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APPROACH TO MAGNETIC SATURATION

IN CuMn and AgMn

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Abstract:

High field magnetic moment measurements on dilute
CuMn and AgMn reveal that the magnetic state of an
isolated Mn in solution may be compatible with the
free ionic spin value $S_0 = \frac{5}{2}$ and Landé factor $g_0 = 2$.

The most dilute sample of each system shows this
directly, after extrapolation of $M$ vs $(H^{-1})$ to $(H^{-1}) = 0$.
Apparent moment reductions at higher concentrations
may be due to residual antiferromagnetic bonds instead
of a real change in the local $S$ or $g$. From a theoretical model, the lowest moments of the bond distribution are determined for the CuMn case.
1. INTRODUCTION

When Mn is implanted in a noble metal, the "ionic" parameters are apparently altered by many body correlations involving the conduction electrons and either a single Mn-site (Friedel, Anderson, Kondo) or several Mn sites (RKKY). It is customary to assign phenomenological values $S \neq S_o = 5/2$ and $g \neq g_o = 2$ to the spin and Landé factor [1].

The literature values for $S$ and $g$ in dilute CuMn and AgMn are largely scattered [2-5]. The main uncertainty may be due to large error bars on the concentration $C$ of Mn, with the tendency of losing Mn in solution. In order to clarify this point we performed high field magnetic measurements at low temperatures (however well above the Kondo temperature $T_K$) on samples of Mn in Cu and Ag for which the concentrations are determined by an analytical technique accurate to $\pm 1\%$ [6].

2. EXPERIMENTAL RESULTS

Here, we present high field magnetizations on two CuMn and two AgMn samples with $C$ between 100-1000 ppm. The measurements were made by moving the sample at constant $H$ between two opposed pick-up coils [6]. They were 40 mm diameter spheres...
cut from ingots prepared by melting degassed 6-9's Cu or Ag and 5-9's Mn in sealed high purity quartz tubes. The melt was "quenched" by plunging the tube into water and the samples machined from the ingots were annealed under an argon atmosphere for two days at 950-975°C.

The magnetization, corrected for diamagnetism, is plotted as $M$ vs. $H^{-1}$ in figures 1 and 2, indicating also $C$ and the ranges of $H$ and $T$. Values of the product $gS$, as determined from linear extrapolation to $H^{-1}=0$ are listed in table 1. They are at least 10% higher than usually reported. The error bars indicated result from $\pm 1\%$ accuracy in $C$ combined with $\pm 0.5\%$ accuracy in $M$, $\pm 2\%$ for the $10^4$ ppm CuMn sample.

3. THEORETICAL RESULTS

We calculated the magnetization of an RKKY-system with quantum spins $S_o = 5/2$, $g_o = 2$ in the pair-approximation [7,8]. The distribution of bonds is described by

$$p(W) = -\frac{1}{\pi} \text{Im} \sum_{k=1,2} \frac{C_k}{W - U_k}, \text{ Im } U_k < 0 \quad (1)$$

with two Cauchy singularities in the complex $W$-plane. This new "Ansatz" allows for skewness of the bond distribution and deviations from RKKY-scaling. The constants are uniquely determined by the first three moments, i.e. normalization of
p(W), average bond \( \langle W \rangle = \overline{W} \) and variance
\[ < (W-\overline{W})^2 > = \Sigma^2 \] plus a constraint: \( p(0) \) is a maximum. The latter expresses the fact that RKKY bonds asymptotically oscillate around \( W = 0 \) in real space. The ensemble averaged magnetization per spin is
\[
m = \frac{1}{4} g \mu_B B_2 S(z) - \text{Im} \sum_{k=1,2} \frac{C_k}{2\pi} \sum_{\lambda=1} S(2S+1) \frac{dW_\lambda(z)}{dH} \left( \frac{\beta(W_\lambda(z) - U_k)}{2\pi \lambda} \right)
\]
Here, \( \beta = (k_B T)^{-1}, z = \beta g \mu_B H \),
\( \{W_\lambda(z), \lambda = 1, \ldots, S(2S+1)\} \) are the roots of the equation \( Z_2(SW,z) = 0 \), where \( Z_2 \) is the pair partition function \([7]\), and \( \psi \) is the digamma function.
In the limit \( U_1 \to 0, U_2 \to 0 \), \( m \) goes to \( C \mu_B B_2 S(z) \), the Brillouin function. Equation (2) is plotted in figure 1 for \( T = .8K, 1.6K \) and \( 4.2K \). The distributions corresponding to the two samples are shown in figure 3 and the optimal parameters are listed in table 1. They show the tendency of building up an average antiferromagnetic bond \( \overline{W} < 0 \) as the concentration increases. The central peak is proportional to \( C^{-1} \), yielding a roughly constant amplitude \( W_1 \), as predicted by the RKKY scaling: \( W_1 = (\pi^2 C p(0))^{-1} \).

4. DISCUSSION

The experimental findings show for the first time a magnetic moment on isolated Mn sites in
noble metals which is compatible with the free
ion state. This is relevant for the internal
consistency of Friedel-Anderson-Kondo type theory
applied to Mn: from the low Kondo temperature $T_K$
one expects in fact that the Friedel resonance lies
well below the Fermi level and contains close to
5 (3d) electrons.

Moment reductions are already apparent at
$C \approx 1000$ ppm, when the linear extrapolation of
$M$ vs. $H^{-1}$ is used. The experimental conditions
$T \gg T_K$, $\mu_B H \gg k_B T_K$ and the $C$-dependence make it
very unlikely that they should be due to the Kondo
effect [1]. In our interpretation [7,8], they are
due to residual antiferromagnetic bonds that can be
decoupled by still stronger fields.

As shown in figure 1, the theory reproduces the
experimental data, in particular their $T$-dependence.
For $H^{-1} \to 0$ the theoretical $M$ tends to
$2.794 \cdot 10^4$ emu/mole or $5 \mu_B$/Mn, which is the
assumed input. We conclude that also the 657 ppm
data are compatible with an unchanged local moment
of $5 \mu_B$. The theory allows a determination of the first
moments of the bond distribution.

An ensemble calculation with a set of explicit
clusters (discrete bond values) is not meaningful
at this concentration. For example, at 657 ppm,
only $0.5\%$ of all Mn atoms would be in one of the
13 clusters considered by Morgownik and Mydosh [9].
The skewness detected in the bond distribution suggests a non random Mn positions or a modification of the spatial RKKY-function at a length scale of ~6 nearest neighbour distances.

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References

Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>g.S</th>
<th>$\bar{W}$</th>
<th>$\Sigma$</th>
<th>$W_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu 104 ppm Mn</td>
<td>5.00 $\pm$ .12</td>
<td>- .53</td>
<td>1.79</td>
<td>765</td>
</tr>
<tr>
<td>Cu 657 ppm Mn</td>
<td>4.66 $\pm$ .05</td>
<td>- 1.52</td>
<td>3.58</td>
<td>735</td>
</tr>
<tr>
<td>Ag 426 ppm Mn</td>
<td>5.00 $\pm$ .06</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ag 902 ppm Mn</td>
<td>4.84 $\pm$ .05</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Table caption: Products gS, determined from experimental data by means of linear extrapolation in the M vs. $H^{-1}$ plot.

For CuMn: Optimized parameters characterizing the bond distribution of two samples; average bond $\bar{W}$, variance $\Sigma$ and RKKY amplitude $W_1$ [6,8].
FIGURE CAPTIONS

Fig. 1: Discrete symbols represent experimental data at the temperatures indicated. Continuous curves a, b, c represent eq. (2) at $T = 0.8$ K, $T = 1.6$ K and $T = 4.2$ K, respectively. The theoretical limit, as $H^{-1} \to 0$, is $2.794 \times 10^4$ emu/mole.

Fig. 2: Experimental results for AgMn.

Fig. 3: The bond distributions $p(W)$ determined for the two CuMn samples of figure 1. They are characterized by the parameters listed in table 1.
Fig. 1

Cu Mn
657 at. ppm

Cu Mn
104 at. ppm

M (emu/mole Mn) x 10^{-4}

$H^{-1}$ (T^{-1})
Fig. 2

Ag Mn
902 at. ppm

$M \text{ (emu/mole Mn)} \times 10^{-4}$

- $0.53 \text{ K}$
- $0.80$
- $1.22$
- $1.61$
- $2.45$
- $4.20$

$H^{-1} (T^{-1})$

Ag Mn
426 at. ppm

$M \text{ (emu/mole Mn)} \times 10^{-4}$

- $0.51 \text{ K}$
- $0.82$
- $1.17$
- $1.66$
- $2.44$
- $4.21$
Fig. 3

\[ P(W) \left[ (k_B \cdot K)^{-1} \right] \]

- \( C = 104 \text{ ppm} \)
- \( C = 657 \text{ ppm} \)
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