Dynamical studies on model spin glasses

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Abstract. The dynamical magnetic properties of a Cu(Mn) Heisenberg spin glass have been investigated by SQUID magnetometry. The zero-field-cooled magnetization has been recorded as a function of the temperature and time after specific cooling protocols, in order to study in detail the so-called memory effect displayed by spin-glasses.

Introduction
As illustrated recently, the non-equilibrium properties of spin glasses [1, 2, 3] can be investigated by recording the temperature-dependent magnetization on reheating after spin configurations are imprinted while stopping at constant temperatures $T_s$ while cooling under the spin-glass phase transition temperature $T_g$. These equilibrations, or agings, are kept in memory on further cooling are retrieved on reheating. Due to the chaotic nature of the spin-glass phase, this memory of the equilibration at $T_s$ is observed only in a finite temperature range around $T_s$, defining memory dips with a finite width. Outside this temperature range, the magnetization recovers its reference level and the system is rejuvenated.

It is helpful to understand in detail the results of such experiment in order to apply it to new spin-glass model systems[4, 5, 6, 7] or other frustrated or glassy materials[8, 9, 10]. We here investigate the temperature-dependent magnetization of a Heisenberg-like Cu(Mn) spin glass, recorded after specific protocols on a home-built squid magnetometer.

Results and discussion
So-called dc-memory experiments can be performed on the zero-field-cooled (ZFC), or theremo- remanent (TRM) magnetizations [1]. The aging phenomenon is illustrated in Fig. 1, which shows ZFC, FC (field-cooled) and TRM relaxation curves recorded after waiting for $t_w = 3s$ and $t_w = 3000s$ before starting recording the magnetization. Note that the here employed magnetic field $H$ is used only as a probe of the system, and the principle of superposition and linear response apply [11]. One can notice in Fig. 1 that at an observation time of about 30s, corresponding to the effective observation time of the magnetization measurement on heating, the ZFC and TRM curves recorded after a 3000s stop lies significantly below (resp. above) the curve recorded nearly immediately ($t_w = 3s$) after reaching $T_m$. The FC magnetization shows in this context marginal relaxation behavior, and we essentially have $M_{FC}(t) - M_{ZFC}(t) \sim M_{TRM}(t)$ [1].

As suggested by the above relaxation measurements, the temperature-dependent measurements also reflect the aging occurring while the system is kept at a constant temperature. As seen in Figure 2, the state equilibrated during the halt is kept in memory and retrieved...
Figure 1. Time \( t \) dependence of the ZFC, FC and TRM magnetization \( M \), plotted as \( \Delta M = M - M(t = 0.3 s) \). The magnetization is recorded after rapidly cooling down the system to \( T_m = 40 \text{ K} \) below \( T_g \) in zero magnetic field (ZFC) or \( H = 0.5 \text{ Oe} \) (FC, TRM). After a wait time \( t_w \), the magnetic field is set to \( H = 0.5 \text{ Oe} \) (ZFC) or kept to \( 0.5 \text{ Oe} \) (FC) or switched from \( 0.5 \text{ Oe} \) to zero (TRM), and the magnetization is recorded as a function of time. The vertical dotted line indicates the experimental time scale of temperature-dependent measurements.

Figure 2. Temperature \( T \) dependence of the ZFC, FC, and TRM magnetization. The \( M(T) \) curves are measured on reheating after cooling the sample to the lowest temperature directly (open symbols) or including a stop at \( T_S = 40 \text{ K} \) for a time \( t_S = 3000 \text{ s} \) (filled symbols). A magnetic field \( H = 0.5 \text{ Oe} \) is employed to record the magnetization.

on reheating. As mentioned above, the equilibration affects the magnetization in a finite temperature range, outside of which the system appears younger or rejuvenated[3].

We now focus on the ZFC magnetization, that is recorded while performing thermal cycles [12]. The ZFC curves presented in Fig. 2 measured on reheating after direct cooling or including a 3000s halt at \( T_S = 40 \text{ K} \) while cooling are used as references. These curves are plotted in dotted lines in Figs. 3-5. The ZFC magnetization is recorded on cooling and reheating according to protocols depicted in the schematic drawings shown at the bottom of Figs. 3-4 and associated captions. As seen in the figures, in both types of experiments, the equilibration which occurred during the initial cooling is kept in memory, as observed in temperature cycling experiments on time-dependent dc- or ac-magnetization experiments[2, 3]. All heating curves eventually merge with their respective references, as illustrated more clearly in Fig. 5.

In the experiments depicted in Fig. 3 (lower curve), the magnetization is recorded as soon as the temperature reaches 40K. Hence the measured ZFC magnetization measured on reheating corresponds to that of a “young” system, which has been frozen in as the temperature was lowered to 20K. In the corresponding experiments depicted in Fig. 4 however, the observed system is slightly older, as the final heating curve has been measured after first lowering the temperature to 20 K, warming to 40 K, and again cooling to 20 K. The aging of the system can also be appreciated in the upper curve of Fig. 3, which was recorded after halting the cooling in a field. It can be seen in Fig. 6 that regardless of the halt at 40K during the initial cooling, the reheating curves measured on the younger system merge earlier with the reference than those measured on the older one. In the latter case, a sizable \( \Delta M/H \) is observed up to about 50K.

It is also interesting to note the apparent lack of rejuvenation effects in these experiments.
Figure 3. Temperature dependence of the ZFC magnetization recorded using the cooling protocol (1) schematically illustrated beneath the figure. The system is rapidly cooled to $T_s = 40K$ in zero magnetic field. After a wait time $t_s = 0s$ (middle curve) or 3000s (lower curve), $H = 0.5$ Oe is applied, and the magnetization is recorded on further cooling down to the lowest temperature, and on subsequent reheating above $T_g$. Similar measurements were performed with $H = 0.5$ Oe applied during the 3000s halt (upper curve). The dotted lines are references ZFC curves measured after direct cooling or including a 3000s stop at $T_s=40K$.

Figure 4. Temperature dependence of the ZFC magnetization recorded using the cooling protocol (2) schematically illustrated beneath the figure. The system is cooled to the lowest temperature in zero magnetic field directly (upper curve) or including a 3000s stop at $T_s=40K$ (lower curve). $H = 0.5$ Oe is applied, and the magnetization is recorded on reheating to $T_s$, and while the system is again cooled down to the lowest temperature, and reheated this time above $T_g$. The dotted lines are references ZFC curves measured after direct cooling or including a 3000s stop at $T_s=40K$.

In conventional dc-memory experiments, as shown in Fig. 2, the low-temperature ZFC or TRM magnetization is not affected by the aging at higher temperatures. As seen in the inset of Fig. 6, $\Delta M/H$ is essentially negligible outside the memory dip. However in our thermal cycling experiments the four magnetization curves presented in Fig. 5 are flat at low temperatures, with different magnetization values. These flat low-temperature magnetization curves are reminiscent of the field-blocked field cooled [13] and TRM[12] magnetization, weakly affected by the spin reorganization on short-length scales occuring on cooling.

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**Figure 5.** ZFC magnetization curves measured on reheating after the experiments depicted in Figs. 3 and 4. The dotted lines are reference ZFC curves measured after direct cooling or including a 3000s stop at $T_s=40$K.

**Figure 6.** Main frame: difference plots of the reheating curves depicted in Fig. 5. The inset shows the memory dip corresponding to the difference plots of the reference curves shown in dotted line in Fig. 5 for comparison.

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