The temperature dependence of the order parameter in a dilute AgMn spin glass

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The magnetization of a dilute AgMn spin glass containing 150 ppm Mn has been measured over the temperature range from 20 mK to 2 K in an applied field of 0.9 Oe, using a SQUID magnetometer. A comparison of the measured magnetization with numerical calculations of the magnetization based on the Mean Random Field (MRF) theory of a 3-D Heisenberg spin glass with an internal field distribution $P(h) = \Delta/[\pi^2(\Delta^2 + h^2)^2]$ yields the temperature dependence of the internal field parameter Δ and hence of the MRF order parameter.

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INTRODUCTION

In the Mean Random Field (MRF) description of spin glasses [1,2], the RKKY interactions between the impurities are represented by an effective internal exchange field $\vec{h}$ with a probability distribution $P(\vec{h})$ which, for a 3-D Heisenberg spin glass, has the form [3,4,5]

$$P(\vec{h}) = \frac{\Delta}{\pi^2} \frac{1}{(\Delta^2+h^2)^2} . \quad (1)$$

In the presence of an applied field $\vec{H}_a$, the modified distribution function which describes the probability that an impurity experiences a total field $\vec{H} = \vec{H}_a+\vec{h}$ is given by [6]

$$P(\vec{H}) = \frac{\Delta}{\pi^2} \frac{1}{[\Delta^2+H^2+H_a^2-2HH_a\cos\theta]^2} , \quad (2)$$

where θ is the angle between the total field $\vec{H}$ and the applied field $\vec{H}_a$. The internal field parameter Δ depends on temperature and the applied field and is proportional to the MRF order parameter m [6]:

$$\Delta \propto m = \int \bar{\mu}(H)\, P(\vec{H})\, d\vec{H} = \int g\mu_B S B_s\left(\frac{g\mu_B SH}{k_B T}\right) P(\vec{H})\, d\vec{H} \quad (3)$$

where $\bar{\mu}(H)$ is the thermal average of the magnetic moment at a single impurity site along the direction of the total local field $\vec{H} = \vec{H}_a+\vec{h}$ ($\bar{\mu}$ depends only on the magnitude of $\vec{H}$ and $\bar{\mu} \geq 0$ for all $\vec{H}$), $B_s(x)$ is the Brillouin function, and $d\vec{H} = H^2 dH \sin\theta d\theta d\phi$ is the volume element for the vector field $\vec{H}$ in spherical polar coordinates.

The application of an external field $\vec{H}_a$ induces a magnetization along the direction of the applied field which is given by

$$M(\text{along } \vec{H}_a) = N \int \bar{\mu}(H)\cos\theta\, P(\vec{H})\, d\vec{H} = N \int g\mu_B S B_s\left(\frac{g\mu_B SH}{k_B T}\right)\cos\theta\, P(\vec{H})\, d\vec{H} \quad (4)$$

where N is the number of magnetic impurites per unit volume. When $\vec{H}_a = 0$ the expression for the magnetization in Eq.(4) vanishes for all temperatures T, while the order parameter m is nonzero below the spin glass freezing temperature T_g and vanishes only for temperatures $T > T_g$.

In the following sections, numerical calculations of the magnetization as a function of 1/T based on Eq.(4) are compared with the measured magnetization of a 150 p.p.m. sample of AgMn in order to determine the temperature dependence of the internal field parameter Δ and hence of the MRF order parameter m.

EXPERIMENTAL AND NUMERICAL DETAILS

The polycrystalline sample of AgMn containing 150 p.p.m. Mn was cooled inside the mixing chamber of a ^{3}He - ^{4}He dilution refrigerator and the static magnetization was measured as a function of temperature between 20mK and 2K with a SQUID magnetometer [7]. An applied field H_a = 0.9 Oe was trapped in a superconducting Nb cylinder surrounding the sample and the sample was cooled in the field. The Mn impurity contribution to the magnetization was obtained by placing the AgMn sample in one coil of an astatic pair, while a pure Ag sample was placed in the other coil thus nulling any other contributions to the magnetization. The temperature T was determined by measuring the magnetization of a right circular cylinder of CMN powder, also mounted inside the mixing chamber, with another SQUID magnetometer.

The integrals appearing in Eq.(4) were evaluated numerically using the Gauss-Legendre quadrature [8] with a 5-point scheme for the θ-integration and a 40-point scheme for the H-integration. Moreover, the upper limit of infinity on the H-integral was replaced by a finite value L = 130Δ so that the total field distribution in Eq.(2) was normalized to 0.99. This procedure introduced a negligibly small error in the numerical results for the magnetization while eliminating oscillations in the convergence.

RESULTS AND ANALYSIS

Figure 1 shows both the calculated and measured magnetization of the 150 p.p.m. sample of AgMn plotted as a function of 1/T for temperatures $T \geq 20$mK. The solid curves represent the calculated magnetization for various fixed (temperature-independent) values of the internal field parameter Δ. The measured magnetization (represented by the data points in Fig. 1) initially increases rapidly with decreasing temperature and then abruptly flattens out for temperatures $T \lesssim 140$mK (i.e., for $1/T \gtrsim 7\ K^{-1}$), eventually saturating at a value of $M_{sat} \cong 3.41 \times 10^{-4}$ Gauss. An analysis of the slope of the measured high-temperature Curie-Weiss law yields an effective spin for the Mn impurity of S = 2.4 (assuming g = 2), in close agreement with the free-ion value of S = 5/2, and a Curie-Weiss temperature of $\theta \cong 30$mK. The temperature dependence of the internal field parameter (and hence of the order parameter) was determined by associating a given value of Δ with the temperature at which the corresponding calculated magnetization curve intersected the measured magnetization data and Fig. 2 shows a plot of

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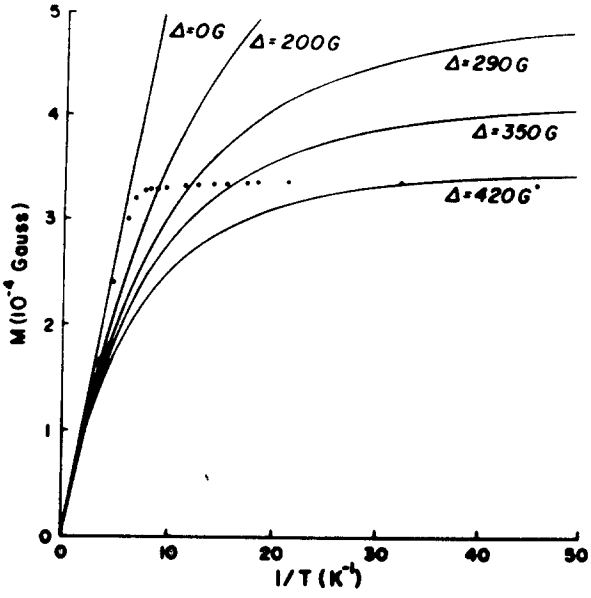

Fig. 1. The measured (dots) and calculated (solid curves) magnetization for a 150 p.p.m. sample of AgMn in a applied field H_a = 0.9 Oe.

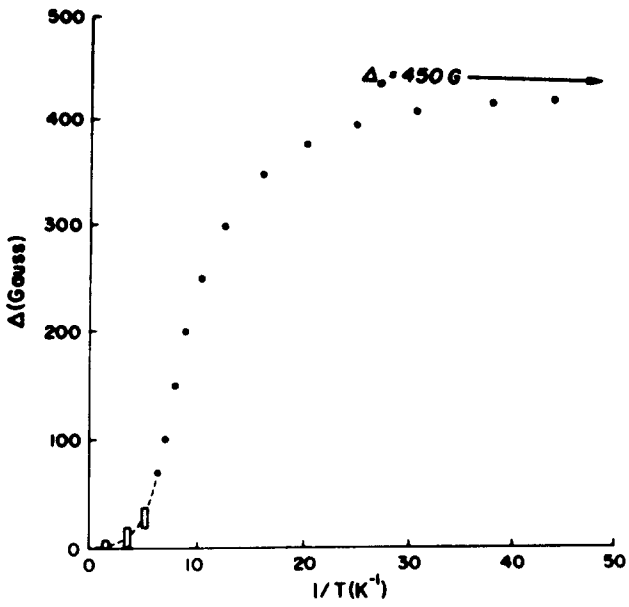

Fig. 2. The internal field parameter Δ for the 150 p.p.m. AgMn sample plotted as a function of 1/T.

the internal field parameter Δ as a function of 1/T obtained in this way from the AgMn data presented in Fig. 1. The large error bars at high temperatures reflect the relative insensitivity of the calculated magnetization curves to changes in the internal field parameter Δ in this temperature regime, and the dashed curve illustrates the expected behaviour of Δ, which must approach zero as $T \to \infty$.

In the limit as $T \to 0$, $x = g\mu_B SH/k_B T \to \infty$, the Brillouin function $B_S(x) \to 1$, and the integrals which appear in the theoretical expression for the magnetization in Eq.(4) can be performed analytically. The result is an expression relating the magnetization at T = 0 to the ratio H_a/Δ_o, where Δ_o is the value of the internal field parameter at T = 0:

$$M(T=0) = \frac{2Ngu_B S}{\pi}\left[\tan^{-1}\left(\frac{H_a}{\Delta_o}\right)+\left(\frac{\Delta}{H_a}\right)^2\tan^{-1}\left(\frac{H_a}{\Delta_o}\right)-\frac{\Delta_o}{H_a}\right] . \quad (5)$$

If we approximate M(T=0) by the measured saturation value $M_{sat} \cong 3.41 \times 10^{-4}$ G and use g = 2 and S = 5/2, then Eq.(5) yields the following estimate for H_a/Δ_o:

$$\frac{H_a}{\Delta_o} \cong .002 \quad (6)$$

and hence, for an applied field H_a = 0.9 Oe, it follows that

$$\Delta_o \cong 450 \text{ G} . \quad (7)$$

An inspection of Fig. 2 shows that the plot of Δ as a function of 1/T does, in fact, appear to be converging toward this value as $T \to 0$.

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