Time decay of the saturated remanent magnetization in a metallic spin glass

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The time decay of the saturated remanent magnetization (M_s) has been studied in the amorphous metallic spin glass $(Fe_{0.15}Ni_{0.85})_{75}P_{16}B_6Al_3$. This relaxation, which by nature is different from the zero-field equilibrium relaxation, shows at low temperatures ($T/T_g < 0.98$) a time variation accurately described by a pure power law. At temperatures in the immediate vicinity of T_g, the experimental time decay can be described by a power law times a stretched exponential functional form: $M_s = M_0 t^{-m} \exp[-(t/\tau_p)^{1-n}]$.

Spin glasses are known to exhibit slow, nonexponential relaxation. This kind of dynamical behavior is a characteristic feature of disordered, strongly interacting systems of condensed matter. The response function of dielectrics,[1] glasses, and glassy polymers[2] resembles that of spin glasses. In particular, it has been experimentally shown that spin glasses display aging phenomena,[3-7] a behavior that is well known from other glassy materials.[2] This implies that the spin-glass "phase" is a thermodynamic nonequilibrium state. In spin glasses aging is revealed by a dependence of the response function on the wait-time t_w prior to the magnetic field step. Especially in the low-field regime the relaxation in a time-domain experiment is dominated by the aging process. This has been experimentally shown in low-field thermoremanent[4-7] and zero-field-cooled[3,4] magnetization measurements. Only at times $t \ll t_w$, the experimental data are representative of a spin-glass relaxation at thermodynamic equilibrium.[3] Thus, comparisons between experiments and theoretical predictions are quite hazardous, since theories[8] only treat spin-glass dynamics at thermodynamic equilibrium. However, the functional form of the relaxation is affected by the magnitude of the applied magnetic field. At sufficiently high fields a thermodynamic equilibrium state is imposed and the decay of the thermoremanent magnetization becomes field and wait-time independent.[9] This time decay of the saturated remanent magnetization is by nature different from the zero-field equilibrium relaxation. The influence of the wait-time and the magnitude of the applied magnetic field on the relaxation require well-defined experimental procedures when searching for a universal functional form of the spin-glass relaxation.

In this Brief Report we investigate the time decay of the saturated thermoremanent magnetization of the amorphous metallic spin glass $(Fe_{0.15}Ni_{0.85})_{75}P_{16}B_6Al_3$. It is found that the time decay accurately follows a pure power law below the spin-glass freezing temperature (T_g). In the immediate vicinity of T_g the functional form of the decay changes and is described by a power law times a stretched exponential form.

Ribbons of the amorphous system $(Fe_xNi_{1-x})_{75}P_{16}B_6Al_3$, were prepared by the centrifugal spin-quenching technique.[10] The magnetic phase diagram and general magnetic properties of this system have been reported elsewhere.[11] Amorphous ribbons with a nominal concentration of $x = 0.15$ and a typical cross section of 0.02×1 mm^2 were cut in pieces 5 mm long. The temperature was measured with a copper thermometer[12] ($T > 20$ K) and with a 100-Ω Allen-Bradley carbon resistor ($T < 20$ K). A superconducting quantum-interference device (SQUID) magnetometer utilizing the S.H.E. Corporation Model-30 electronic system was used to measure the time decay of the thermoremanent magnetization (TRM). The measurements were performed in the temperature range $0.50 < T/T_g < 1.02$, where $T_g = 22.6$ K as determined from static scaling experiments on the same spin-glass sample.[13] The sample was cooled from the reference temperature $T_{ref} = 23.8$ K in a constant magnetic field (50–300 G) to the measurement temperature. The magnetic field was then switched off and the time decay of the saturated remanent magnetization (M_s) was measured in the time interval $3-3 \times 10^4$ sec. The sample was then heated to T_{ref}, where the zero value of the magnetization was established. The intrinsic relaxation of the magnetometer after a field step was measured at T_{ref} and found to be negligible for $t > 3$ sec. The switch time of the magnetic field is shorter than 0.01 sec.

In Fig. 1 $M_{TRM}(H)$ is plotted for different observation times t at the temperature $T/T_g = 0.96$. Also visualized in the figure is the field dependence of the isothermal remanent magnetization $M_{IRM}(H)$. $M_{IRM}(H)$ was measured by cooling the sample in zero applied magnetic field to the measurement temperature. A magnetic field pulse of 30-sec duration was applied and the time decay of the remanent magnetization was measured after the field removal. As is seen from Fig. 1, the $M_{IRM}(H)$ and $M_{TRM}(H)$ curves merge at fields larger than 10 G and become field independent at fields larger than 20 G. Since the experimental values of $M_{TRM}(H)$ and $M_{IRM}(H)$ are identical at sufficiently large magnetic fields it implies that an equilibrium state is imposed on the system by the field. Thus the time decay of the saturated remanent magnetization is independent of the magnitude of the applied field and the wait-time history of the sample.[14]

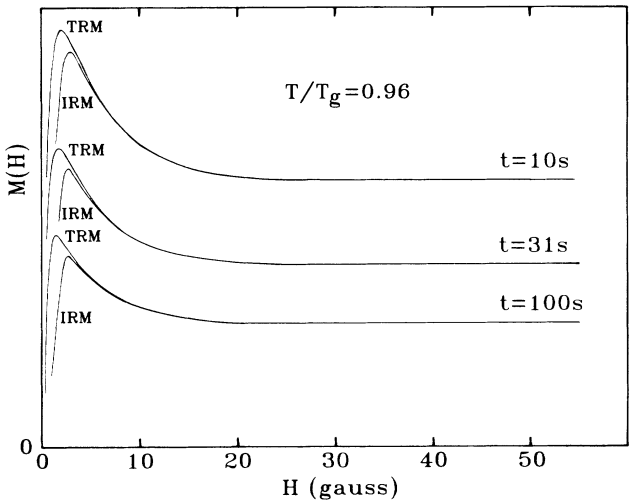

FIG. 1. Remanent magnetization of $(Fe_{0.15}Ni_{0.85})_{75}P_{16}B_6Al_3$ at 21.7 K ($T/T_g=0.96$). The thermoremanent magnetization (TRM) and isothermal remanent magnetization (IRM) at $t=10$, 31, and 100 sec after the field removal are shown.

In Fig. 2 the time decay of the saturated remanent magnetization is plotted in a semilogarithmic diagram for different temperatures. In Fig. 2(b) the veritical scale is enlarged by a factor of 80. The magnitude of the saturated remanent magnetization decreases rapidly with increasing temperature. At T_g the value of the remanence at $t=3$ sec is only a fraction of a percent of the corresponding value at low temperatures. In an experiment it is exceedingly difficult to pinpoint the zero level of the remanent magnetization. Due to the extreme smallness of the remanence at high temperatures only a minor deviation from the true zero level has a devastating influence on the shape of the time decay when plotted in a log-log diagram. In order to give an adequate presentation of the experimental data, the time derivative of the remanent magnetization, determined from a sliding five-point differentiation of the raw data, is plotted in a log-log diagram in Fig. 3. At temperatures $T/T_g<0.98$, in the time window of our experiments, the relaxation accurately follows a power law:

$$M_s=M_0t^{-m} . \tag{1}$$

It has been suggested that a stretched exponential functional form, $\exp[-(t/\tau_p)^{1-n}]$, accurately describes the time decay of the thermoremanent magnetization.[15] Fits of our experimental data to a pure stretched exponential form give $n=1.00\pm0.01$ for all temperatures $T/T_g<0.98$. Such a value of the exponent n implies that the time decay is algebraic, thus supporting the power-law decay of the remanent magnetization. Using a rather high magnetic field an algebraic decay of the thermoremanent magnetization has also been reported at temperatures well below the spin-glass freezing temperature for the short-range Ising spin glass $Fe_{0.5}Mn_{0.5}TiO_3$.[16]

The measured relaxation starts to deviate from a pure power law at temperatures in the vicinity of the spin-glass freezing temperature ($T/T_g>0.98$) but can accurately be

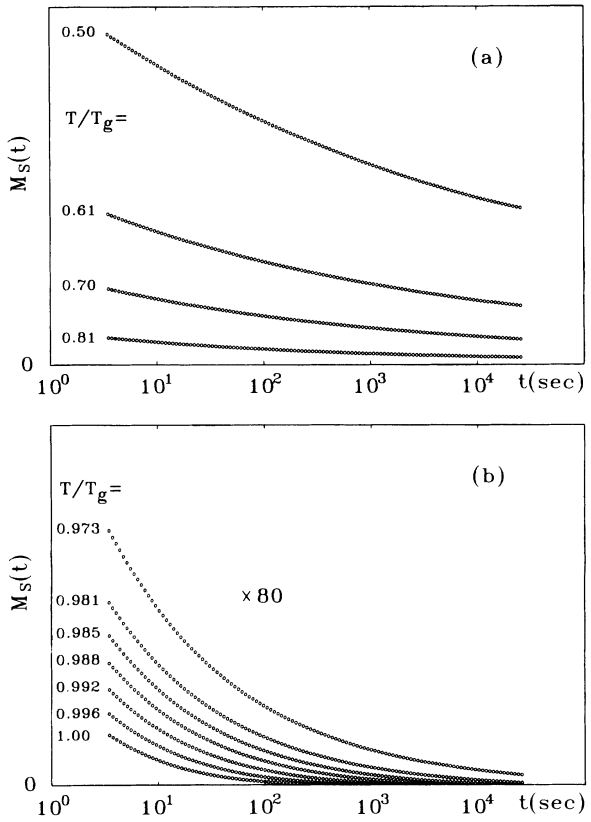

FIG. 2. Time decay of the saturated remanent magnetization of $(Fe_{0.15}Ni_{0.85})_{75}P_{16}B_6Al_3$ in a semilogarithmic diagram (a) $0.50<T/T_g<0.81$, (b) $0.973<T/T_g<1.00$. The vertical scale is enlarged by a factor of 80.

described by the following empirical functional form:

$$M_s=M_0t^{-m}\exp[-(t/\tau_p)^{1-n}] . \tag{2}$$

The parameters m, n, and τ_p were determined by nonlinear regression analyses of the data to Eq. (2). The solid lines in Fig. 3 are plotted using the deduced parameters. To ac-

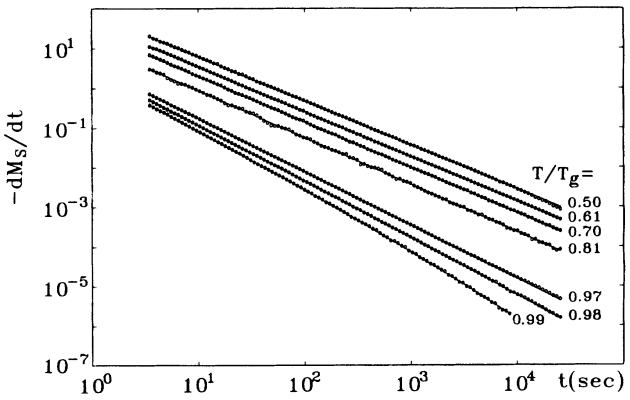

FIG. 3. $\log(-dM_s/dt)$ vs $\log(t)$ at different temperatures. Solid lines are the best fits of the experimental data to Eq. (2).

count for the uncertainty in the zero level of the measured remanence, the fitting function also included an additative constant. In Fig. 4 the temperature dependence of the parameters m, n, and τ_p are plotted as a function of the reduced temperature. As can be seen from the figure, τ_p increases very rapidly with decreasing temperature, and is beyond the experimental time window at temperatures $T/T_g < 0.98$. Accordingly, only a power law is found. In a very limited temperature interval close to the spin-glass freezing temperature, $0.98 < T/T_g < 1.00$, both terms in Eq. (2) could be resolved in the analyses. At slightly higher temperatures the stretched exponential becomes predominant and the value of the parameter m loses significance. On further increase of the temperature ($T/T_g > 1.02$) all relaxation occurs at shorter times than our time window.[17]

Recently, Ogielski[18] has performed Monte Carlo (MC) simulations in order to investigate the dynamics of the equilibrium fluctuations of a short-range three-dimensional (3D) Ising spin glass at zero magnetic field. He obtains for the spin-spin correlation function $q(t)$ a time decay of the same functional form as in Eq. (2). At temperatures below the spin-glass freezing temperature the simulations only yield a power-law decay. Although the agreement with our results is striking a direct comparison is incorrect due to the fundamentally different nature of the time decay of the saturated remanent magnetization and the zero-field equilibrium relaxation. The experimental quantities that directly mirror $q(t)$ at zero field are the frequency dependence of the zero-field ac susceptibility and the low-field equilibrium relaxation of the zero-field-cooled and the thermoremanent magnetization. The behavior of the zero-field equilibrium relaxation of the same amorphous metallic spin glass will be reported in a forthcoming publication.[19] A more adequate comparison between the present experimental survey and MC simulations is obtained from simulations performed by Kinzel.[20,21] He investigated the time decay of the remanent magnetization and its field dependence of a short-range 2D Ising spin glass[20] and an infinite-range Ising spin glass.[21] In these simulations it is found that the time decay of the saturated remanent magnetization follows a power law, a result in agreement with the present experimental study.

Conclusively, the functional form of the time decay of the saturated remanent magnetization is accurately described by a power law times a stretched exponential form [Eq. (2)]. Due to a limited experimental time window and the rapid temperature variation of τ_p the stretched exponential term is only resolved in a very narrow temperature interval in the immediate vicinity of the spin-glass freezing temperature. For a given temperature, the value of τ_p is a measure of the time at which the relaxation process ends. Thus, in some way the rapid increase of τ_p reflects the divergence of the maximum relaxation time of the system at zero field.[17] At low temperatures the measured relaxation is purely algebraic.

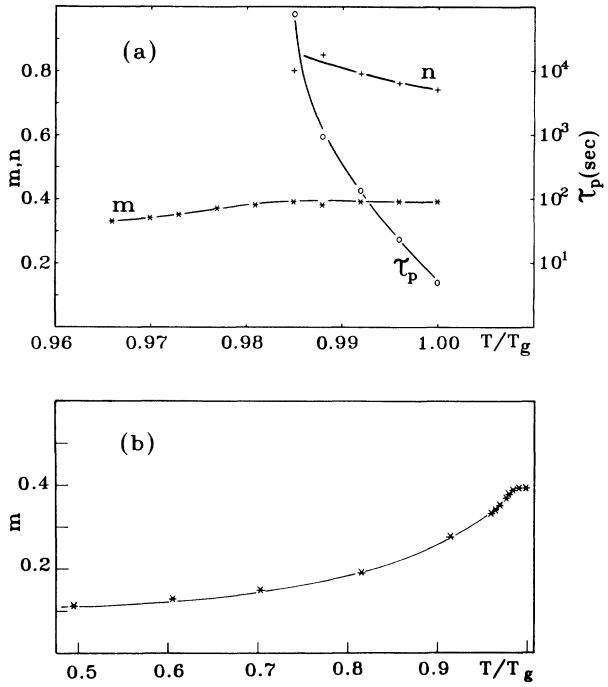

FIG. 4. The parameters m (*), n (+), and τ_p (○) of Eq. (2) plotted vs reduced temperature. (a) Close to T_g. (b) The parameter m plotted in a larger temperature interval.

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[14]The minimum amplitude of the applied field (H_s) needed to ensure saturated remanent magnetization is a strongly material-dependent quantity. H_s increases rapidly on decreasing temperature. To measure the time decay of the saturated remanent magnetization it is thus often necessary to use very high applied magnetic fields. The switch-off time for large fields is generally not negligible. It is therefore difficult to define a correct start time for the measured relaxation. Since this definition is of paramount importance for the deduced functional form, it is only relevant to use data at times much longer than the switch-off time for the field (in a logarithmic time perspective) when analyzing the data.

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