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FIELD DEPENDENCE OF THE COMPLEX SUSCEPTIBILITY OF THE SPIN GLASS Eu_{0.4}Sr_{0.6}S IN THE ZERO FREQUENCY LIMIT¹

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Abstract. - Measurements of the field dependence of the ac susceptibility of the spin glass Eu_{0.4}Sr_{0.6}S have been extrapolated to zero frequency. Scaling of the nonlinear susceptibility in this limit gives exponents $\beta = 0.5$ and $\gamma = 2.7$. The temperature dependence of an exponent $\nu(T, H)$ which describes the dynamics of the system is used to define a critical line in the $H$-$T$ plane.

A study of the field dependence of the susceptibility of spin glass (sg) materials reveals important properties which characterize the sg state:

1) the nonlinear susceptibility, $\chi_{nl} = \chi(0) - \chi(H)$, is predicted to diverge at $T$ approaches $T_c$. General arguments based on critical scaling imply $T_c$ near $T_c$, where $t = (1 - T/T_c)$ is the reduced temperature;

2) below $T_c$ it has been suggested that the instability line of de Almeida and Thouless [2] (A-T line) is also a critical line [3] for the disappearance of macroscopic irreversible behavior for the Heisenberg sg. The suppression of the critical temperature with field, is given by (with $h = g\mu_B S H / k_B T_c$)

$$1 - T_c(H)/T_c(0) = (5/4)^{1/3} h^6.$$  (2)

Observations of A-T line behavior and scaling reported extensively in the literature are not always in good agreement. This may be in part due to the unusual dynamic properties of the sg state, where very long relaxation-times diverge at $T_c$ and obscure what may be otherwise a sharp phase transition.

We have previously proposed [4] a novel approach to this problem: by making high-sensitivity ac measurements it is possible to extrapolate the observed time dependent trends to that which would be obtained at infinitely long measuring times. We base our extrapolation on a power law frequency dependence, the motivation for which is well established within the dynamic mean field models [5].

In this paper we extend the analysis to include the field dependence of Eu_{0.4}Sr_{0.6}S above and below $T_c$. Measurements of $\chi'$ and $\chi''$ for a single crystal were made with an ac SQUID magnetometer over the frequency range 7-5000 Hz. The sample had an approximately ellipsoidal shape, and to minimize demagnetization corrections the fields were applied parallel to the long axis. With this geometry, the measured susceptibility $\chi_s = M/H_s$ defined by the ac applied field $H_s$ was (in the vicinity of $T_c$) approximately 50% of the internal susceptibility $\chi_i = M/H_{int}$ where $H_{int} = H_s - 4\pi N M$.

We have fit the measured complex susceptibility data $X_s = \chi'(\omega) + i\chi''(\omega)$ to the power law expression

$$X(\omega) = \chi_0 - (2/\pi)(A/\nu)\omega^\nu + iA\omega^\nu.$$  (3)

The resulting field and temperature dependent exponent $\nu(T, H)$ obtained by a linear least-squares fit of $\chi''(\omega)$ to the complex part of the logarithm of equation (3) is shown in figure 1 for various values of the dc field.

Fig. 1. - Exponent $\nu(T, H)$ vs. $T$ for applied dc fields (curves from right to left) $H_s = 0, 1, 2, 3, 4, 6, 8, 10, 15$ and 20 Oe. Solid heavy line: curves shifted in temperature to coincide with $\nu(T, 0)$ (displaced to the right for clarity). Inset: temperature shift $T_c(H)/T_c(0) - 1$ vs. $H_{int}$. Solid line is a fit to the points giving $\theta = 0.64$ K.

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An interesting outcome of figure 1 is that the curve expressing the strong temperature dependence of the exponent $\nu(T, H)$ does not appreciably change shape but is merely shifted to lower temperature with increasing field. The peak in the zero frequency extrapolation of $\chi'$ at $T_c \approx 1.54$ K (see Fig. 2) occurs at a point where $\nu$ crosses over to an approximately temperature independent behavior with decreasing $T$. This point marks the departure from paramagnetism at infinitely long time scales to the onset macroscopic irreversibility in this limit. We therefore associate the onset of temperature independence of $\nu(T, H)$ with a dynamic transition at zero frequency into the sg state at the A-T line. The suppression of the critical temperature $T_c - T_c(H)$ may be found by how much the $\nu(T, H)$ curve must be translated along the temperature axis to superimpose on the $H = 0$ curve (heavy solid line Fig. 1). The A-T line deduced this way is plotted in the inset of figure 1. The solid line is a fit to the points and gives an exponent $\theta = 0.64 \pm 0.1$ in reasonably good agreement with the mean field prediction of 2/3. Recasting equation (1) as $H_c = k (1 - T_c(H)/T_c)^{1/2}$ we find for $k = (4/5)^{1/2} (k_B T_c / g\mu_B S)^{3/2}$ a value of 147 Oe which is some 20 times smaller than what would be expected for the non-interacting spin case ($k = 2900$ Oe for $S = 7/2$). However, if corrections [6] are made for the Curie-Weiss behavior $\chi' \sim (T_c - \theta_0)^{-1}$ above $T_c$ (where $\theta_0 = 0.25$) and $g\mu_B$ is replaced by the larger observed effective moment [4] $P_{eff} \approx 38.5 \mu_B$ due to short range correlations, then the expected value of $k$ is reduced to 440 Oe, which is closer to that found above.

The zero frequency in-phase susceptibility $\chi'_0(T, H)$ used for the scaling of $\chi_{nl}$ has been calculated by writing the real part of equation (3) as $\chi_0 = \chi'_0(\omega) + (2/\pi)(A/\nu)\omega^{\nu}$ and using $A(T, H)$ and $\nu(T, H)$ obtained from the fitting procedures together with $\chi'_0(T, H)$ data set at a fixed frequency ($\omega = 370$ Hz). The $\omega = 0$ extrapolation along with the original data are displayed in figure 2 after being corrected for the demagnetization effects $\chi'_1 = \chi'_0(1 - 4\pi N A')$. A trend observed in the $\chi_1(\omega)$ data towards increasing sensitivity to superimposed dc fields at lower frequencies is greatly magnified in the zero frequency extrapolations. The scaling of $\chi_{nl}$ according to equation (1) using the internal dc field and corrected for $\theta_c = 0.25$ K gives $\beta = 0.5 \pm 0.1$ and $\gamma = 2.7 \pm 0.3$ for $T_c = 1.53$ K $0.02$. The value for the cross-over exponent $\phi = \beta + \gamma = 3.2$ is in excellent agreement with the scaling relation [7] $\phi = 2/\theta = 3.1$. However, a value of $\beta = 1$ obtained from an analyse [4] of the Edwards-Anderson order parameter $q_{EA}$ below $T_c$ is in contrast with this $\beta$ obtained above $T_c$.

In conclusion, our results provide a self-consistent picture of sg behavior which suggest a sharp phase transition could be observed directly if measurements were made at infinitely long time scales. Important to our picture is the extrapolation of equation (1) to zero frequency above $T_c$, where we recover a paramagnetic response. Recent measurements of the decay of the TRM [8] suggest a stretched exponential in this region. However, comparison of our frequency data to the TRM are not straightforward. Clearly lower frequency measurements with correspondingly longer cooling rates are needed.