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Mesoscopic tests for thermally chaotic states in a *Cu*Mn spin glass

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The random conductance of a mesoscopic sample of *Cu*Mn spin glass was measured under various thermal cycling conditions. Although a random spin-dependent conductance similar to that predicted by prior theory was found, no convincing evidence was found for the chaotic dependence of the spin configuration on temperature. This negative result sets some limits on the applicability of scaling theories of the spin-glass state.

Several years ago Feng, Bray, Lee, and Moore[1] proposed that the random conductance associated with the frozen spin disorder in metallic spin glasses would be measurable, thanks to the universal conductance fluctuation (UCF) effect, and that the random changes as a function of temperature in mesoscopic spin-glass samples would provide a probe of the thermally chaotic nature of the spin-glass state expected from scaling theories.[2,3] The sensitivity of UCF's to the spin configuration has been amply confirmed experimentally.[4–9] However, although mesoscopic fluctuation experiments have proved very valuable in testing spin-glass (SG) models,[7,9] there have been no reports of specific tests of the FBLM prediction of thermally chaotic resistance fluctuations. In this paper, we report such tests, with negative results, in *Cu*Mn.

There are three important length scales for these effects. $L_\Delta(T)$ is the length scale over which the thermal equilibrium spin configurations lose correlation for a temperature change of Δ in a droplet scaling picture of the SG state. $L_E(\tau,T)$ is the typical length scale over which equilibrium is reached in time τ. $L_I(T)$ is the inelastic scattering length for the conduction electrons. L_I sets the maximum distance scale over which relative orientations of spins can affect the conductance via UCF effects.[10]

In a measurement at true equilibrium, one expects that for sufficiently large temperature change, $\Delta, L_\Delta < L_I$, so that, following FBLM, one expects that

$$\langle [R(T)-R(T+\Delta)]^2\rangle \approx \langle (\delta R)^2\rangle_T \ , \tag{1}$$

where the right-hand side gives the total variance (over all spin configurations) in R from the spin-dependent UCF's. In practice, after a small temperature change is made spin rearrangements on long distance scales will not occur except after impractically long times. Thus in order for condition (1) to hold, one also needs $L_\Delta(T) < L_E(\tau,T)$, so that rearrangements can occur on the distance scale over which the temperature change has altered the equilibrium spin correlations.

Droplet scaling[1–2] provides approximate expressions for both L_Δ and L_E. We have

$$L_\Delta \approx b(T_G^2/T\Delta)^{1/\zeta} \ , \tag{2}$$

where T_G is the SG freezing temperature and b is the typical nearest-neighbor distance of the spins. ($b\approx 0.5$ nm for $Cu_{0.91}Mn_{0.09}$.) The exponent $\zeta=(d/2)-\theta\approx 1.3$ in a standard droplet picture in three dimensions. Also

$$L_E \approx b[\ln(\tau/\tau_0)T/T_G]^{1/\psi} \ , \tag{3}$$

with $\psi\approx 0.6$ and $\tau_0\approx 10^{-12}$ sec, if experiments can properly be interpreted in terms of ψ.[11] In practice, mesoscopic noise experiments[7,9] allow us to set a minimum value for L_E without relying in detail on Eq. (3).

We performed several experiments which should have been sensitive to thermal chaos in the SG state. These were (i) quick thermal cycling to look for deviations from simple scaling when the putative length L_Δ became comparable to the other relevant lengths; (ii) slow thermal cycling to look for reproducible random components in $R(T)$. This technique is the closest to the explicit FBLM proposal; (iii) noise experiments in the presence of periodic joule heating from ac currents, which might have shown peculiar nonlinear effects if the joule heating drove the samples through states different on a small enough length scale.

Samples of $Cu_{0.91}Mn_{0.09}$ were prepared as described previously.[7,9] The data described here come from sample 4 of Ref. 7, with a volume of roughly 4×10^{-15} cm^3 and $T_G\approx 30$ K.

Our rapid thermal cycling experiments have been described elsewhere.[7–9] The sample is directly heated by a brief current pulse, allowing rapid return to the base temperature (see Fig. 1). The resistance variance between cycles depends on both the base temperature T and the peak heating temperature $T_H > T$ (see Fig. 2). $\langle \delta R(T,T_H)^2\rangle$ is a decreasing function of T below T_G (and too small to measure above T_G) and an increasing function of $T_H < T_G$, as shown in Fig. 2. As argued elsewhere,[9] the saturation of $\langle \delta R(T,T_H)^2\rangle$ for $T_H\approx T_G$ strongly implies that the random resistance comes from spins, not moving defects, for which diffusion and electromigration were *a priori* expected to be very small anyway.

Since δR can only come from actual kinetically allowed changes in the spin configuration, not from changes in the ideal equilibrium state, one expects to find very little δR from thermal cycling for $L_\Delta > L_E$. On the other hand, for $L_\Delta < L_E$ and $L_\Delta < L_I$, one expects

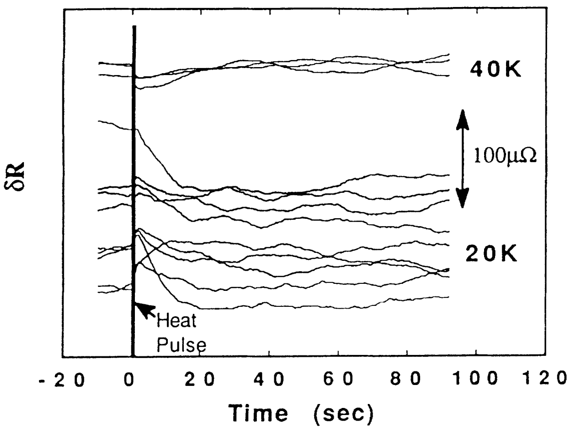

FIG. 1. The effects of rapid (about 100 msec) thermal cycling to about 60 K on R are shown for base temperatures of 20 K (below T_G) and 40 K (above T_G) for a sample with $R \approx 25\ \Omega$. The systematic changes for times of under 20 sec after the pulse are from the recovery of the electronics from the pulse. At 40 K cycling gives no detectable variation above the noise, in sharp contrast to the 20-K behavior.

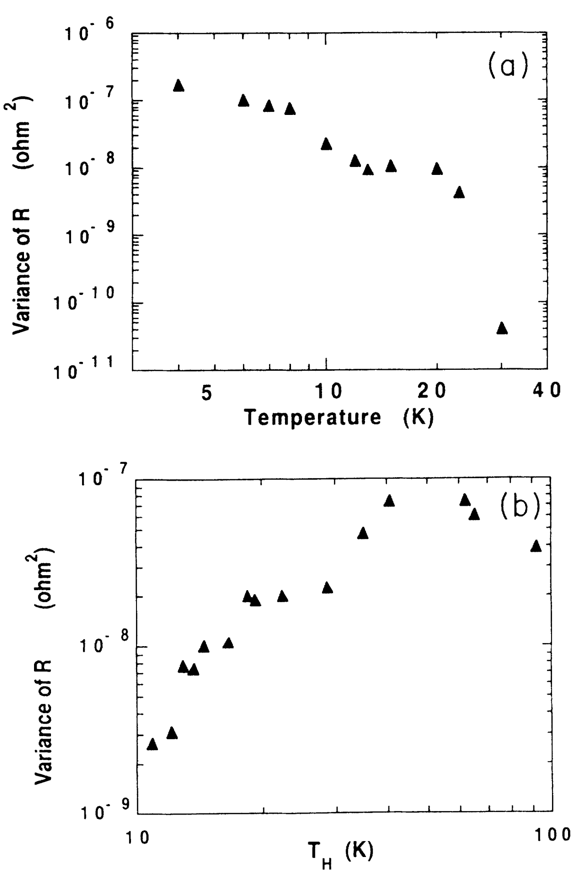

FIG. 2. The variance in R after quick cycles up to T_H is shown as a function of the base temperature and T_H. Each point comes from a variance taken from about 20 cycles, and thus has a standard deviation of about 30%. (a) With $T_H \approx 60$ K, $\langle(\delta R)^2\rangle_E$ (the excess variance above thermal noise) is shown as a function of the measurement temperature. (b) The $\langle(\delta R)^2\rangle_E$ with $T = 6$ K is shown as a function of T_H.

$\langle(\delta R)^2\rangle$ to saturate, since ΔT will change spin correlations on length scales greater than L_Δ while a full statistical sampling of smaller scale rearrangements will occur as spontaneous thermal fluctuations. Some relevant lengths are $L_I(13\ K) \approx 11$ nm, $L_I(19\ \text{K}) \approx 9$ nm,[9] and, if the groups of spins flipping coherently are compact droplets, L_E (18 K)≈ 15 nm and L_E (12 K)≈ 12 nm.[7,9] For $T = 6$ K, we then expect $\langle(\delta R^2)\rangle$ to grow slowly for T_H below about 10 K, at which point there should be a rather rapid rise to near saturation. We find instead that $\langle(\delta R^2)\rangle$ grows smoothly as a function of T_H, with no sign of a threshold for small $T_H - T$ or of saturation below $T_H \approx T_G$.

Thus, contrary to what might have been guessed from a droplet scaling picture, there was no indication that a particular length or time scale was associated with a particular Δ. On the other hand, there was unmistakable evidence that at each temperature many metastable states were available.

In the slow cycling, T was varied between 13 and 19 K sinusoidally at about 2×10^{-3} Hz by modulating the set point for the temperature control of the cryostat cold finger. The time constant of the cold finger was about 10 sec, and the temperature-sensing diode was located directly behind the sample, so there should be very little phase lag between the measured and actual T. Because the residual resistance of the mesoscopic arm was greater than that of the other arm, a systematic bridge imbalance voltage developed as a function of T. This was removed by subtracting the best quadratic fit to $R(T)$. Figure 3 shows typical results for the remainder $\delta R(T)$, which of course includes the ordinary $\delta R(t)$. During these cycling experiments $\langle[\delta R(T)]^2\rangle = 15 \times 10^{-10}\ \Omega^2$. As one would guess by looking (in Fig. 3) at comparable data taken on the same time scale at fixed T, this value is slightly larger than that found when no temperature changes are applied. At 17 K, using the identical measuring setup, $\langle[\delta R(t)]^2\rangle = 10 \times 10^{-10}\ \Omega^2$. This value is only weakly sensitive to T. Some increase on cycling is to be expect-

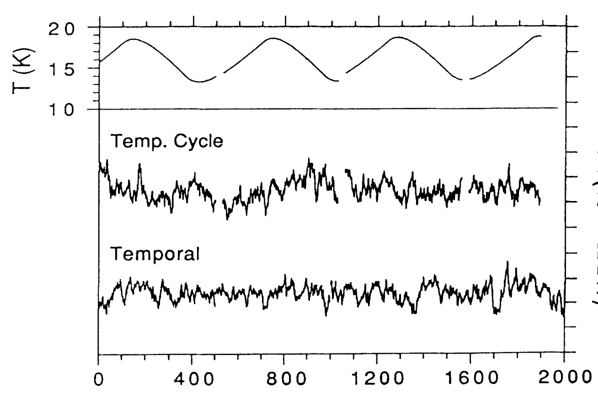

FIG. 3. The top trace shows the sinusoidal temperature variation vs time for the slow cycling. The resistance vs time during this cycling is shown in the middle trace. A similar plot of resistance at fixed $T = 17$ K is shown in the bottom trace. Small gaps in the records result when the computer is recording the stored data.

ed, since it is well known that SG noise and χ'' temporarily increase after the temperature is lowered.[12]

In the slow cycling experiments, $L_E > L_I$, so that a near-equilibrium interpretation of the results is natural. Thus in a droplet picture we would expect a reproducible $\langle [\delta R(T)]^2 \rangle$ at least comparable to that obtained after thermal cycling to above T_G. The random $\delta R(T)$ should not be removed by the quadratic fit to the residual systematic imbalance, because in this range the expected minimum Δ required to scramble δR (i.e., to make $L_\Delta < L_I$) is only about 1.2 K, from Eq. (2).

We found no evidence of any correlation between $\delta R(T)$ on different sweeps—the variance of the average of $\delta R(T)$ over the different sweeps is about $2\times10^{-10}\ \Omega^2$, compared with the net variance on cycling to above T_G of 50 to $100\times10^{-10}\ \Omega^2$ in the temperature range 13–19 K. Thus we have not confirmed the prediction of FBLM that the full random δR can be found by changing T by a small amount predictable from scaling exponents.

We briefly mention a final qualitative result. Initial noise experiments on mesoscopic samples used such big currents that several K heating occurred periodically at a frequency twice that of the applied current (about 1 kHz). We were unable to find consistent differences in the noise spectrum or the high-order statistical behavior of the noise between data taken under these conditions and data taken with dc bias or smaller ac biases. Without claiming any quantitative rigor (even at the modest level of the preceding points), we believe that this result also suggests that the equilibrium spin configuration does not change as abruptly as a function of T as expected from the droplet scaling picture.

In conclusion, we did not find the effects predicted by the simple scaling picture used by FBLM. We did find that at any given temperature, the spin configuration could land in a large number of metastable states with different resistances. These states then differ not only globally, but also on a scale of L_I or smaller, which is consistent with the sort of picture that arises from the Parisi solution.[13] If the spin configuration changed more as a function of T than it would change anyway as a function of time, that effect was not dramatic.

One interpretation, in agreement with detailed analysis of the noise fluctuation statistics,[9] would be that the droplet scaling picture is simply inapplicable to *Cu*Mn in the regime we studied. However, other less drastic interpretations are possible. Some assumptions of the scaling picture used by FBLM are oversimplified, notably that a narrow distribution of characteristic times would be found for a given length scale. Dimensionless prefactors in Eq. (2) could make L_Δ larger than expected. Perhaps more importantly, the spatial structure of the spin correlations affecting the UCF δR (other than the cutoff at L_I) has not been worked out. If the dependence of δR on the correlation between two spins were a sharply enough decreasing function of the distance between them, the thermally chaotic states would be hard to detect because one would require a much smaller L_Δ than originally estimated.[1]

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