Ordering in a spin glass under applied magnetic field

Dorothée Petit, L. Fruchter and I.A. Campbell

Laboratoire de Physique des Solides, Université Paris Sud, 91405 Orsay, France

Torque, torque relaxation, and magnetization measurements on a AuFe spin glass sample are reported. The experiments carried out up to 7T show a transverse irreversibility line in the ($H, T$) plane up to high applied fields, and a distinct strong longitudinal irreversibility line at lower fields. The data demonstrate for that type of sample, a Heisenberg spin glass with moderately strong anisotropy, the spin glass ordered state survives under high applied fields in contrast to predictions of certain "droplet" type scaling models. The overall phase diagram closely resembles those of mean field or chiral models, which both have replica symmetry breaking transitions.

For the infinite dimension or mean field spin glass, there is a true replica symmetry breaking (RSB) phase transition under an applied field with, for Heisenberg spins, a transverse irreversibility onset followed at lower fields by a crossover to longitudinal irreversibility [1,2]. The mean field ($H, T$) phase diagram including the effect of anisotropy has been extensively studied theoretically. It has been strongly argued that the physics of spin glasses below the upper critical dimension $d = 6$ is basically similar to that in infinite dimension [3]. If real spin glasses in dimension three undergo an RSB transition, one should expect to find an in-field phase diagram qualitatively similar to that of mean field. Alternatively if the standard Fisher-Huse scaling (or "droplet") scenario is physically correct, in three dimensions a true transition should exist only in zero field [4] and no irreversibilities should be seen under applied fields. The experimental situation is not clear cut and is complicated by the fact that it has been hard to find a crucial physical measurement to rule out or alternatively to definitively establish the existence of an in-field frozen state. Magnetization experiments have been analysed in terms of transition lines in the ($H, T$) plane [5–7], while susceptibility data (on an Ising like material) have been interpreted as demonstrating an absence of ordering in a finite field [8].

Torque measurements have the advantage of being directly sensitive to transverse irreversibility. The Dzyaloshinski-Moriya (DM) interaction is the source of magnetic anisotropy in spin glasses, leading to torque when an applied field is turned [9]. Because of the special character of the spin glass anisotropy, this torque is observed only if there is a frozen-in spin arrangement. If the spin glass is in a paramagnetic state, meaning that the spins can reorganize themselves locally as soon as the field is turned, there will be no torque for an isotropic polycrystalline sample. The torque criterion for identifying a frozen spin glass state was exploited early on over a restricted field range [10–13], but although the question of spin glass ordering and aging has been addressed by progressively more sophisticated magnetization and susceptibility experiments (see [14] for instance), the torque technique has been neglected; in particular there have been no systematic comparisons of torque and magnetization on one and the same sample over an extended field range. Thus the theoretical predictions have only been incompletely tested. Here we report extensive torque, torque relaxation, and magnetization measurements to high fields on a sample of the archetype spin glass, AuFe. The torque data show a clear transverse irreversibility transition line below which the spin arrangement remains frozen over very long times even under strong applied fields. The magnetization data indicate a quite distinct strong longitudinal irreversibility line. The experimental in-field phase diagram bears a striking qualitative resemblance to that of the Heisenberg mean field model with strong anisotropy [15].

We studied a sample of Au5% Fe prepared by standard metallurgical techniques. AuFe is a Heisenberg spin glass with moderately strong DM anisotropy [16]. The sample was heavily cold worked and then annealed to guarantee homogeneity. The $T_g$ estimated with applied field extrapolated to zero is 20.6K. The torque measurements were performed using a capacity method; applied fields up to 7T were provided by a horizontal superconducting Helmholtz coil. The main experimental difficulty was eliminating parasitic signals arising from the interaction of the sample moment with a residual field gradient from the coils. Magnetization measurements were carried out on a commercial SQUID instrument.

The principal protocol used for the torque measurements was to field cool (FC) the sample in an applied field $H$ to the measuring temperature $T$; once the temperature was established, the field was turned, typically by an angle of 5°. The torque was measured from a few seconds after the field was turned, typically by an angle of 5°. The torque was measured from a few seconds after the turn and for times up to an hour. We will first describe the overall pattern of the torque signals as a function of $H$ and $T$. Fig.6 shows the observed torque values; each point corresponds to a separate FC run. We have chosen to plot the points measured at 30 seconds after the field was turned. Relaxation effects will be discussed later on.

The DM anisotropy is due to a sum of terms of the form $D_{ij}(S_i \wedge S_j)$ [6]. Each time a sample is cooled either in field or in zero field, the spins conspire to minimize the to-
tal spin-spin interaction plus anisotropy energy by taking up an appropriate configuration. Once a rigid configuration has been established, turning it bodily costs energy leading to anisotropy with respect to its original orientation. If the spins can completely rearrange, they can take up a configuration which is different on the microscopic level, so the anisotropy reorients, and the torque disappears. Zero torque thus indicates a paramagnetic state[11].

\[ \theta = H^2 \] because the magnetization is proportional to \( H \), when the limit \( HM >> K \) is reached the torque will saturate at a field independent value depending only on \( K \sin \theta \) [10]. This is what is observed at the lowest temperatures in Fig. 1. However at higher temperatures, the observed torque signal initially increases with field as at low temperatures; it reaches a peak at a field \( H_c(T) \) and then for higher fields it decreases again until it becomes unobservably small at a critical field \( H_c(T) \).

Thus the data show that at low temperatures, \( K \) tends to become field independent for the range of fields available to us, i.e. the spin configuration is almost rigid and the DM anisotropy after cooling in field is almost independent of the value of the field. With increasing temperature the low field behaviour is still of the same form so \( K(T) \) is still essentially field independent, but \( K(T) \) decreases regularly. This is because local spin-wave-like fluctuations reduce the time average effective local spin moments \( <S_i> \), so each term in the DM expression above becomes weaker on increasing temperature. Higher fields lead to the peak effect, showing that a combination of temperature and field begins to weaken the rigid state. The spins are still frozen but they have become free to select configurations for which the DM terms are weaker, producing a progressive reduction in \( K(H, T) \) with field. Finally above \( H_c(T) \) the system can completely rearrange the spins on a time short compared with the time scale of the measurement, and there is no more observable anisotropy. Above this critical field the system has entered the paramagnetic state. (The precise form of the behaviour of a spin glass with weak anisotropy may well be rather different). This measurement gives detailed information on the progressive manner by which a spin glass system loses rigidity under increasing applied fields and temperatures.

Individual points on the \( H_c(T) \) curve were estimated by plotting \( \log(\Gamma(H, T)) \) against \( T \) and observing the intersection with the noise level, which was typically 0.01 in the units of Figure 1. We have also estimated the position of the critical line \( H_c(T) \) in a complementary and more sensitive way by measuring the torque signal as a function of time after turning. \( H_c(T) \) is then defined as the field above which there is no observable torque relaxation (so no observable torque above the noise). The two sets of estimates are entirely consistent. Error bars are indicated on Figure 2.

Magnetic measurements provide an alternative method for identifying an irreversibility line. Field cooled and zero field cooled (ZFC) magnetizations are compared ; the onset of difference between the two indicates irreversibility [3,4]. For a CuMn sample Kenning, Chu and Orbach [4] observed ”strong” and “weak” irreversibility lines ; they identified the latter with a transverse irreversibility as had been seen in torque measurements over a restricted range of fields [13]. We have carried out magnetization measurements on the present sample. Follow-

![Graphs showing the torque measured 30 seconds after field cooling](image)

**FIG. 1.** The torque measured 30 seconds after field cooling followed by turning the field by \( 5^\circ \). Each point correspond to a separate field cooling run. The torque is in arbitrary units but the units are the same for the three plots. The temperatures are, from top to bottom: (a) 5K, 6K, 7K, 8K, 9K, 10K, 11K; (b) 11K, 12K, 13K, 14K; (c) 14K, 15K, 16K, 17K

Suppose that a spin glass has a strictly rigid spin configuration with magnetization \( M(H) \) and a field independent spin glass anisotropy \( K \). Then the torque signal \( \Gamma \) when the applied field \( H \) is turned by an angle \( \theta \) is given by [10]

\[ \theta/\Gamma = 1/K + 1/M_r H \] (1)

For a series of points each taken after cooling in field, the torque signal \( \Gamma(H) \) will initially increase with field
ing Kenning et al, we have plotted the difference between $M_{FC}$ and $M_{ZFC}$. $(M_{FC} - M_{ZFC})/M_{FC}(5K) < 10^{-3}$ gives a criterion which defines an effective critical temperature at each field. (In any case, theory suggests this line is a crossover and so intrinsically fuzzy). To the precision of our SQUID measurements, we could not observe a weak irreversibility line, and our critical points $H_{cm}(T)$ correspond to the strong irreversibility of Kenning et al. It can be noted that while the torque gives a transverse irreversibility criterion for $H_c(T)$ which is very clear cut experimentally, the weak longitudinal irreversibility criterion of Kenning et al requires painstaking measurements of tiny magnetization differences between successive FC and ZFC runs. Even the strong irreversibility signal becomes small at high fields (less than 1 percent of $M_{FC}$ at 6K by 3T). Although the transverse irreversibility line can be taken as representing a true transition, it is a "stealthy" transition - essentially invisible in any longitudinal measurement, whether by magnetization differences or a.c. susceptibility. This implies that except in low fields, no longitudinal magnetization measurement can be used as a reliable probe of the onset of true spin freezing, and transverse irreversibility must be studied in order to establish an $(H, T)$ phase diagram.

![Figure 2](image-url)

**FIG. 2.** Irreversibility onsets estimated for transverse irreversibility ($H_c(T)$ from torque measurements, full circles) and longitudinal irreversibility ($H_{cm}(T)$ from SQUID measurements, open circles, squares and triangles). Open circles correspond to temperature increment of 0.2K, squares to 0.1K, triangles to 0.25K. The full triangles correspond to the torque peaks $H_p(T)$ of Fig.1. The inset is a schematic drawing of the mean field phase diagram with longitudinal d’Almeida-Thouless (AT) [1] and transverse Gabay-Toulouse (GT) [2] irreversibility onset lines. For a sample with strong random anisotropy, theory predicts a transverse irreversibility onset with a crossover, following the full line (Kotliar and Sompolinski [15]).

The results for the phase diagram using these alternative criteria are displayed in Fig.2. The $H_c(T)$ line is of similar form to that already observed in torque measurements on a Au2%Fe sample at low fields [13]; the present results extend the torque data by an order of magnitude in field range and provide longitudinal measurements on one and the same sample. The $H_c(T)$ form is characteristic of RSB predictions for samples with strong anisotropy, where the transverse transition line follows AT behaviour at low fields and then crosses over towards GT like behaviour at high fields [14], see inset. Clearly the present $H_c(T)$ line resembles the full line in the inset, reaching the crossover region but not the GT limit.

We can note that for this sample the peak field $H_p(T)$ line from the torque experiments lies very close to the longitudinal irreversibility line.

Although qualitative agreement between theory and experiment appears excellent there is an important caveat. It would not appear meaningful to use the standard model to analyse the field dependences of the transition temperature, because the three dimension Heisenberg spin glass transition calculated with the standard Edwards Anderson order parameter is already at zero temperature in zero field [17,18], so an alternative model must be sought.

A most attractive explanation for the observation of the finite temperature transitions in real Heisenberg spin glasses is that of Kawamura [16] who proposes that the transition is fundamentally chiral, and that it is "revealed" by the presence of even weak anisotropy. Calculations show that the chiral model $(H, T)$ transition behaviour is of an RSB type, and mimics the mean field behaviour [19,20]. For fields strong compared to the anisotropy the transverse irreversibility transition line lies at $H_c \propto (T - T_g)^{0.5}$ as for the GT line. For low fields $H_c \propto (T - T_g)^{\phi}$ with $\phi$ between 1.3 and 1.5 much as for the AT line [20]. There is an anisotropy dependent crossover from AT-like behaviour to GT-like as in the mean field model. In the chiral model the transition irreversibility line is a true transition line, but the transition may well be of a very different nature from that in the mean field model (it might be one step RSB for instance [13]). The present transverse irreversibility data are completely compatible with the chiral model predictions for the irreversibility onset if we consider that the steep rise at lower temperatures indicates that even at 7T the system is still in a crossover regime and the true GT-like regime would require yet stronger fields (c.f. [15]). The longitudinal irreversibility $H_{cm}$ line follows an AT like behaviour with exponent $\phi$ about 1.5 from $T_g$ to near 0.8$T_g$ and then takes a larger exponent.

We now turn briefly to the question of relaxation. In the region below $H_c(T)$ the torque signal always relaxes with time in the algebraic or quasi-logarithmic manner familiar from spin glass magnetization measurements, Fig.3. This is true above and below the $H_{cm}(T)$ line. This form of signal decay means that there is no maximum characteristic time for the relaxation, which is a criterion indicating that the system is in a glassy frozen
state and that the signal decay reflects a form of magnetic creep. We conclude that when the torque signal is observable, the system is frozen in this sense; there is a line of true freezing transitions at or very near to the $H_c(T)$ line in Fig. 2. Though chiral model simulations have so far only been carried out in zero field, the slow quasi-algebraic form of relaxation found experimentally appears compatible with the equilibrium simulation relaxation data \cite{19}.

![Torque relaxation as a function of time in seconds after field cooling followed by turning by 5° at temperature 11 K. The values of the applied field are indicated on the figure. A straight line on a log-log plot corresponds to algebraic decay of the torque signal.](image)

The experimental torque aging effects after cooling in field appear to be negligible (as in CuMn \cite{21}), in contrast to those always observed in spin glass magnetization experiments at zero field \cite{22}, and to the aging observed in the zero field chiral simulations \cite{19}. Simulations to check for an in-field suppression of aging in the chiral approach would provide an important verification of the model.

In conclusion, by combining torque and magnetization information over a wide range of applied fields, we find that a Heisenberg spin glass with strong random DM anisotropy has an in-field phase diagram which is remarkably similar to that of the chiral ordering model \cite{18} (which mimics the well established mean field type 2 RSB): a transverse irreversibility onset line corresponding to a true RSB freezing transition, plus a lower and quite distinct strong longitudinal irreversibility line which can be identified from magnetization data. The two lines fuse at low applied fields. To make a realistic quantitative comparison with theory concerning characteristics like the in-field aging and the transverse magnetization decay, we must await full in-field simulations in the chiral ordering scenario \cite{19} with strong anisotropy. Already the striking qualitative similarities between the experimental phase diagram and the chiral (or mean field) spin glass model phase diagram is strong evidence that the essential physics of real life Heisenberg spin glasses is very close to that of the RSB class of models. Scaling approaches of the Fisher-Huse droplet type \cite{4} do not appear to be compatible with the experimental data, as they predict that whenever the applied field is non-zero, there will be no transition to a frozen state at any finite temperature.

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