Oscillations in the residual magnetization of spin glasses

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Oscillations in the residual magnetization have been detected in the spin glass $Zn_{0.4}Cd_{0.6}Cr_2Se_4$ after successive magnetization of the specimen in fields of different magnitude and direction. The specimen was magnetized in a field $H_1 = 7$ kOe and then in a field $H_2 = 400$ Oe pointing in the opposite direction. It was found that, after the magnetizing fields were turned off, the residual magnetization consisted of two oppositely directed components, one of which relaxed slowly and was parallel to H_1 and the other relaxed rapidly and was parallel to H_2. This suggests that the spin glass contains magnetic clusters with different energy and temporal characteristics.

1. INTRODUCTION

The characteristic property of spin glasses is their magnetic viscosity. Magnetization and the relaxation of magnetization do not occur in spin glasses at the exponential rate observed for other magnets. It has been shown[1–3] that the magnetization of spin glasses (for historical reasons, it is referred to as the residual magnetization M_R) relaxes slowly in accordance with the expression $M_R \propto (t/\tau)^{-\alpha}$ for $t \gg \tau$, where t is the time that has elapsed since the external magnetic field was turned off. The constant τ is usually 10^{-13}–10^{-4} s and $\alpha \ll 1$. The rate of remagnetization in spin glasses is a function of τ and α. It has been shown[2] that the magnitude of α for a given specimen can be varied within wide limits by varying the temperature, magnetizing field, and duration of magnetization. The corresponding mean duration of relaxation processes varies from fractions of a second to 10 hours or more. The magnetic viscosity of spin glasses can be explained in terms of the cluster model.[3] The essential point of this model is that the magnetic subsystem of a spin glass is microscopically inhomogeneous and has an enormous number of metastable states which may be looked upon as the perturbed states of individual clusters. It is assumed that the parameters of these clusters are distributed between wide limits. This approach does not exclude the possibility of an interaction between them or of the existence of an infinite cluster, i.e., long-range order in some particular parameter.

The cluster model of spin glasses has one interesting consequence. Let us consider small perturbations in a spin glass during magnetization in low enough field H and at a low enough temperature. A sufficiently low external field will produce a realignment of the magnetic moments of clusters that are weakly bound to the environment and are well separated from one another, i.e., do not interact. The analysis is then much easier. For simplicity, we shall assume that the i-th cluster has only two stable states, namely, magnetic moment up or down. One of these states is the ground state and the other a metastable state. The states are separated by an energy barrier E_i. The quantities E_i are distributed between wide limits. The relaxation time τ_i from the metastable state to the ground state of a cluster is described by the Arrenius law $\tau_i = \tau_0 \exp(E/k_B T)$, where k_B and T are, respectively, the Boltzmann constant and temperature. Let $h_i = E_i/m_i$ be the field sufficient to realign the magnetic moment m_i of the ith cluster. We shall arrange the clusters in the order of increasing h_i, i.e., $h_{i+1} > h_i$. We shall assume that we then also have $\tau_{i+1} > \tau_i$. This is possible, for example, when $E_i \propto n_i$ and $m_i \propto n_i^{1/2}$, where n_i is the number of magnetic ions per cluster. The quantities h and τ will then monotonically increase with increasing n. It turns out that this system exhibits a relatively unusual phenomenon, namely, damped oscillations of residual magnetization $M_R(t)$ if the system is first successively magnetized in fields $H_1^+ > H_2^- > H_3^+ ... > H_n^-$ (the superscripts + and − indicate the up and down field directions, respectively), provided the entire process of successive magnetization can be performed in a sufficiently short time $\Delta t < \tau_k$, where k is defined by the condition $h_k < H_n$. One can then observe $n/2$ oscillations. In fact, when H_1^+ is turned on, the magnetic moments of all clusters with $h_i \leqslant H_1^+$ will point up, the field H_2^- will realign in the downward direction the magnetic moments of a fraction of these clusters with $H_i \leqslant H_2^+$, and so on. The resultant magnetic moment of the system will therefore be

$$\mathfrak{M} = -\sum_1^a m_i + \sum_{a+1}^b m_i - \sum_{b+1}^c m_i + \ldots,$$

where $a, b, c, \ldots$ are determined from the conditions $h_a = H_n^-, h_b = H_{n-1}^+, h_c = H_{n-2}^-, \ldots$.

When the external field is turned off, the magnetic moment of the system will at first rise, largely as a result of the relaxation of the moment

$$-\sum_1^a m_i,$$

which points down (this is the magnetic moment of the group of clusters with $h_i \leqslant H_n^-$), and will then rise to the value

$$\sum_{a+1}^b m_i - \sum_{b+1}^c m_i + \ldots$$

in a time $\sim \tau_a$. The moment $\mathfrak{M}$ will then decrease, mainly as a result of relaxation of the magnetic moment of the group of clusters with $H_n^- < h_i < H_{n-1}^+$, down to—$\Sigma_{b+1}^c m_i + \ldots$

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in a time $\sim\tau_b$, and so on. Such oscillations of the moment $\mathfrak{M}$ of the system are possible because the inequality $h_b > h_a$ leads to $E_b > E_a$, i.e., $\tau_b \gg \tau_a$ since $\tau_i \propto \exp(E_i/k_B T)$. Actually, for each E_i and τ_i, there will be clusters with different magnetic moments m_i, so it is not possible to arrange all the clusters strictly in the order of increasing h and τ. However, whenever this approach does correspond to reality, at least approximately, it is possible to observe "smeared out" and time-overlapping oscillations in the residual magnetic moment.

To verify these predictions experimentally, we have investigated spin glasses of the form $Zn_xCd_{1-x}Cr_2Se_4$ with "freezing temperature" $T_f \approx 21$ K and $x \approx 0.4$. The magnetic properties of these spin glasses have been examined in detail in the literature.[2,4–6]

2. EXPERIMENTAL METHOD

The residual magnetic moment was measured in a rotating-specimen magnetometer.[7] The axis of rotation of the specimen lay along the Z axis of the laboratory Cartesian frame. The external field H^+ or H^- was applied along the X direction (the superscripts + and − indicate that the field had the positive and negative direction, respectively). A synchronous motor, rotating the specimen about the Z axis at 18 Hz, was turned on after the external field was removed. The specimen was in the form of a disk, placed symmetrically relative to the axis of rotation in the XY plane (the plane of rotation). The rotating specimen induced an emf in the receiving coils of the magnetometer at a frequency proportional to its residual magnetic moment $\mathfrak{M}_R$. The emf was measured using an amplifier with the UPI-1 synchronous detector. The reference signal was generated by a chopper rotating synchronously with the specimen and placed between the photo- and emitting-diodes. The threshold sensitivity of the system for the residual magnetic moment was $\sim 10^{-5}$ G·cm³. The standard volume of the specimens was 0.001–0.01 cm³. We note that the rotating-specimen magnetometer can be used to determine the residual magnetic moment even in the presence of an external magnetic field. The residual magnetic moment rotates together with the specimen, whereas the magnetic moment induced by the external field is parallel to H or oscillates relative to H at the even harmonics of the rotation frequency if the specimen is anisotropic. When $\mathfrak{M}_R = 0$, the parasitic signal at the rotation frequency does not exceed 10^{-5} G·cm³ in a field of about 100 Oe. Thus, by rotating the specimen with the residual magnetic moment in the external magnetic field, it was possible to investigate the relaxation of its residual magnetic moment. In other words, we were able to investigate the influence of the rotating magnetic field H_ω on the residual magnetic moment.

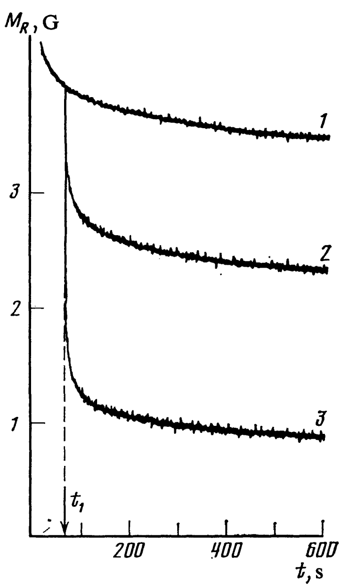

FIG. 1. Relaxation of M_R at 4.2 K in $Zn_{0.4}Cd_{0.6}Cr_2Se_4$ after magnetization by $H = 7$ kOe (the field H was turned on at a time $t = 0$). The following fields were turned on at time t_1: 1—$H_\omega = 0$; 2—$H_\omega = 200$ Oe; 3—$H_\omega = 400$ Oe.

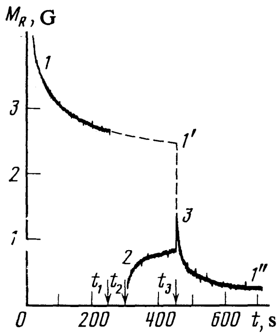

FIG. 2. Relaxation of M_R at 4.2 K in $Zn_{0.4}Cd_{0.6}Cr_2Se_4$ after magnetization in the field $H_1^+ = 7$ kOe (the field H_1^+ was turned on at time $t = 0$). Curve 1–1′–1″: the rotating field $H_\omega = 400$ Oe was turned on at time t_3. Curve 1–2–3–1″: the specimen was magnetized by the constant field $H_2^- = 400$ Oe opposite in direction to H_1^+ between t_1 and t_2; the rotating field $H_\omega = 400$ Oe was turned on at time t_3.

Figure 1 shows the effect of the rotating magnetic field H_ω on the relaxation of the residual magnetization M_R at 4.2 K in the case of the $Zn_{0.4}Cd_{0.6}Cr_2Se_4$ specimen magnetized isothermally in a field of 7 kOe. Curve 1 corresponds to relaxation in zero field (the initial time $t = 0$ corresponds to the time at which the magnetizing field was turned off). Curves 2 and 3 correspond to the rotation of the specimen in fields $H_\omega = 200$ and 400 Oe (the field H_ω was turned off at time t_1). We found that the relaxation process could be described by $M_R \sim t^{-\alpha}$ for different H_ω, including $H_\omega = 0$ (Ref. 2). The exponent α is proportional to H_ω^2. Thus, the rate of relaxation of M_R can be substantially increased by introducing the rotating field H_ω.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the relaxation of residual magnetization M_R at 4.2 K for the $Zn_{0.4}Cd_{0.6}Cr_2Se_4$ specimen magnetized by the field $H_1^+ = 7$ kOe (curve 1 − 1′, the origin of time corresponds to the point at which the field H_1^+ was turned off). The rate of relaxation of M_R can be substantially increased by turning on the rotating magnetic field $H_\omega = 400$ Oe (curve 1′ − 1″).

The same figure shows the behavior of M_R for a speci-

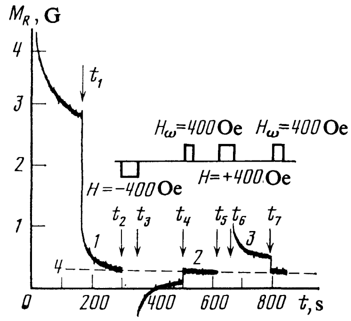

FIG. 3. Relaxation of M_R at 4.2 K in $Zn_{0.4}Cd_{0.6}Cr_2Se_4$ after magnetization in the field $H_1^+ = 7$ kOe (the field H_1^+ was turned off at time $t = 0$). The rotating field $H_\omega = 400$ Oe was applied to the specimen between t_1 and t_2; a constant field $H_2^- = 400$ Oe was applied between t_2 and t_3; the rotating field $H_\omega = 400$ Oe was introduced for 30 s at t_4; the constant field $H_3^+ = 400$ Oe was present between t_5 and t_6, and the rotating field $H_\omega = 400$ Oe was applied at t_7.

men magnetized in the field $H_1^+ = 7$ kOe under the following conditions. The rotation of the specimen was stopped at time t_1 (the specimen was aligned in a standard way in the initial position) and the field $H_2^- = 400$ Oe, opposite to H_1^+, was turned on. When the former field was turned off (at time t_2), the residual magnetization was found to decrease, but then began to increase in the positive direction (curve 2). To accelerate the relaxation process, the rotating field $H_\omega = 400$ Oe was turned on at time t_3. The residual magnetization rose rapidly and then relaxed along the curves 3–1″. This behavior of M_R can only be understood in terms of the cluster model of the spin glass. In fact, the magnetic moment of the group of clusters with $h_i < H_2^-$ will be negative, whereas the magnetic moment of the group with $H_2^- < h_i < H_1^+$ will be positive. The magnetic moment of the group of clusters with small h_i relaxes more rapidly, which explains the increase in M_R after magnetization in the field H_2^-. When the rotating field is introduced, this produces a still more rapid relaxation of the magnetic moment of the group of clusters (rapid rise in M_R at time t_3), and subsequent relaxation is due to relaxation field of the magnetic moment of the group of clusters with $H_2^- < h_i < H_1^+$.

Figure 3 shows the relaxation of M_R when, after magnetization in $H_1^+ = 7$ kOe, the specimen is partially demagnetized in the rotating field $H_\omega = 400$ Oe, and is then magnetized in the field $H_2^- = 400$ Oe. After the field H_2^- is turned off (at time t_3), the residual magnetization is negative (curve 2). It then relaxes in the absence of the external field to zero, changing sign and rising to level 4, which gradually relaxes to zero as shown by the dashed line in Fig. 3 (the relaxation process was accelerated by turning on the rotating field $H_\omega = 400$ Oe at time t_4). If, between t_5 and t_6, the specimen is magnetized by the constant field $H_3^+ = 400$ Oe, the relaxation of M_R after this field is turned off occurs along curve 3 (symmetric to curve 2 relative to level 4).

The behavior of M_R, shown in Fig. 3, can readily be understood in terms of the cluster model. The application of the rotating field $H_\omega \ll H_1^+$ ensures that only clusters with sufficiently high h_i become magnetized, and the sum of their magnetic moments determines level 4 and relaxes very slowly even in the rotating field. Subsequent magnetization by fields H_2^-, $H_3^+ \ll H_1^+$ ensures that the group of clusters with $h_i < H_2^-, H_3^+$ acquires a magnetic moment which relaxes at a much greater rate, i.e., relatively rapid relaxation of the magnetic moment of the group of clusters with small h_i is observed (curves 2 and 3 in Fig. 3) against the background of the slowly relaxing magnetic moment of the group of clusters with large h_i (level 4).

4. CONCLUSIONS

We have observed oscillations in the residual magnetization of a spin glass after the specimen has been magnetized by fields of different strength and direction. In other words, by magnetizing the specimen in some particular direction by the field H_1^+ and then in the opposite direction by the field $H_2^- < H_1^+$, one is able to observe a spontaneous rise in the residual magnetization, followed by its relaxation to zero. Under certain definite conditions, it is even possible to observe a spontaneous variation in the direction of the residual magnetization. This behavior of M_R can be explained in terms of the cluster model of spin glasses. It is then clear that the temporal and energy characteristics of clusters are distributed between wide limits. An analogous behavior of M_R was previously seen[8] in the spin glass $Fe_{65}Ni_{20}Cr_{15}$ at $T = 4.2$ K ($T_f \approx 20$ K).

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