Spin-glass response near the glass temperature

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The time dependence of the thermoremanent magnetization (TRM) for the spin glass Ag:$Mn_{2.6}Sb_{0.46}$ (at.%) has been observed to be of the form $\sigma_{TRM}=\sigma_0\exp[-(t/\tau_p)^{1-n}]$. We have measured the temperature and magnetic field dependence of the apparent response rate, $1/\tau_p$, in the immediate vicinity of the glass temperature, T_g. We observe that $\log_{10}(1/\tau_p)\propto[1/(1-n)]$. This relationship is in accord with the predictions of De Dominicis *et al.* for the time-dependent response of a spin glass.

The time-dependent response of the field-cooled magnetization, after the field is cut off, has been shown to be of the "stretched exponential" form[1]

$$\sigma_{TRM}(t)=\sigma_p\exp[-(t/\tau_p)^{1-n}] \ , \tag{1}$$

where τ_p is referred to as the apparent response time, and the exponent $1-n$ varies with temperature. In a recent Letter, Hoogerbeets, Luo, and Orbach[2] found that the temperature dependence of the apparent response rate $1/\tau_p$ of the spin glass, As:Mn (2.6 and 4.1 at.%), depended exponentially upon the ratio T_g/T, where T_g is the "glass temperature," for $T_g/T\geq 1.2$. They showed in this temperature range that

$$\frac{1}{\tau_p}=A\exp[-\alpha(T_g/T)] \ . \tag{2}$$

For temperatures closer to T_g (i.e., for $1\leq T_g/T\leq 1.2$), their observations exhibited a much more rapid increase in $1/\tau_p$ as one approached T_g from below. Indeed, a glance at their Fig. 1 would lead one to the conclusion that $1/\tau_p$ diverges at $T=T_g$. In addition, they found that $1/\tau_p$ did not scale as T_g/T in this narrow temperature range in the vicinity of T_g. In order to resolve this departure from the form of Eq. (2), we have performed a series of measurements on the spin glass Ag:$Mn_{2.6}Sb_{0.46}$ (at.%), both as a function of temperature ($T/T_g\simeq 0.91$, 0.95, 0.97, and 0.98) at fixed values of the cooling field, and as a function of the magnitude of the cooling field ($H=5$–30 Oe) at fixed temperature.

The Ag:$Mn_{2.6}Sb_{0.46}$ sample consists of several foils with approximate dimensions $12\times 5\times 0.025$ mm^3. The magnetization was measured with a superconducting quantum interference device (SQUID) magnetometer which has been described in detail previously.[3] The measurement procedure was as follows. The sample placed in the upper coil of the pickup coil system was field cooled from a temperature above T_g to the temperature of measurement below T_g. After approximately 5 min (the "waiting time") the applied field was cut off, and the time response of the magnetization was observed over a period of 500 sec. Next, the sample was warmed up to a temperature above T_g and the baseline was established. The entire procedure was repeated with the sample placed in the lower coil of the pickup coil system in order to allow subtraction of any systematic background signal.

Using Eq. (1) to fit to the experimental data, we exhibit the relationship between $\log_{10}(1/\tau_p)$ and $1/(1-n)$ in Fig. 1 for different cooling fields and temperatures. The linear relationship between these two quantities can be expressed as

$$\log_{10}(1/\tau_p)=[1/(1-n)]\log_{10}M \ . \tag{3}$$

We have anticipated our subsequent discussion by denoting the slope of the data points in Fig. 1 by $\log_{10}M$. From Fig. 1, $M\simeq 4.4$ for $T/T_g=0.98$, and $M=3.8$ for T/T_g

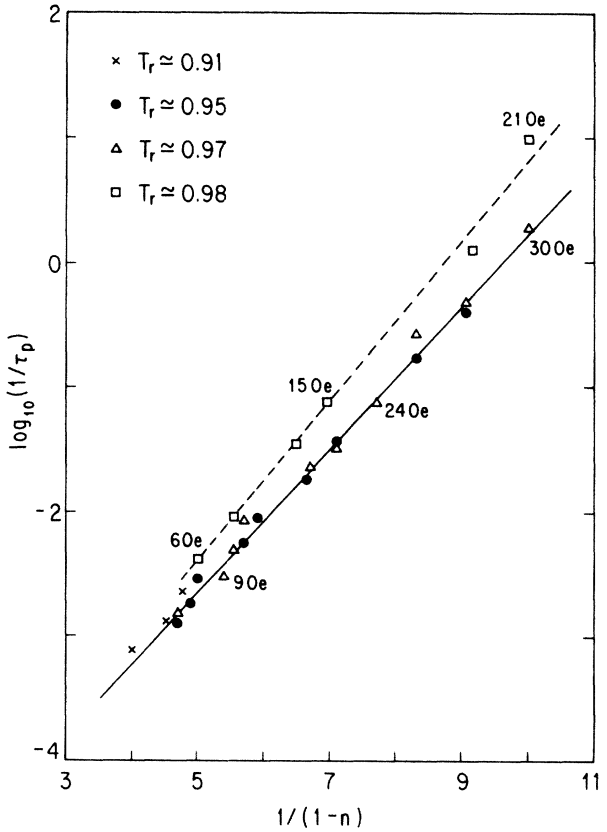

FIG. 1. A plot of the dependence of $\log_{10}(1/\tau_p)$ on $1/(1-n)$ at several reduced temperatures ($T_r=T/T_g$) and magnetic fields (5–30 Oe). The solid line represents the best fit of the form, $\log_{10}(1/\tau_p)=C+[1/(1-n)]\log_{10}M$, to the experimental data for $T_r\simeq 0.91$, 0.95, and 0.97, with $C=-5.5$ and $M=3.8$. The broken line represents the fit to the experimental data for $T_r\simeq 0.98$, yielding $C=-5.6$ and $M=4.4$. The small variation ($\simeq 10\%$) of the slope of the data with temperature suggests that M is increasing as one approaches T_g from below.

$=0.91$, 0.95, and 0.97. The latter value of M is in good agreement with the value obtained from a fit of Eq. (2) to previous measurements of the temperature dependence of $1/\tau_p$ just below T_g at fixed field ($H \simeq 6$ Oe).[4]

The significance of Eq. (3), apart from its intrinsic interest, is the direct overlap with the model calculation of De Dominicis, Orland, and Laineé.[5] They have used a "simple approximation" to the transition probability in the master equation for the time rate of change of occupancies of the mean-field-theory states of Mézard, Parisi, and Virasoro[6] for the Sherrington-Kirkpatrick model of a spin glass.[7] They find

$$\frac{1}{\tau_p} = 2M^{1/(1-n)}\Gamma(n)^{1/(1-n)} \exp(-f_c/k_B T)/\tau_0 \ . \qquad (4)$$

Here, Γ is the gamma function, M is the number of states, f_c is an upper cutoff of the free energy fluctuations of the degenerate states (valley bottoms) that characterize the infinite-range Ising spin glasses,[7] and τ_0 is an appropriate (constant) relaxation rate.

The factor $\Gamma(n)^{1/(1-n)}$ in Eq. (4) varies only from 2.25 to 1.95 over the range of measurement reported in Fig. 1 (close to T_g). Hence, the addition to Eq. (3) implied by Eq. (4), $\log_{10}[\Gamma(n)^{1/(1-n)}]$, varies only from 0.35 to 0.29. This change would not be visible in Fig. 1, and has been omitted from Eq. (3) for clarity. The other parameters in Eq. (4) have been obtained from a fit of the measured values of $1/\tau_p$ over the entire temperature range of measurement ($1 > T/T_g > 0.25$) and constant magnetic field (Fig. 10 in Ref. 4); $f_c = 3.3 k_B T_g$, and $\tau_0 = 2.2 \times 10^3$ sec.

The factor M enters Fig. 1 as the slope. Our value of ~ 4 is not very reasonable in view of the meaning of M according to De Dominicis, Orland, and Laineé.[5] They used an infinite-range Sherrington-Kirkpatrick[7] model for a dense system. Under these conditions, M is the number of states. For our physical system, the range is finite, and the concentration of magnetic ions 2.6 at.%. We suspect that these differences may affect the numerical coefficient of the argument of the exponent in Eq. (1). Remembering that M is just such a coefficient $[(1/\tau_p)^{1-n} \propto M]$, the differences between what one would expect for the number of states, and our value for the coefficient of the "stretched" time in the exponent of Eq. (1), may be rationalized.

We see that the De Dominicis, Orland, and Laineé form, Eq. (4), predicts the relationship, Eq. (3), which is satisfied by our data in the immediate vicinity of T_g. This remarkable agreement suggests that the infinite-range mean-field model may have direct application to relaxation dynamics in real spin-glass systems.

We acknowledge assistance from Dr. N. Bontemps, who pointed out to us that the magnetic field dependence of $1/\tau_p$ (implicit in Fig. 1) could explain the differences observed for $Eu_{0.40}Sr_{0.60}S$ observed by many groups in the immediate vicinity of T_g. We also acknowledge helpful conversations with Dr. N. Bontemps and Dr. C. Pappa, who have shown that the data contained in Fig. 1 can yield a relationship between $1-n$ and the temperature and magnetic field. This relationship is still being probed, and eventually may enable us to express our results in terms of the microscopic parameters contained in the Parisi[8] model for the spin-glass order parameter.[9] This research was supported by the National Science Foundation, under Grants No. DMR 81-21394 and No. INT 83-12985.

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