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Time decay of the thermoremanent magnetization in spin-glasses as a function of the time spent in the field-cooled state

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We have measured the time decay of the thermoremanent magnetization (σ_{TRM}) in Ag:Mn as a function of the wait time (t_w) that the sample spent in the field-cooled state before the field was removed. When the results are analyzed in terms of a stretched exponential, $\sigma_{TRM}(t)=\sigma_0\exp[-C(\omega t)^{1-n}/(1-n)]$, we find that the effect of t_w can be empirically characterized as an exponential decrease of the relaxation frequency with increasing wait time: $\omega=\omega_0\exp(-t_w/t_0)$, where $\omega_0=3.3\times10^{-4}$ sec^{-1} and $t_0=650$ sec. This fact has two implications. First, even though the field-cooled magnetization is constant in time, the field-cooled state is not in equilibrium for finite t_w. And second, if $t_w\rightarrow\infty$ then the field-cooled spin-glass will have a permanent magnetic moment.

In a recent Letter[1] (henceforth referred to as Ref. 1) it has been reported that the time decay of the thermoremanent magnetization in spin-glasses can be accurately characterized by a stretched exponential:

$$\sigma_{TRM}(t)=\sigma_0\exp[-C(\omega t)^{1-n}/(1-n)] \quad . \tag{1}$$

The measurements of Ref. 1 were made without regard for the waiting time that the sample had been in the field-cooled state before the field was removed to initiate the decay of σ_{TRM}. Recently, Lundgren, Svedlindh, Nordblad, and Beckman[2] have shown that the relaxation rate of the remanent magnetization depends on this waiting time. We have remeasured $\sigma_{TRM}(t)$ and find that the effect of the waiting time can be quantitatively characterized by an exponential decrease in the relaxation frequency (ω) with increasing waiting time. To within experimental accuracy the prefactor (σ_0), time-stretch exponent (n), and exponential factor (C) do not depend on the waiting time.

The sample measured is the 2.6% Ag:Mn + 0.46% Sb sample described in Ref. 1. Its glass temperature ($T_g=9.30$ K) was determined from the maximum in the magnetization in a static field of 3 Oe. $\sigma_{TRM}(t)$ was measured using a SQUID magnetometer as follows. (1) A magnetic field ($H=6$ Oe) was applied to the sample when in the paramagnetic regime. (2) The sample was field cooled through T_g to a temperature in the spin-glass region. (3) After waiting a certain length of time, H was removed and σ_{TRM} was measured as a function of time. (4) After 500 sec, the sample was warmed through T_g to establish the base line. The wait time (t_w) is defined as the interval between the instant the sample is field cooled through T_g and the instant that H is turned off. We believe t_w is the only significant cooling parameter because, to within the accuracy of these measurements, $\sigma_{TRM}(t)$ does not depend on the temperature at which H is applied (provided H is applied above T_g) nor the rate at which the sample is cooled (we used ~0.05 and ~0.5 K/sec). $\sigma_{TRM}(t)$ was measured at ten different temperatures for $t_w=5$, 10, 15, and 20 min.

The effect of the wait time on the decay of the remanent magnetization is shown in Fig. 1. The initial remanent magnetization (σ_0) does not depend on t_w, but the rate of decay of $\sigma_{TRM}(t)$ does; in agreement with Lundgren *et al.* we find that the remanent magnetization relaxes more slowly for longer t_w. Figure 2 is a plot of $\log\{-d[\ln(\sigma_{TRM})]/dt\}$ vs $\log(t)$ for the data of Fig. 1. The solid lines are the best fits to the data in the time regime where Eq. (1) holds ($t\geq5$ sec). To within experimental resolution, the slope of these lines ($-n$) does not depend on t_w, whereas the $t=1$ sec intercept ($C\omega^{1-n}$) monotonically decreases with increasing wait time. The relative dependences of ω and C on t_w can be extracted by plotting $\log(C\omega^{1-n})$ as a function of $1-n$ (Fig. 3). Again to within experimental resolution, the $1-n=0$ intercept of the linear fits to the data (C) is not a function of the wait time: $C=0.35\pm0.02$. The slope of these lines ($\log\omega$), however, decreases more or less linearly with increasing t_w. This linear dependence suggests that ω must decrease exponentially with increasing t_w, and indeed, using $C=0.35$ we show in Fig. 4 that $\omega=3.3\times10^{-4}\times\exp(-t_w/650)$ sec^{-1} is an accurate empirical characterization of the effect of t_w on $\sigma_{TRM}(t)$.

We note that this t_w dependence explains why we now find different values for C and ω than those reported in

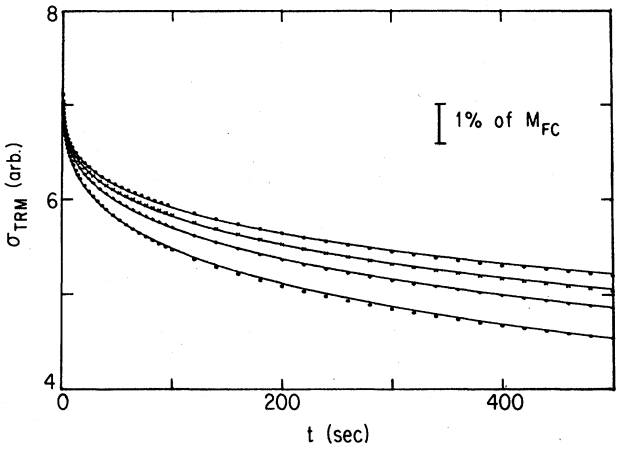

FIG. 1. Time decay of σ_{TRM} in 2.6% Ag:Mn + 0.46% Sb as a function of the wait time at $T=0.809T_g$ for $t_w=5$, 10, 15, and 20 min. σ_0 is not a function of t_w but σ_{TRM} relaxes more slowly for longer t_w (the bottom set of data is for $t_w=5$ min and the top set is for $t_w=20$ min). The curved lines are the best stretched exponential fits to each set of data.

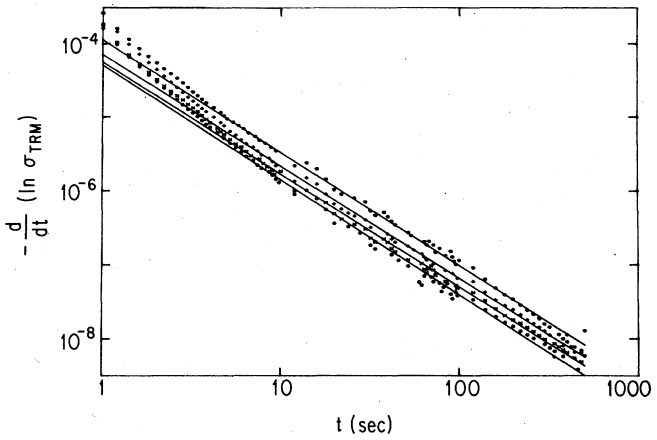

FIG. 2. log-log plot of $-d[\ln(\sigma_{TRM})]/dt$ as a function of time for the data of Fig. 1. The uppermost set of data is for $t_w = 5$ min and the bottom set is for $t_w = 20$ min. The straight lines are the best fit to each set of data for times greater than 5 sec. To within experimental resolution the slope of the lines $(-n)$ is not a function of t_w but the $t = 1$ intercept $(C\omega^{1-n})$ is.

Ref. 1; since it takes longer to cool the sample to lower temperatures, the low-temperature $(1 - n \simeq \frac{1}{3})$ data points of Ref. 1 had systematically longer waiting times, which induced an artificial skew.

The observed dependence of the relaxation of σ_{TRM} on t_w has two profound implications. First, even though the magnetization is constant in the field-cooled state,[3] some property (which must be independent of the magnetization) is changing exponentially with time. And second, if the sample is allowed to remain in the field-cooled state long enough before the field is removed, then σ_{TRM} will not relax: as $t_w \rightarrow \infty$ the field-cooled spin-glass has a permanent magnetization of σ_0 in zero field.

Although a complete theory for the decay of the remanent magnetization in spin-glasses is not yet available, we will present a possible mechanism for the observed dependence of $\sigma_{TRM}(t)$ on t_w. Using the model of Bantilan and

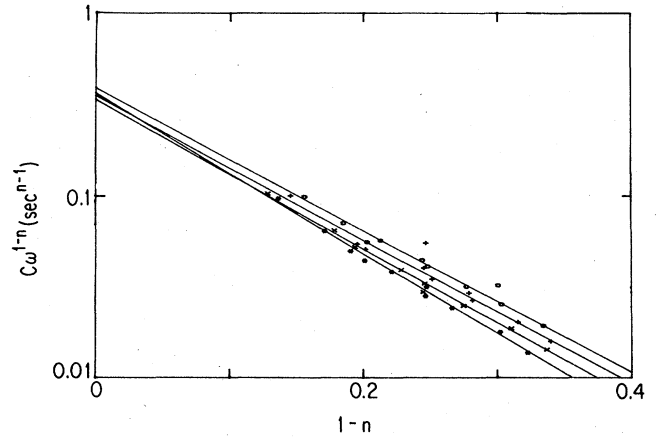

FIG. 3. $\log(C\omega^{1-n})$ as a function of $1 - n$ for $t_w = 5(\circ)$, $10(+)$, $15(\times)$, and $20(*)$ min. The lines are the best fits to the data. To within experimental accuracy the $1 - n = 0$ intercepts of the lines are not functions of $t_w (C = 0.35 \pm 0.02)$ but the slope $[\log(\omega)]$ decreases more or less linearly with increasing t_w.

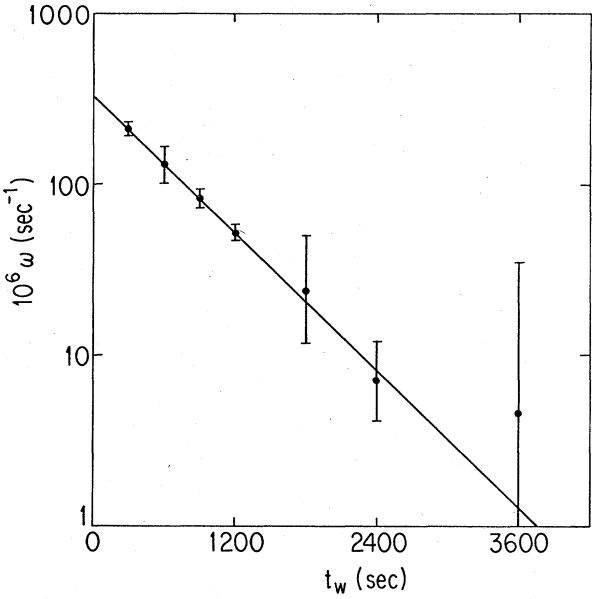

FIG. 4. The relaxation frequency decreases exponentially with increasing wait time. The best fit to the data gives $\omega = \omega_0 \times \exp(-t_w/t_0)$ where $\omega_0 = 3.3 \times 10^{-4}$ sec^{-1} and $t_0 = 650$ sec.

Palmer,[4] the energy of a spin-glass can be pictured as a labyrinthine surface in spin configuration space, containing many maxima and local minima and several quasidegenerate ground-state minima. In this model the configuration of a particular domain in the spin-glass is represented by a point on the labyrinthine surface which diffuses randomly over the surface until it is trapped into one of the ground-state minima. At long times, the approach to equilibrium of a diffusing system with randomly placed traps is given[5] by a stretched exponential similar to that of Eq. (1), where the relaxation rate (ω) is proportional to the diffusion rate of the system. Thus, the effect of t_w on ω may be thought of as an exponential slowing down of the motion in configuration space, possibly due to a deepening of the local minima. In this picture, a field-cooled configuration will not depend on t_w since it is stationary in a ground-state minimum, but the approach toward equilibrium of a remanent configuration will be impeded by the deepening local minima.

In summary, we have measured the decay of the thermoremanent magnetization in a spin-glass after waiting a controlled interval of time in the field-cooled state. When analyzed in terms of Eq. (1) we find that the effect of this wait time can be empirically expressed as an exponential decrease of ω with increasing t_w. The dependence of ω on t_w has two implications: first, even though the field-cooled magnetization is constant in time, the field-cooled state is not in equilibrium for finite t_w; and second, as $t_w \rightarrow \infty$ the field-cooled spin-glass has a permanent magnetization, even in zero field. The effect of t_w can be qualitatively interpreted as an exponential slowing down of the relaxation rate in spin configuration space, but the theoretical picture is not yet complete.

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[1]R. V. Chamberlin, G. Mozurkewich, and R. Orbach, Phys. Rev. Lett. **52**, 867 (1984).

[2]L. Lundgren, P. Svedlindh, P. Nordblad, and O. Beckman, Phys. Rev. Lett. **51**, 911 (1983).

[3]L. Lundgren, P. Svedlindh, and O. Beckman, Phys. Rev. B **26**, 3990 (1982), measure a time dependence of the field-cooled magnetization (M_{FC}), but this effect is small ($\Delta M_{FC} \leq 0.1\%\ M_{FC}$). Any time dependence of M_{FC} in our sample is smaller than the resolution of our measurements ($\Delta M_{FC} < 0.1\%\ M_{FC}$) so the effect of t_w on the decay of σ_{TRM} is much greater than any effect on M_{FC}. We also note that the time dependence of M_{FC} measured by Lundgren *et al.* is consistent with the effect one might expect to see due to the small temperature dependence of M_{FC} and the resulting corrections to the local field. Thus, we speculate that any observed time dependence of M_{FC} may be a consequence of the fact that the sample is not cooled in a constant local field.

[4]F. T. Bantilan, Jr. and R. G. Palmer, J. Phys. F **11**, 261 (1981).

[5]P. Grassberger and I. Procaccia, J. Chem. Phys. **77**, 6281 (1982).