Evidence for Power-Law Spin-Correlation Decay from Muon Spin Relaxation in *Ag*Mn Spin-Glass

D. E. MacLaughlin and L. C. Gupta [a]
University of California, Riverside, California 92521

and

D. W. Cooke, [b] R. H. Heffner, M. Leon, and M. E. Schillaci
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

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Muon spin relaxation measurements have been carried out below the "glass" temperature T_g in *Ag*Mn spin-glasses. The muon spin-lattice relaxation rate varies with field H as $H^{-0.46\pm0.05}$ for $0.30 \leq T/T_g \leq 0.66$. This suggests that impurity-spin correlations decay with time as $t^{-\nu}$, $\nu \simeq 0.54 \pm 0.05$ in contrast to the more usual exponential decay. The present data therefore agree quantitatively with the prediction $\nu \simeq \frac{1}{2}$ of mean-field dynamic theories.

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There is a great deal of experimental and theoretical interest in the effects of random exchange interactions upon the dynamic properties of magnetic systems.[1] In simple models of *nonrandom* magnetic systems, the spin autocorrelation function typically exhibits decay with an *exponential* time dependence outside the critical region.[2] By contrast, the recent calculations of Sompolinsky and Zippelius[3] for a *disordered* (spin-glass) system show that the correlation function decays *algebraically* in time, in agreement with earlier Monte Carlo simulations.[4] It is therefore of considerable interest to try to distinguish experimentally the effects of disorder upon the spin dynamics.

The theoretical approach to spin-glass dynamics has been varied. Harmonic excitations (spin waves in nonrandom magnets) have been studied theoretically in more or less realistic models,[5] with some success in explaining the magnetic specific heat. Other theories,[3,6] which use Langevin equations to represent the dynamics of the Edwards-Anderson model,[7] approach the problem from a more phenomenological viewpoint. The theory of Sompolinsky and Zippelius is a mean-field theory of the latter kind, in which both slow and rapid spin-glass dynamics are treated consistently. This theory identifies time-dependent order parameters (which vanish over arbitrarily long times), and also predicts short-time properties such as spin response and correlation functions. A remarkable property of the response function is that it vanishes *algebraically* with frequency ω (as ω^{ν}, with $\nu \leq \frac{1}{2}$ for dynamic stability) for $T \leq T_g$. The fluctuation-dissipation theorem then gives a noise spectrum (Fourier transform of the spin correlation function) which diverges at low frequencies as $\omega^{\nu-1}$, yielding spin correlations which decay in time as $t^{-\nu}$. Earlier mean-field dynamic theories[6] also gave algebraic decays, with $\nu=\frac{1}{2}$, but used low-order approximations and a static (therefore suspect) definition of the order parameter.

This Letter reports the results of longitudinal-field muon spin relaxation (μSR) experiments in the spin-glass *Ag*Mn, which give evidence for the algebraic correlation decay predicted by the mean-field dynamic theories for disordered systems. Information from other experimental techniques is scanty below T_g, although neturon-scattering,[8] ESR,[9] and μSR[10,11] experiments have studied fluctuations as T_g is approached from above. The recent zero-field NMR experiments of Alloul, Murayama, and Chapellier[12] in the spin-glass *Cu*Mn bear directly on the form of the decay well below T_g, however, and will be required to interpret the μSR data.

Our results may be summarized as follows:

(1) The positive-muon (μ^+) spin-lattice relaxation rate $\lambda_{\parallel}$ varies as $H^{\nu-1}$, with $\nu = 0.54 \pm 0.05$, over a wide range of fields, for $0.3 < T/T_g < 0.7$, and for several Mn concentrations. Here H is an effective field as explained below. On general grounds we expect $\lambda_{\parallel} \propto J(\omega_{\mu})$, where $J(\omega)$ is the noise spectrum of fluctuating dipolar fields produced at μ^+ sites by Mn spins and ω_{μ} is the μ^+ Larmor frequency. Thus the field dependence of $\lambda_{\parallel}$ gives the functional form of $J(\omega)$, *if* the external field $H_{\parallel}$ does not affect the functional form of $J(\omega)$ directly. The zero-field NMR results[12]

are consistent with the *same* functional form of $J(\omega)$ obtained from the field dependence of $\lambda_{\parallel}$, at least for $T \ll T_g$, and therefore support this condition. Our data provide the first experimental evidence, to our knowledge, that spin correlations decay algebraically in spin-glasses below T_g. The observed value of ν at $T \ll T_g$ is within experimental error of that obtained from dynamic theories.[3,6]

(2) The field dependence of $\lambda_{\parallel}$ for $T/T_g \simeq 0.9$ is approximately $H^{-0.76}$, which yields $\nu \simeq \frac{1}{4}$. This result is *not* in agreement with the dynamic theories, which predict $\nu(T_g) = \frac{1}{2}$. It may be, however, that $J(\omega)$, like the low-field ac susceptibility,[1] is directly affected by the applied field near T_g, where corroborating zero-field NMR data are not available.

(3) A scaling law of the form

$$\lambda_{\parallel} = x^2 f(T/T_g, H/T_g)/T_g, \tag{1}$$

where x is the Mn concentration and $f(u, v)$ is a dimensionless function, is obeyed. This form is expected for dilute spin-glasses, where the dipolar coupling (which enters the relaxation rate as a matrix element squared) scales as x, and spin-glass energies (and frequencies) scale as T_g.[13] Dimensional analysis then yields Eq. (1).

$Ag_{1-x}Mn_x$ alloys, with $x = 1.6$, 3, and 6 at.%, were prepared by arc melting, followed by a homogenizing anneal and quenching. A sharp cusp in the ac susceptibility was observed at the glass temperature T_g of each sample. Details of sample characterization will appear in a forthcoming article. μSR experiments were carried out at the Clinton P. Anderson Meson Physics Facility (LAMPF) at Los Alamos National Laboratory. It has been determined[14] that implanted μ^+ are essentially immobile in silver below ~200 K and occupy interstitial sites at random,[10] and that the coupling between Mn and μ^+ spins is predominantly dipolar.[10] Data were taken for 0.15 kOe $\leq H_{\parallel} <$ 5 kOe, and 2 K $\leq T \leq T_g$.

In addition to the applied field $H_{\parallel}$, the local dipolar fields contribute to the *total* static field seen by the muon. When averaged over all μ^+ sites, the local field is Lorentzian[15] with a width Δ which is known[10] from zero-field μSR measurements. [$\Delta \simeq 230$ Oe for *Ag*Mn(1.6 at.%).] In order to approximate the effects of Δ, we take the effective field H at the muon site to be $(H_{\parallel}^2 + \Delta^2)^{1/2}$. Note that the meaured Δ depends upon temperature,[10] analogous to the magnetization in an ordered magnet.

The data yield an experimental μ^+ spin-lattice relaxation function $G_{\parallel}(t)$.[10,11] The form of this function in spin-glasses is not obvious, because of random inhomogeneity in the dipolar coupling and, possibly, in the noise spectrum $J(\omega)$ itself. In addition, the statistical properties of the Mn-spin fluctuations and the resulting fluctuations of the μ^+ dipolar field are not necessarily the same. On very general grounds, however,[16] the rate W_i of transitions between spin states of a μ^+ at the ith site is

$$W_i \simeq [\omega_{\mathrm{dip}}(i)]^2 J_i(\omega_{\mu i}), \tag{2}$$

where $\omega_{\mathrm{dip}}(i)/\gamma_{\mu}$ is the dipolar field at the ith μ^+ site (γ_{μ} is the μ^+ gyromagnetic ratio), $\hbar\omega_{\mu i}$ is the μ^+ Zeeman splitting, and $J_i(\omega)$ is the noise spectrum of the fluctuating field. The effects of inhomogeneity in $\omega_{\mathrm{dip}}(i)$ and possible inhomogeneity in $J(\omega)$ remain, however, and are difficult to estimate, particularly for spatially correlated Mn-spin fluctuations.

The problem of a random fluctuating field also arises in μ^+ and nuclear spin-lattice relaxation in dilute alloys containing paramagnetic impurities,[10,17] where an average over environments of μ^+ or nuclear spins yields the "root" exponential form

$$G_{\parallel}(t) \propto \exp\{-(\langle W_i \rangle t)^{1/2}\}. \tag{3}$$

Here $\langle W_i \rangle$ is an average of W_i over the spatial disorder. We have chosen to fit our data by the root-exponential form, with $\lambda_{\parallel} = \langle W_i \rangle$, to take crude account of the random dipolar field. This typically gives fits comparable to or better than fits with the exponential function $\exp(-\lambda_{\parallel} t)$.

We believe that uncertainty in the functional form of $G_{\parallel}(t)$ does not invalidate our basic conclusions, because the time scale of the relaxation is in any case set by $\langle W_i \rangle^{-1}$. Nevertheless, such uncertainty could introduce an unknown systematic error into the value of ν.

Complex short-time behavior of $G_{\parallel}(t)$, due to static components of the μ^+ dipolar fields, sets in for $H_{\parallel} < \Delta$. This problem was dealt with in the fitting of $G_{\parallel}(t)$ by excluding data from the short-time region $t \lesssim (\gamma_{\mu}\Delta)^{-1}$, so that only spin-lattice relaxation processes contribute to the fitted data.

Figure 1 gives scaled isotherms $\lambda_{\parallel}(H)$ for a number of temperatures below T_g. Scaling behavior [Eq. (1)] is quite well obeyed. These data were fitted by two functional forms: A Lorentzian distribution (corresponding to an exponential correlation function) and a power law, $\lambda_{\parallel} \propto H^{\nu-1}$. The data for $0.3 \leq T/T_g \leq 0.66$ show a nearly temperature-independent value for ν: $\nu = 0.54 \pm 0.05$.

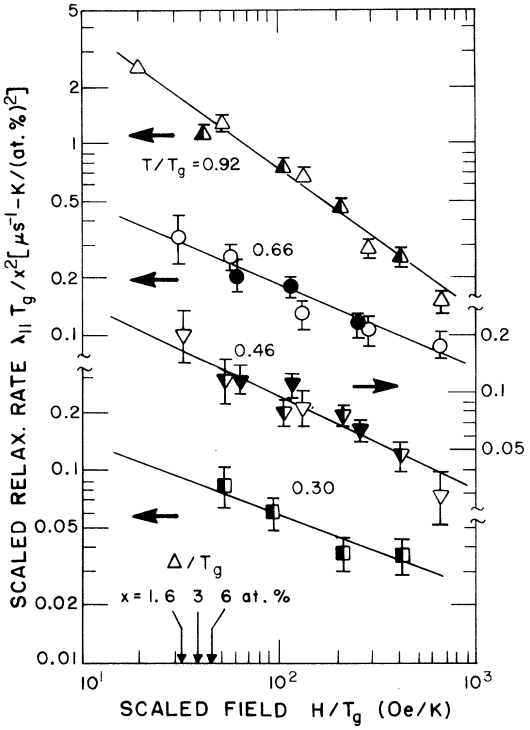

FIG. 1. Scaled isotherms of μ^+ spin-lattice relaxation rate $\lambda_{\parallel}$ vs effective longitudinal field H, for temperatures below T_g in $Ag_{1-x}Mn_x$ spin-glasses. Open symbols: $x = 1.6$ at.%. Half-filled symbols: $x = 3$ at.%. Filled symbols: $x = 6$ at.%. Least-squares fits with a power law are shown for each scaled temperature T/T_g. Scaled widths Δ/T_g of the μ^+ dipolar field distributions for the various Mn concentrations are shown by arrows on the horizontal axis.

For each temperature the power-law fit gave a smaller value of reduced χ^2 than the Lorentzian form (Table I). The confidence level (P) arising from fits to all of the data below $T/T_g = 0.66$ (allowing separate values of ν at each temperature) is $P = 0.8$ for the power law and $P = 0.015$ for the Lorentzian forms. Here P is defined[18] as the probability of obtaining a given χ^2 from the correct fitting function. Thus the choice of a power law is statistically significant. At $T \approx 0.9 T_g$, we find a smaller value, $\nu = 0.24 \pm 0.02$. Here χ^2 for the power-law fit is high ($P \simeq 0.01$), but χ^2 for the Lorentzian fit is so much higher that a power law clearly gives a much better approximation to the data.

Sensitivity to the assumed form of $G_{\parallel}(t)$ was tested by fitting the data with an exponential function. This procedure yielded relaxation rates (not shown) which also exhibited a power-law field dependence, with somewhat larger values of ν than obtained from the root-exponential fits. The scaling behavior of these results was poor, however, which suggests that a root-exponential form for $G_{\parallel}(t)$ is a better choice than an exponential form.

TABLE I. Values of the exponent ν obtained from power-law fits to the field dependence of $\lambda_{\parallel}$ (see Fig. 1). Values of reduced χ^2 for the power-law fits $[(\chi^2)_{pl}]$ and for fits by a Lorentzian functional form $[(\chi^2)_{Lor}]$ are also shown.

T/T_g	ν	$(\chi^2)_{pl}$	$(\chi^2)_{Lor}$
0.92	0.24 ± 0.02	2.62	24.1
0.66	0.55 ± 0.07	0.653	3.12
0.46	0.51 ± 0.07	0.808	1.06
0.30	0.59 ± 0.15	0.445	1.91

μSR data alone cannot determine whether the applied field affects $J(\omega)$ directly. Corroborating evidence for no direct effect of field comes from the zero-field NMR spin-lattice relaxation measurements of Alloul, Murayama, and Chapellier[12] in *Cu*Mn spin-glasses. The hyperfine couplings between Mn spins and ^{63}Cu nuclei in near-neighbor shells around Mn sites could be obtained from the NMR frequencies ω_{hf}. Then the (transverse) NMR spin-lattice relaxation rate $1/T_2$ is given by

$$1/T_2 \simeq (\omega_{hf})^2 J(\omega_{hf}) \propto (\omega_{hf})^{\nu+1}, \quad (4)$$

where the last proportionality follows from the assumed form of $J(\omega)$. Although the data are only available for two near-neighbor NMR lines,[12] a power law fits the above dependence of $1/T_2$ on ω_{hf} with $\nu = 0.4 \pm 0.2$. This is in reasonable agreement with the μSR results given above. We conclude that the data are consistent with a field-independent $J(\omega)$, noting, however, that the NMR data are available only for $T \ll T_g$. A field-independent $J(\omega)$ is expected, after some assumptions, from the theory of Sompolinsky and Zippelius.[3]

The power-law fit to the data for $T/T_g = 0.92$ yields a considerably smaller value of ν than found at lower temperatures. (It has been noted previously[10] that $\lambda_{\parallel}$ is inversely proportional to field at $T = T_g$.) We cannot conclude that the prediction $\nu(T_g) = \frac{1}{2}$ of the dynamic theories is incorrect, however, because the field may affect $J(\omega)$ directly. Neutron spin-echo results[8] near T_g are consistent with our μSR results, but do not constrain the value of ν enough to indicate a contradiction with theory.

The present results call for further theoretical

work. A calculation of $G_{\parallel}(t)$ which includes effects of spatial inhomogeneity and correlation in all relevant quantities is clearly required. The most fundamental question, perhaps, is whether algebraic correlation decays can be obtained from more realistic models.

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[a]Permanent address: Tata Institute of Fundamental Research, Bombay 400 005, India.

[b]Permanent address: Memphis State University, Memphis, Tenn. 38152.

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