIG. 2. $H_0(n, T)/n$ as a function of the "reduced temperature" T/n for the 565 and 1180 ppm Mn alloys. The straight line indicates the fit to the equation $H_0/n = Ak_BT/n + BV_0$ for the 1180 ppm Mn data. See text for the definition of H_0.

From the plots of M vs H^{-1} one obtains $M_{sat} = g\mu_B S n$ in the limit $H^{-1} \to 0$ and also the temperature and concentration dependent slope $H_0(n, T)$ where $M = M_{sat}(1 - H_0/H)$. Our results for the slope yield $H_0(n, T) = Ak_BT + BnV_0$ and, by comparison with Eq. (1), we assume that $B = 2(2S+1)/3g\mu_B$. This dependence of H_0 on n and T has been previously noted for both ZnMn (Ref. 10) and AuMn (Ref. 11). In Fig. 2 we plot $H_0(n, T)/n = Ak_BT/n + BV_0$ as a function of T/n for the 565 and 1180 ppm Mn alloys. The straight line drawn through the data points has an intercept at $T/n = 0$ equal to BV_0 and a slope equal to Ak_B. From the intercept we find $V_0 = (3.5 \pm 0.4) \times 10^{-37}$ erg cm^3, using $g = 2$ and $S = 1.95$ to determine B. We note that $V_0/k_B = (1.5 \pm 0.1)$ K/at.% Mn for AgMn. From the slope we find $Ak_B = (1.4 \pm 0.2) \times 10^3$ G/K.

Using $J^2 = 16\pi n E_F V_0/3z^2$, with $n = 0.594 \times 10^{23}$ cm^{-3}, $E_F = 5.48$ eV, and $z = 1$ for Ag, from our result for V_0 we obtain $|J| = 1.1 \pm 0.05$ eV for AgMn. By comparison, $|J| = 0.9$ eV for AuMn[11] (from $V_0 = 2.4 \times 10^{-37}$ erg cm^3) and $|J| = 2.6$ eV for ZnMn[10] (from $V_0 = 2 \times 10^{-36}$ erg cm^3). We observe that the spin per Mn impurity decreases as J increases for these three alloy systems. In particular $S = 2.25$ for Mn in Au,[11] $S = 1.95$ for Mn in Ag (this work), and $S = 1.25$ for Mn in[10] Zn (for $n \sim 100$ ppm Mn). This trend is consistent with theory.[1,3]

Our result, $|J| = 1.1 \pm 0.05$ eV for AgMn, is greater than the value $J_{eff}(\mathrm{RKKY}) = -0.79$ eV deduced from EPR[2] and resistivity[5] results on AgMn by Davidov *et al.*[2], but is in very good agreement with the value $|J_{eff}(\mathrm{RKKY})| = 1.12 \pm 0.10$ eV deduced by the same authors[2] from the NMR results of Mizuno[12] for AgMn. (Walstedt and Walker[1] have noted that the NMR results for AgMn obtained by Mizuno are apparently caused by more than one type of broadening agent, perhaps indicating the presence of metallurgical problems in Mizuno's samples.)

Davidov *et al.*[2] used the measured coefficient of the $\ln T$ (Kondo) term in the resistivity[5] to deduce $J_{\text{eff}}(\text{RKKY}) = -0.79$ eV for AgMn. This is a questionable procedure as $\ln T$ behavior is predicted theoretically only for $T \gg T_K$. In practice, the $\ln T$ term in the resistivity observed below 4 K is generally assumed to be the Kondo $\ln T$ term. This assumption overestimates the value of the coefficient of the $\ln T$ term.

Caroli[13] has recently estimated values of J from specific-heat measurements on CuMn, AgMn, AuMn, and ZnMn. He finds $J = 1.5$, 0.8, 0.9, and 2.5 eV for the four alloy systems, respectively. The latter two values, for AuMn and ZnMn, are in excellent agreement with our results for $|J|$ (obtained from V_0) for these two alloy systems. We plan to extend our measurements of V_0 and $|J|$ to CuMn to further check this agreement.

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