Relaxation of the field-cooled magnetization of an Ising spin glass

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The time and temperature dependence of the field-cooled magnetization of a three dimensional Ising spin glass, Fe$_{0.5}$Mn$_{0.5}$TiO$_3$, has been investigated. The temperature and cooling rate dependence is found to exhibit memory phenomena that can be related to the memory behavior of the low frequency ac-susceptibility. The results add some further understanding on how to model the three dimensional Ising spin glass in real space.

I. INTRODUCTION

During the last decades the slow relaxation and the attributed non-equilibrium phenomena of spin-glasses have been frequently investigated. The experimental tools have usually been measurements of the relaxation of the zero-field-cooled magnetization (ZFC) [1], thermoremanent magnetization (TRM) [2] or the ac-susceptibility [3]. The small but significant relaxation of the field-cooled (FC) magnetization has been less investigated and only a few studies of the relaxation behavior of the FC-magnetization can be found in the literature [4,5]. In this paper this conspicuous relaxation is systematically studied for the Ising spin-glass Fe$_{0.5}$Mn$_{0.5}$TiO$_3$. The results are discussed and interpreted in terms of a real space phenomenology that has been developed in the spirit of the droplet model [6]. This way of interpreting the droplet model has recently been used [7] to understand the predicted [8] and observed [7,9] memory effects in the relaxation of the ZFC-magnetization and the ac-susceptibility of three dimensional spin glasses.

II. EXPERIMENTAL

The experiments have been performed in a non-commercial dc-SQUID set-up described in Ref. [10]. The magnetic field was induced in a solenoid working in persistent mode to ensure field stability. In all experiments the field, $h = 0.5$ Oe, was applied at a temperature well above the spin-glass transition temperature, $T_g \approx 21$ K [11].

The investigated sample is a Fe$_{0.5}$Mn$_{0.5}$TiO$_3$ ($2 \times 2 \times 5$ mm$^3$) single crystal which is regarded as a good model system for a short-range interacting Ising spin-glass [2].

III. BASIC RESULTS

The field-cooled magnetization, $m_{FC}(T)$, is measured by cooling the sample in a constant magnetic field. The field used in this study (0.5 Oe) is low enough to yield a linear response in a zero-field-cooled experiment at low temperatures. In a field-cooled experiment however, any field causes a non-linearity of $m_{FC}(T)$ when passing through the spin glass temperature $T_g$. In fact, the magnitude of $m_{FC}(T)$ is governed by the amplitude of the applied field at all temperatures of order $T_g$ and below. In spite of this, to study the dynamics associated with the FC magnetization we limit our investigation to using only one but a representative low field. Fig. 1 shows the FC-magnetization on cooling and heating using two different cooling and heating rates. The squares represent a fast rate (0.4 K/min) and the circles a slow rate (0.01 K/min), filled symbols denote cooling curves and open symbols the behavior on reheating, at one and the same heating rate for both curves (0.4 K/min). For reference, the inset shows the zero-field-cooled and field-cooled magnetization curves for our sample. As is seen from the main figure, there is a significant cooling rate dependence of the FC-magnetization. The slow cooling curve has a higher magnetization than the fast cooling curve at temperatures just above and through $T_g$, at a

FIG. 1. The magnetization vs. temperature when cooling the sample Fe$_{0.5}$Mn$_{0.5}$TiO$_3$ in a field, $h = 0.5$ Oe, to 11.5 K with the rates 0.01 K/min (filled squares) and 0.4 K/min (filled circles). The subsequent heatings, in the same field, are made with the rate 0.4 K/min in both cases and are shown with the corresponding open symbols. The inset shows zero-field-cooled and field-cooled vs. temperature curves in an applied field, $h = 0.5$ Oe.
lower temperature the two curves cross and the slow cooling curve achieves a lower magnetization value. This behavior implies a dynamic nature and thus a relaxation of the FC magnetization if the sample is kept at constant temperature during cooling. Fig. 2 shows the relaxation of the FC-magnetization at some constant temperatures just below $T_g$ after cooling at a rate of 2 K/min from a temperature well above $T_g$. There is an upward relaxation at higher temperatures; a downward relaxation at short times followed by an upward relaxation at longer times at a slightly lower temperature; and only a downward relaxation at even lower temperatures. This behavior is consistent with the cooling rate dependence observed in Fig. 1. Turning back to Fig. 1 and looking at the heating curves it is seen that they always deviate downward from their corresponding cooling curves until they merge at the equilibrium level well above $T_g$. It is however noteworthy that in spite of having the same heating rate, their temperature dependences still reflect the original cooling rate all the way up to where they merge at equilibrium, of certain interest is that also the two heating curves cross at a high temperature.

Additional information on the non-equilibrium phenomenon of spin glasses is achieved from intermittent stops at constant temperature during the cooling process. In Fig. 3 $m_{FC}(T)$ at a cooling/heating rate of 0.4 K/min is drawn. The sample has in these measurements been intermittently kept at constant temperature for two or three hours at (a) 18 K, (b) 15 K and (c) both at 18 and 15 K. The result of the stay at constant temperature is that the magnetization relaxes downward and on continued cooling after the stop, $m_{FC}(T)$ remains on a lower level than the reference continuous cooling curve. On reheating, the heating curve merges with the corresponding reference curve only well above the temperature where the sample was kept at constant temperature. It is also worth to note that the heating curve ‘touches’ its cooling curve just at the temperature of the intermittent stop, not only for one but also when two or three well separated intermittent stops have been imposed during cooling. To further illustrate this behavior we have in Fig. 4 compared the heating curves for the experiments where the sample has been intermittently kept at constant temperature during cooling to the reference behavior without such stops. What is plotted in the figure is then $\Delta m = m_{FC}(T) - m_{refFC}(T)$. Fig. 4a shows such difference plots for experiments where one intermittent stop has been made during cooling, circles show the results when the sample was kept at constant temperature at 18 K for 2 hours, squares at 15 K for 3 hours and

![FIG. 2. The relative field-cooled magnetization change vs. time at some temperatures below the transition temperature, $T_g \approx 20.9\text{K}$ for the spin-glass sample Fe$_{0.5}$Mn$_{0.5}$TiO$_3$, $h = 0.5\text{ Oe.}$](image1)

![FIG. 3. The magnetization vs. temperature for the sample Fe$_{0.5}$Mn$_{0.5}$TiO$_3$ cooled in a constant field, $h = 0.5\text{ Oe,}$ to 11.5 K (filled circles). The cooling rate of 0.4 K/min is halted at (a) 18 K for 2 hrs, (b) 15 K for 3 hrs, and (c) both at 18 K and 15 K for 2 hrs and 3 hrs, respectively. The subsequent heatings from 11.5 K in the same field are shown with open symbols. Included for reference purposes, shown with solid lines, are the cooling and heating curves obtained with the rate 0.4 K/min but without intermittent halts.](image2)
IV. THE DROPLET MODEL

To interpret the experimental results discussed above we use a phenomenology based upon the droplet model developed for Ising spin-glass systems by Fisher and Huse [8]. The ground state configuration, $\psi$, is in the droplet model two-fold degenerate by a global spin-flip; $\bar{\psi}$. Furthermore, adopted in the same theory and very essential for the following discussion of the experimental results, is the concept of chaos with temperature [13], i.e. the ground state spin configuration $\psi$ rearranges completely if the temperature is changed any amount, $\psi = \psi(T)$. However, there is a length scale, $l(\Delta T)$, within which no essential change in the ground state configuration can be observed after a temperature change, $\Delta T$. This so called overlap length is trivially, infinite, at $\Delta T = 0$ but decreases rapidly toward zero with increasing $|\Delta T|$. To demonstrate some consequences of this spin-glass model it is instructive to make a hypothetical experiment where an Ising spin-glass system is quenched in zero field from infinite temperature to a temperature $T_1$ in the spin-glass phase [9]. At $t = 0$ after the quench to $T_1$ there are two ground states, $\psi(T_1)$ and $\bar{\psi}(T_1)$, to map each spin on. In average, half of the spins will map to $\psi$ and defines $\psi$-domains while the other half of the spins defines the $\bar{\psi}$-domains. This identification forms a fractal domain pattern which means that domains of many sizes exist at $t = 0$ after the quench. In a percolation problem like this, when excluding the infinite domains (clusters), there is a characteristic maximum size of the fractal domain sizes which is set by the percolation threshold, $p_c$, compared to the site occupation probability, $p = 0.5$. In this simple picture where only temperatures well below $T_g$ are considered, the domain wall thickness can be defined and is one lattice spacing. In order to introduce dynamics into the present, quenched, spin configuration it is assumed in the droplet model that collections of ordered spins coherently can flip their directions anywhere in the sample. Such a droplet excitation is associated with an energy barrier, $B$, that must be surmounted. Fisher and Huse [8] made the ansatz that the barrier grows as

$$B \propto L^\psi$$

(1)

where $L$ is a measure of the linear size of the droplet and $\psi$ is a barrier exponent. This is a thermally activated process implying that larger and larger energy barriers can be surmounted as time evolves. The linear size, $L$, of the largest droplet excitations after the time, $t$, is typically

$$L \propto \left( \frac{T \ln(t/\tau_0)}{\Delta(T)} \right)^{1/\psi}$$

(2)

Here $\Delta(T)$ is an energy scale that increases with decreasing $T$ and $\tau_0$ the microscopic spin flip time. One key

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FIG. 4. Relative heating curves $\Delta m(T)/h$: $\Delta m(T) = m_{FC}(T) - m_{FC_{ref}}(T)$. $m_{FC_{ref}}(T)$ is measured after continuous cooling at 0.4 K/min to 12 K and thereafter recording the magnetization on heating at 0.4 K/min. $m_{FC}(T)$ is measured on heating the sample at 0.4 K/min, after cooling the sample at 0.4 K/min and employing intermittent halts at different temperatures. (a) One halt at 18 K for 2 hrs (squares); one halt at 15 K for 3 hrs (circles); and one halt at 12 K for 3 hrs (triangles). (b) One halt at 18 K for 2 hrs (squares); one halt at 18 K for 2 hrs and one halt at 15 K for 3 hrs (circles); and one halt at 18 K for 2 hrs, one halt at 15 K for 3 hrs and one halt at 12 K for 3 hrs (triangles). $h = 0.5$ Oe.

Triangles at 12 K for 3 hours. Fig. 4b shows the corresponding curves, but now sequences of intermittent stops at the same temperatures and times as used in Fig. 4a have been imposed on the sample during cooling. Squares mark the curve with only one stop at 18 K (the same curve is also drawn in Fig. 4a), circles mark a curve where two stops were imposed, the first at 18 K and the second at 15 K, and the triangles mark the behavior when stops were made at 18, 15 K and 12 K. All curves coalesce at temperatures above their common stop temperatures! It is remarkable that the downward relaxation accumulated at the low temperatures does not sustain at temperatures above the temperatures of the intermittent stops.
point when trying to grasp the dynamics of this spin glass model is that the quenched spin glass at $t = 0$ is a static system with fractal spin glass domains of many sizes. It is only with time at constant temperature or age, $t_a$, that the system can start to equilibrate through droplet excitation. It is also important to remember that droplets of a specific size always only include a fractional part of the total number of spins in the system. Note that droplet excitations of size $L(t)$, where $t$ is a time much less than $t_a$, have reached equilibrium in the sense that the number of these droplets is constant. These droplet excitations can be regarded as paramagnetic fluctuations when the system is observed at an observation time, $t_{obs} \ll t_a$. One crucial effect of the droplet excitations is also to remove domain structures of size $L(t)$ and smaller, i.e. as the age of the system increases, a larger and larger part of smaller domain structures are washed out. Since however, the droplets of a specific size always are scarce, a substantially longer time is required to with help of these and larger droplet excitations remove most of the domain structures of size $R \approx L(T, t)$. On the other hand, a logarithmic time perspective must be used when dealing with these slow dynamics and the result of this discussion can roughly be compared to the result by Fisher and Huse [6], who conclude that the minimum distance, $R$, between domain walls typically is

$$R \propto L(T, t)$$

(3)

after an equilibration time, $t$. In summary, the effect of the droplet excitations on the original quenched domain pattern after an aging time $t_a$ is: domains of size $R \ll L(T, t_a)$ have effectively been washed out, whereas the number and size of fractal domains of size $R \approx L(T, t_a)$ and larger are yet essentially unchanged. The effect of the aging on these larger domain structures has been frequent but only fractional displacement of their domain walls. Thus, spin structures on these large length scales still remain essentially unaffected by the aging process.

When a magnetic field is applied to a spin glass at a low temperature, the magnetization process is governed by polarization of droplets. The composition of a droplet is a collection of spins of random directions. This implies that the fluctuation in the ratio between up and down spins is typically $L^{d/2}$ where $d$ is the spatial dimension of the spin glass. A droplet thus carries a magnetic moment of this order of magnitude. In zero field the moments of the excited droplets are randomly directed and a macroscopic sample carries no net magnetization (the original quenched spin structure that is mapped to the equilibrium configuration is of course also assumed to have zero net magnetization). When applying a weak field to a ZFC spin-glass system, however, the sample becomes magnetized through a polarization of droplets that is linear in field at low enough field strengths. Small droplets are first polarized and as time increases, larger and larger droplets become polarized and the magnetization continuously increases. It is always only the very largest active droplets that contribute to the increase of the magnetization, the smaller droplets rapidly reach a stationary state where an equal number of droplets are polarized and depolarized simultaneously. As long as the time after the field application (observation time) is much shorter than the age of the system, only thermalized paramagnetic droplets contribute to the magnetization process. However, when the observation time, $\log t$ becomes of order $\log t_a$, the largest droplets coexist with and also annihilate domain structures of the same size. In this region the number of excited droplets of this size is larger than the equilibrium number. This is seen from a larger magnetization value and an increase of the relaxation rate of the magnetization at these time scales [6] compared to the magnetization and rate of the same system at the same observation time when measured at quasi-equilibrium (i.e. measured on a system where $t \ll t_a$). (It is worth to notice that this enhanced number of droplet excitations of size $L(t_a, T)$ also implies that the domain structures of this size are more rapidly annihilated than only the equilibrium number of droplet excitations would allow.)

We assume that the polarization of droplets of any size always scales with the number of excited such droplets. Consequently, the equilibrium magnetization, obtained at infinite time, is governed by ‘paramagnetic’ droplet excitations on all length scales occurring anywhere in the sample. The droplet picture we advocate here thus prescribes that the magnetization process is governed by the existing droplet excitations: on short time scales, the number of droplets is stationary, whereas on time scales of the order of the age of the system there is an enhancement of the number of excited droplets compared to the stationary state. The largest size of active droplets is governed by the age of the system. An important consequence of this is that experiments on short observation times only probe a minor part of existing droplet excitations, whereas essentially all excited droplets (from the smallest to the largest) are polarized to ‘equilibrium’ in an experiment where the observation time and the age of the system are of a similar order of magnitude. We then observe an ensemble of droplets that is adequately magnetized with respect to its momentary distribution of droplets and the applied field. Of course, this system still experiences a magnetic relaxation since larger and larger droplets become active and polarized with time. As the age of the system increases, the enhanced number of droplets appearing at the momentary age of the system relaxes toward the equilibrium number, there is thus a decreasing number of droplets of a specific size with increasing age of the system. This is directly observed in a decay of the out-of-phase component of the low frequency ac-susceptibility when the sample is kept at constant temperature [6]. The ac-susceptibility probes the
system at one constant observation time, \( t = 1/\omega \) and the magnitude of the out-of-phase component gives a direct measure of the number of droplets of the size \( L(T, 1/\omega) \). It is also interesting to note that it can be shown from low frequency ac-susceptibility experiment that a large length scale domain structure can be imprinted on the system by keeping the sample intermittently at constant temperature at a specific temperature during cooling, then after cooling to a lower temperature and reheating the sample, there will be a memory of the intermittent stop imprinted in the domain structure that is seen as a dip in the out-of-phase component of the susceptibility at this temperature \([18]\).

The basis for understanding the relaxation of the magnetization in a spin glass lies in the domain structure and how it is affected by the droplet excitations. These properties are essentially unaffected by a weak applied magnetic field. Changes of the magnetization are always caused by polarization or depolarization of droplets of a size corresponding to the observation time of the experiment. In a FC experiment, the field is always applied during the experiment and the relevant droplet excitations that cause a magnetization change are those of size \( L(T, t_e) \). Two effects contribute to the relaxation: (i) depending on if the initial polarization of the droplet excitations (due to the finite magnetization of the sample) spontaneously is larger or smaller than the adequate polarization of these, an increase and a decrease of the magnetization will occur, respectively, and (ii) the changing number of these droplets as the age of the system increases causes some relaxation. I.e. there is a possibility for a relaxation towards higher magnetization and lower magnetization depending on temperature, cooling rate and the initial value of the magnetization.

Before ending the discussion on the droplet picture, we complement the picture with some sentences on the effect of the applied magnetic field on the equilibrium spin glass phase. It is contained in the droplet theory \([6]\) and supported by experimental results \([14]\) that any applied field field destroys the thermodynamic spin glass phase. This fact is important for magnetization experiments when passing through \( T_g \) and also for the magnitude of the magnetization achieved at low temperatures in a FC experiment. However, the dynamic response to a small field change in the spin glass state is linear and the field does not affect the ongoing equilibration process. The effect of the field is to limit the maximum size of the droplets on a length scale well beyond the sizes obtained on our experimental time scales, except very close to \( T = T_g \) \([14]\).

V. DISCUSSION

When discussing the continuous cooling processes of the sample it is convenient to introduce an effective age of the system, \( t_e \), which is set by the interplay between reinitialization of the system due to chaos with changing temperatures, the overlap length and the equilibration process described by Eq. \([8]\) \([9]\). A slower cooling rate allows the equilibration process to proceed to longer length scales, which yields a higher effective age, \( t_e \). The age of the system defines the largest size of active droplet excitations and thus also the typical distance between remaining domain walls \( R(T, t_e) \) at each temperature, \( T \), according to Eq. \([8]\). In Fig. 1 \( m_{FC} \) was shown vs. \( T \) when cooling the sample with the rates 0.4 K/min and 0.01 K/min from a temperature well above \( T_g \). The subsequent heating curves, after these two cooling procedures, have been obtained with the rate 0.4 K/min and are shown with the corresponding open symbols. Regarding the cooling curves, it was observed that the magnetization corresponding to the slower cooling rate is larger at high temperatures while smaller at lower temperatures. When cooling from a high temperature, the correlation length increases due to critical slowing down and, thus, spin glass correlated regions can form on larger and larger length scales. When the system falls out of equilibrium at a temperature above \( T_g \) this means that droplets with larger relaxation times than the effective age of the system have not yet been excited. To polarize these a slower cooling rate is required. This implies that the amplitude of the magnetization should increase with decreasing cooling rate in this temperature region. On continued cooling through \( T_g \) to lower temperatures, the correlation length becomes infinite at \( T_g \) and the system remains critical also below \( T_g \) due to the chaotic nature of the spin glass phase. However, the length scale or size of the largest droplet excitations is limited by the effective cooling rate and thus this size rapidly decreases with decreasing temperature. Considering this fact, the change of the magnetization of the sample will depend upon whether the initial spontaneous polarization of the droplet excitations due to the magnetization of the sample is larger or smaller than the ‘equilibrium polarization’ for these droplets. Apparently, from the lower magnetization for the slower cooling rate at lower temperatures, the spin glass has achieved a too high magnetization when passing through \( T_g \) compared to the ‘equilibrium polarization’ for the excited droplets on time scale \( t_e \). It also worth to note that the heating curves, which are recorded at one and the same rate (0.4 K/min) do carry a memory of their different cooling rates. It is especially noteworthy that the curve corresponding to the slow cooling rate even cross the curve corresponding to fast cooling rate to again become more magnetized at a higher temperature. There is a memory of the cooling procedure imprinted on the system, we will discuss this memory effect further in connection with the experiments employing intermittent stops during cooling.

In Fig. 2 the relaxation of the FC-magnetization at constant temperature at some temperatures just below
The behavior of course accords with the indications from the cooling rate dependence, in that there is an upward relaxation at the highest temperature and a downward relaxation at lower temperatures. The fact that, at intermediate temperatures, the magnetization first relaxes downward and then at longer time scales relaxes toward higher magnetization does support the droplet consequence that the relaxation is governed only by the largest droplet excitations and that the ‘equilibrium polarization’ for these can be to large compared to the spontaneous polarization on small length scales (short times) and to small compared to the ‘equilibrium polarization’ on large length scales. Since we do not know where the thermodynamic equilibrium magnetization for a spin glass is to be found, it is not possible to, from the measured relaxation of the field-cooled magnetization, extrapolate the thermodynamic equilibrium value. It is not even possible to determine whether this value is larger or smaller than the measured FC-magnetization at any low temperature in the spin glass state. It is however possible to predict that at long enough time scale, there will always be an upward relaxation of the FC magnetization, since the original mapping prescribes a largest cut-off length scale for the spin glass domains, whereas droplet excitations are allowed on all length scales and these largest length scales droplets will be polarized by an applied field toward a larger magnetization value. It is possible that the upward relaxation observed on long time scales at high temperatures just around T_g is a consequence of this prediction. It should be added that the constant level of the magnetization seen for the shortest time scales in Fig. 2 can be attributed to the effective age of the system. The figure is misleading in the sense that t = 0 on time axis actually corresponds to an age t_c ≈ 10 s which has been obtained during the finite cooling rate.

Fig. 3 and Fig. 4 showed as discussed above consequences of one or more intermittent stops during cooling and the influence of these stops on the subsequent continuous heating curves. The results may be considered in the light of our droplet phenomenology. During cooling, the maximum size of excited droplets is determined by the temperature and the effective age, t_c, of the system. At the constant temperature of an intermittent stop, droplet excitations are free to occur on length scales only limited by the time at constant temperature, t_a. Thus, domain structures are removed up to the length scale of order of the largest droplet excitations, L(T, t_a). These large length scale excitations also cause a downward relaxation of the magnetization. When the cooling is recaptured, the size of the droplet excitations are again restricted by T and t_c. However, droplet excitation of all sizes up to L(T, t_c) always occur, these excitations strive to reach the ‘equilibrium polarization’ adequate for the actual distribution of excited droplets. The trend, on decreasing the temperature and from subsequent stops at lower temperatures, is that the magnetization always decreases with time and temperature. It should also be emphasized that the decrease of the magnetization obtained during an intermittent stop is essentially maintained on continued cooling. The magnetization does not asymptotically approach the continuous cooling curve (see Fig. 3). On reheating, the magnetization falls below the cooling curve, indicating that some additional downward relaxation occurs on the length scales of the cooling process (t_c ≈ t_h). However, when the temperature for an intermittent stop is reached, a high degree of the originally obtained ground-state order is recovered. The relaxation processes that have occurred at lower visited temperatures just appear as small and dilute regions with a lower magnetization in average. Due to the faster dynamics at this higher temperature these regions are quickly incorporated in the larger domains and hence the magnetization in these regions return as well. Heating through and above the temperature of the stop implies that longer

![Graph](attachment:graph.png)

FIG. 5. (a) The solid line and the filled symbols show the field-cooled magnetization obtained with the cooling rate 0.01 K/min and 0.4 K/min, respectively. Open symbols show the magnetization when cooling the sample with the rate 0.01 K/min to 15 K followed by the rate 0.4 K/min from 15 K to 11.5 K. After these different cooling procedures the sample is heated with the rate 0.4 K/min and these curves are shown in (b) with the corresponding notation. h = 0.5 Oe.
length scales are explored and when the temperature has reached out of the overlap region around the stop temperature, the heating curve coalesce with the reference heating curve. It should again be stressed that as Fig. 4b shows, the FC heating curves all coalesce at high temperatures when one, two or three intermittent stops have been made during cooling. A behavior that shows that the spin glass can record the memory of several well separated temperature stops during cooling in one and the same ensemble of interacting spins. The key to an understanding of this ability is the chaotic nature and the different length scales that are affected by the largest droplet excitations in the system at the different stop temperatures.

These memory effects can also be illustrated by heating curves which are followed by a cooling procedure where the rate has been changed at some temperature. Open symbols in Fig. 5 (a) shows the FC-magnetization vs. temperature during cooling the sample with the rate 0.01 K/min to 15 K where the cooling rate is changed to 0.4 K/min. Filled symbols and the solid line show the magnetization during cooling with the constant rates 0.4 K/min and 0.01 K/min, respectively, down to 11.5 K. The subsequent heating curves are shown with corresponding notation in Fig. 5 (b) and are all recorded with one and the same rate, 0.4 K/min. Apparently, the heating curve which follows after the change in the preceding cooling rate at 15 K, merges at the same temperature with the heating curve obtained after cooling the sample with 0.01 K/min to 11.5 K. Above 15 K, and in accordance with the previous presented results, the system is unaware of the magnetization history which have occurred at temperatures below 15 K. The age, and hence also the magnetization, at each temperature is to a large extent determined during the preceding cooling process.

VI. CONCLUSIONS

The relaxation of the magnetization of a three dimensional Ising spin glass can qualitatively be understood in terms of a real space droplet phenomenology. The response to a field change (e.g. in a zero-field-cooled magnetization or an ac-susceptibility experiment), both the short time scale equilibrium response and the non-stationary relaxation on time scales of the order of the age of the system, can adequately be accounted for only by a polarization of droplet excitations. The memory behavior is also nicely accounted for in this picture. Also the relaxation of the FC-magnetization reported in this paper can qualitatively be accounted for within this droplet picture. There are however still important difficulties as to quantitative measures in the phenomenology, e.g. we do not know where the equilibrium magnetization of the spin glass is to be found and we also do not know the momentary ‘equilibrium polarization’ of the ensemble of excited droplets at a specific age of the system. I.e. the direction of the relaxation of the FC-magnetization is entirely determined empirically and only indicates the direction toward the momentary equilibrium but it does not allow an extrapolation to the thermodynamic equilibrium magnetization. To shed further light on the properties of the FC-magnetization it would be most useful to employ MC-simulations, since they allow instantaneous quenches and heatings of the sample and additionally allow arbitrary and adequately magnetized initial spin configurations for the relaxation studies.

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