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

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From measurements of the magnetic properties of some dilute CuMn 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 $V_0 = 7.5 \times 10^{-37}$ erg cm^3. The corresponding value of the s-d exchange parameter is $|J| = 2.2$ eV.

I. INTRODUCTION

There has been considerable interest recently in the determination of values of the s-d exchange parameter J from a variety of experiments, with particular emphasis on dilute alloys of Mn in the noble metals.[1-3] These attempts have taken into account the anisotropy of J, and have indicated the correct form of the exchange for each relevant experiment, a procedure which had not always been followed by previous workers. We have completed an experimental study of the magnetic properties of dilute alloys of Mn in Au (Ref. 4) and Ag (Ref. 5) and have determined the strength V_0 of the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction[6] between the Mn impurities, given by $V(r) = (V_0 \cos 2k_F r)/r^3$. We have also been able to determine $|J|$ from our results for 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.[6] We report here a study of the magnetic properties of three dilute CuMn alloys. Values of V_0 and $|J|$ for CuMn are obtained which are compared both with our previous results for AuMn,[4] AgMn,[5] and ZnMn,[7] and with recent results for CuMn.[1-3]

II. EXPERIMENT

Magnetization measurements from 0 to 50 kG and from 1.2 to about 250 K have been made on three CuMn alloys (203-, 543-, and 1080-ppm Mn). The samples were prepared by melting the constituents (Asarco 99.999% Cu and Johnson Matthey 99.99% Mn) under an argon atmosphere in an arc furnace. The polycrystalline samples, whose masses were 0.6–0.7 g, were annealed in vacuum for 28 h at 600 °C 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[8] $n_1 = 3.91 \times 10^3 \rho$. 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 $M_{sat} = n_2 g \mu_B S$. Eliminating the spin S and solving for n_2, we have $n_2 = M_{sat}^2/(3k_B C - g\mu_B M_{sat})$. Throughout this work we have assumed $g = 2$ for Mn impurities in Cu. 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 Cu, which was assumed to be -0.088×10^{-6} emu/g.[9]

III. RESULTS AND DISCUSSION

Our results for the magnetic susceptibility $\chi(T)$, determined graphically from the slope of M vs H

TABLE I. Mn concentrations of CuMn alloys studied.

n_0 (ppm Mn—nominal)	n_1 [a] (ppm Mn)	n_2 [b] (ppm Mn)	n [c] (ppm Mn)
200	187	219	203 ± 16
500	535	550	543 ± 8
1000	1175	982	1080 ± 100

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

[b] Concenrations 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 CuMn alloys studied.

n (ppm Mn)	C [a] (10^{-6} emu K/g)	Θ (K) [b]	M_{sat} [c] (10^{-3} emu G/g)	S [d]	S [e]
203	8.4 ± 0.3	0.3 ± 0.1	68 ± 2	1.85 ± 0.11	1.91 ± 0.20
543	23.5 ± 1.3	0.2 ± 0.1	182 ± 2	1.90 ± 0.07	1.91 ± 0.05
1080	46.8 ± 1.4	0.5 ± 0.2	347 ± 5	1.90 ± 0.14	1.83 ± 0.23

[a] Measured Curie constant C.
[b] Measured Curie-Weiss temperature Θ.
[c] Measured saturation magnetization M_{sat}.
[d] Spin S per Mn atom determined from the measured Curie constant C.
[e] Spin S per Mn atom determined from the measured saturation magnetization M_{sat}.

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 and Θ are listed in Table II. Deviations from Curie-Weiss behavior occur below 2 K for $n = 543$-ppm Mn and below 4 K for $n = 1080$-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) are consistent with an average spin $S = 1.88 \pm 0.05$. This value is about 5% lower than those of Hurd[10] and Franz and Sellmyer,[11] and is about 5% higher than that of Hirschkoff *et al.*[12] In Fig. 1, $\chi(n, T)$ is plotted as a function of T/n to test the scaling prediction[13] for the susceptibility. 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.*[14] for the approach to saturation of the magnetization, valid for $g\mu_B H \gg k_B T$ and nV_0,

$$M = g\mu_B Sn[1 - 2(2S+1)nV_0/3g\mu_B H]. \quad (1)$$

From the plots of M vs H^{-1} one obtains $M_{sat} = g\mu_B Sn$ 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 $H_0(n, T) = Ak_B T + BnV_0$ 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 ZnMn,[7] AuMn,[4] and AgMn.[5] In Fig. 2 we plot $H_0(n, T)/n = Ak_B T/n + BV_0$ as a func-

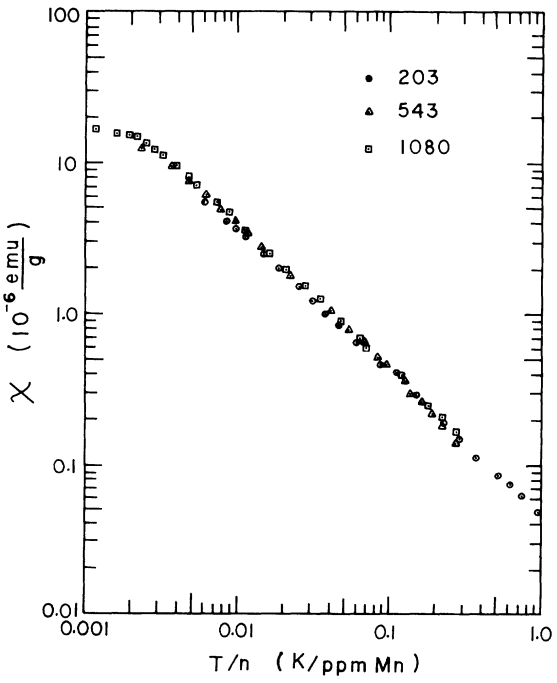

FIG. 1. Magnetic susceptibility χ for three CuMn alloys (203-, 543-, and 1080-ppm Mn) as a function of "reduced temperature" T/n.

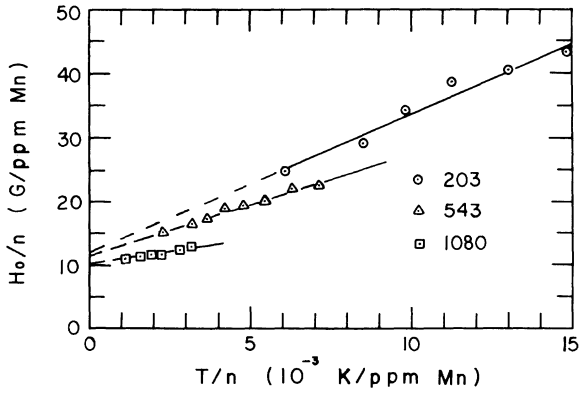

FIG. 2. $H_0(n, T)/n$ as a function of the "reduced temperature" T/n. The straight lines indicate the fit to the equation $H_0/n = Ak_B T/n + BV_0$ for the three alloys. See text for the definition of H_0.

tion of T/n for the three alloys. The straight line drawn through the data points for each alloy has an intercept at $T/n = 0$ equal to BV_0 and a slope equal to Ak_B. To within experimental error, we find $BV_0 = 11 \pm 1$ G/ppm Mn for the three alloys, which yields $V_0 = (7.5 \pm 0.9) \times 10^{-37}$ erg cm^3 (using $g = 2$ and $S = 1.88$ to determine B). We note that $V_0/k_B = 4.7 \pm 0.6$ K/at.% Mn for CuMn. This result is in good agreement with our Θ values for the 543- and 1080-ppm Mn alloys. From the slopes we find $Ak_B = 0.83$, 1.61, and 2.16 (all in units of 10^3 G/K) for the 1080-, 543-, and 203-ppm Mn alloys, respectively.

Using $J^2 = 16\pi n E_F V_0/3z^2$, with $n = 0.855 \times 10^{23}$ cm^{-3}, $E_F = 7.0$ eV, and $z = 1$ for Cu, from our result for V_0 we obtain $|J| = 2.2 \pm 0.15$ eV for CuMn. In Table III we summarize our results for V_0, $|J|$, and S for alloy systems with Mn as the magnetic impurity. The trend of decreasing S with increasing $|J|$ is consistent with theory.[1,6] Since the Kondo effect has been observed in these four alloy systems, we can assume that $J < 0$.[15]

Walstedt and Walker[1] have carefully analyzed a wide range of experimental results on CuMn and have found values of the total exchange between 2.0 and 2.5 eV. Our result is in good agreement with their findings. Davidov *et al.*[2] have undertaken a similar analysis for CuMn and have concluded that $|J_{\text{eff}}(\text{RKKY})| = 1.65$ eV from host NMR results is a valid result. Similarly, from the slope of the Kondo $\ln T$ term in the resistivity, Caroli[3] has determined $|J|$ to be in the range 1.2–1.8 eV for CuMn.

TABLE III. Experimental values of s-d exchange parameter and spin S.

Alloy system	V_0 (10^{-37} erg cm^3)	$\|J\|$ (eV)	S
AuMn [a]	2.4±0.3	0.9±0.1	2.25±0.1
AgMn [b]	3.5±0.4	1.1±0.05	1.95±0.1
CuMn [c]	7.5±0.9	2.2±0.15	1.88±0.05
ZnMn [d]	20 ±3	2.6±0.4	1.2 ±0.1

[a] Reference 4.
[b] Reference 5.
[c] This work.
[d] Reference 7.

IV. CONCLUSIONS

We have determined the strength of the RKKY interaction in dilute CuMn alloys to be $V_0 = (7.5 \pm 0.9) \times 10^{-37}$ erg cm^3, which yields a value of the s-d exchange parameter $|J| = 2.2 \pm 0.15$ eV. This value for $|J|$ is in good agreement with the value obtained by Walstedt and Walker,[1] but is about 50% higher than values obtained by other workers.[2,3]

Values of V_0 and $|J|$ are now available for dilute alloys of Mn in Au, Ag, Cu, and Zn. These results should provide a useful test for theoretical models which predict values for the strength of the s-d interaction in real metals.

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