Spin glass dynamics in RKKY interacting disordered magnetic system

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Using the dynamical Monte Carlo method we investigate the nonequilibrium effects in RKKY-coupling disordered spin glass. By the simulation we reproduce the well-known aging and memory phenomena and find the energy relaxation at a certain temperature happens only to the corresponding spins, which directly causes the nonequilibrium effects. Combining the master equation and the energy relaxation we analyse these phenomena and explain them from the dynamical perspective.

Keywords: RKKY, spin glass, aging, memory
PACC: 7115Q, 7510N, 7540M, 7550L

1. Introduction

Since spin glass was discovered[1,2] this complex magnetic system has attracted much attention.[3−6] It seems that spin glass possesses a series of puzzling characters, e.g., the obvious susceptibility cusp in contrast to the broad specific heat transition,[7] the slow magnetic relaxation up to second scale,[8] and the exchange anisotropy[9] after field cooling below its transition temperature $T_{\rm g}$. Among them the most well-known phenomena are aging and memory effects[10−12] which can be observed by following certain magnetic measuring protocols. Both of the effects manifest that magnetization of spin glass is directly related to its relaxation history, i.e., its age. Later, these phenomena were also found in nanoparticles,[13−15] perovskite manganite,[16] superconductors[17] and polymers.[18] It seems as if spin glass states have the characters common to many systems.

Due to the interaction and site disorder in spin glass, conventional mean-field theory fails to give proper explanations. Although phenomenological models, e.g., droplet model[19,20] and hierarchical model,[21] provide some qualitative explanations, the comprehensive understanding of these nonequilibrium phenomena is still absent. However, by powerful numerical simulations some valuable insights can still be gained. In this article we use the dynamical Monte Carlo method to study the nonequilibrium properties in RKKY interacting disordered systems.

Since in the conventional spin glass this oscillating coupling dominates, our simulation is obviously different from the others, for it originates directly from an experimental prototype. By simulation we reproduce the well-known aging phenomenon and the memory phenomenon as well as the susceptibility cusp in contrast to the broad specific heat transition. Moreover, we find that the relaxation at a certain temperature happens only to the corresponding spins and strengthens their couplings, which directly causes aging and memory effects. Combining the master equation and the energy relaxation we analyse these nonequilibrium phenomena qualitatively and explain them from the dynamical perspective. The rest of the present article is organized as follows. In Section 2 we present our model and method in addition to some parameters. In Section 3 we present the main simulation results and discuss them in Section 4. Finally we draw some conclusions from the present study in Section 5.

2. Model and method

We investigate the magnetic atoms diluted simple cubic lattice with $L\times L\times L$ size. Lattice size L is set to be 20 and the distance between the nearest-neighbour sites takes $1/k_{\rm F}$ in which $k_{\rm F}$ is the Fermi wave vector of the host metal. The dilution of magnetic impurities in our simulation is set to be 10% which is close

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to those in most spin glass samples.[11]

The RKKY coupling between the ith and the jth atoms can be written as

$$J_{ij} = J_0 \left(\frac{\cos(2k_{\rm F}r_{ij})}{(2k_{\rm F}r_{ij})^3} - \frac{\sin(2k_{\rm F}r_{ij})}{(2k_{\rm F}r_{ij})^4} \right), \qquad (1)$$

in which r_{ij} is the distance between the ith and the jth magnetic atoms, and J_0 is the constant and takes 8.0 meV. Due to the oscillating nature of J (r_{ij}) the interaction is cut off at $k_{\rm F}r_{ij} = 6.0$, at which J/J_0 is sufficiently small. Then the Hamiltonian of the ith magnetic atom in external field h can be written as

$$H_i = \sum_j J_{ij}\sigma_i \cdot \sigma_j - \sigma_i \cdot h. \qquad (2)$$

Spin variable σ only takes 1 or -1 in Eq. (2). The observables such as susceptibility, specific heat, and autocorrelation function are calculated as

$$\chi = (\sigma - < \sigma >)^2/k_{\rm B}T, \qquad (3)$$

$$C_{\rm v} = (E - < E >)^2/k_{\rm B}T^2, \qquad (4)$$

$$C(t, t_{\rm w}) = \frac{1}{N}\sum_i [< \sigma_i(t_{\rm w})\sigma_i(t + t_{\rm w}) >], \qquad (5)$$

where N is the total number of spins, the brackets $\langle \ldots \rangle$ and $[\ldots]$ mean the calculations take thermal and disorder averages respectively. In our dynamical simulations the periodic boundary condition is used and spins are flipped according to Glauber algorithm.[22] Furthermore, time is measured by the Monte Carlo sweeps (MCS) though the whole lattice. At each step the simulation takes 2000 sweeps, that is to say, our time unit is $t_0 = 2000$ MCS. The magnetization takes the normalized unit and external field h is denoted by the Zeeman energy of magnetic atom.

3. Results

The zero-field-cooled (ZFC) magnetization is simulated by cooling the glass from 210 K down to 1 K without field and then a small field is applied and the magnetization is simultaneously calculated. In contrast to the ZFC, the field is applied at beginning and while cooling the field-cooled (FC) magnetization is calculated. The curves for magnetization, susceptibility, and specific heat versus temperature in different fields are shown in Figs. 1(a), 1(b), and 1(c) respectively.

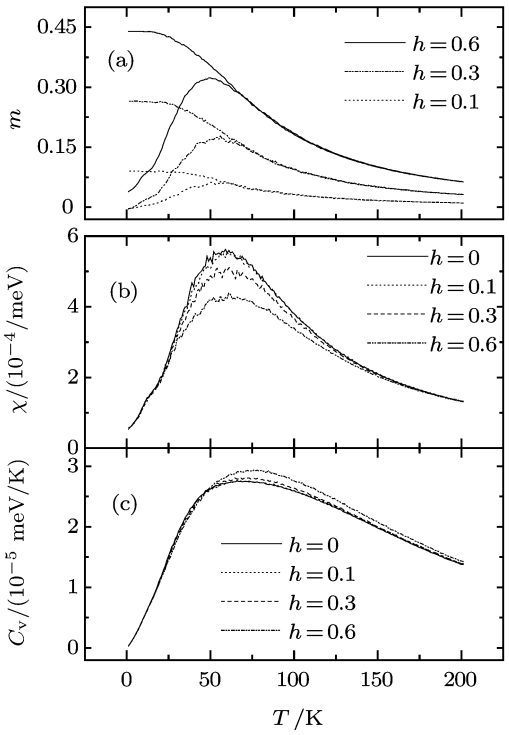


Fig. 1. Plots of ZFC and FC magnetization (a), susceptibility (b), and specific heat per spin (c) each as a function of temperature with the values of external field h being 0, 0.1, 0.3 and 0.6 meV.

From Fig. 1 the FC magnetization rises smoothly as temperature decreases and soon becomes flat below transition temperature $T_{\rm g}$. The susceptibility rises rather abruptly in small field while becomes rounded in larger field. In contrast to the susceptibility the specific heat is little affected by the external field and shows much broader transition near $T_{\rm g}$. Since the mean-field theory can give only the sharp transitions of both the susceptibility and the specific heat, our simulations reveal that the disordered RKKY interaction can enough generate these typical spin glass behaviours, which are consistent with the experiment results.[7,23] The peak of susceptibility corresponds to 58 K, which is a little larger than ZFC peak point 55 K.

Experimentally the aging affect is observed by the following protocol. First the spin glass is cooled in zero field below $T_{\rm g}$ and waits for a certain time ($t_{\rm w}$) at a temperature ($T_{\rm s}$). After that a small field is applied and the magnetization is measured as a function of time. In our simulations the system is cooled from 201 K to 10 K and waits for 10, 30, 100 t_0 respectively. Then the field $h = 0.1$ meV is applied and the magnetization is calculated. The results are shown in

Fig. 2.

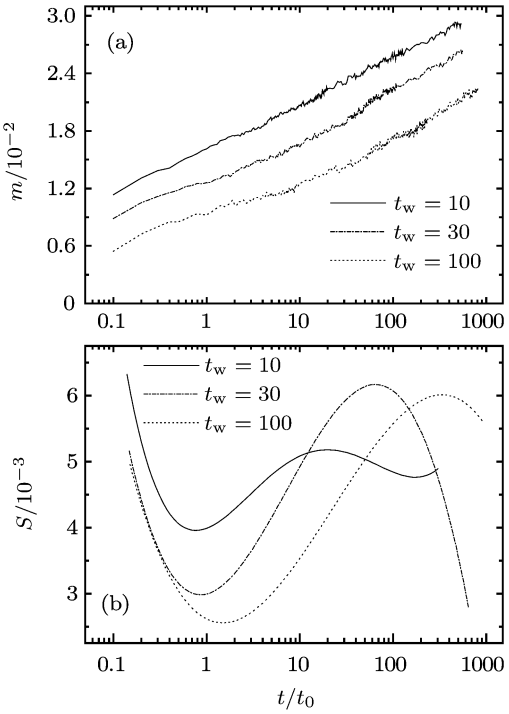


Fig. 2. Magnetization (a) and relaxation rate (b) each as a function of time. The temperature is 10 K and the system waits for 10, 30 and 100 t_0 respectively before the field is applied.

Obviously, the longer the waiting time is, the less the corresponding magnetization will be. Moreover, as measuring time increases the magnetization makes a progressive dip near $t_{\rm w}$. By defining relaxation rate $S = \partial m/\partial \log(t)$, the rate is found to peak at corresponding $t_{\rm w}$. Our simulations reveal that the magnetization and its relaxation rate strongly depend on relaxation time, or in other words, its age. This behaviour accords well with the experimental results.[10]

Waiting also affects the autocorrelation function greatly. The correlation function is calculated according to Eq. (5). $C\ (t,\ t_{\rm w})$ and coupling energy E per spin each as a function of time are plotted in Fig. 3.

It is noticed that the longer the waiting time is, the more slowly the autocorrelation will decrease. The slow decay of correlation reveals that after waiting the system is more stable than the previous state. The autocorrelation of $t_{\rm w} = 0$ decays linearly and only slightly bends when $t > 1000$. By waiting the energy relaxations become also much different from each other as shown in Fig. 3(b). For the waiting glass, when measuring time $t < t_{\rm w}$ the relaxation almost keeps horizontal while linearly decays for $t > t_{\rm w}$. But for the glass without waiting the energy relaxes almost linearly with $\log(t)$. For $t >> t_{\rm w}$ all the $E(t)$ curves of the waiting glass merge into a line. Inspired by Ref. [11] we plot all the $E(t + t_{\rm w})$ curves in the inset and they overlap each other and can be well fitted by $E = a + b\log(t + t_w)$, in which a and b are the fitting parameters and take -5.20 meV, -0.06 meV respectively.

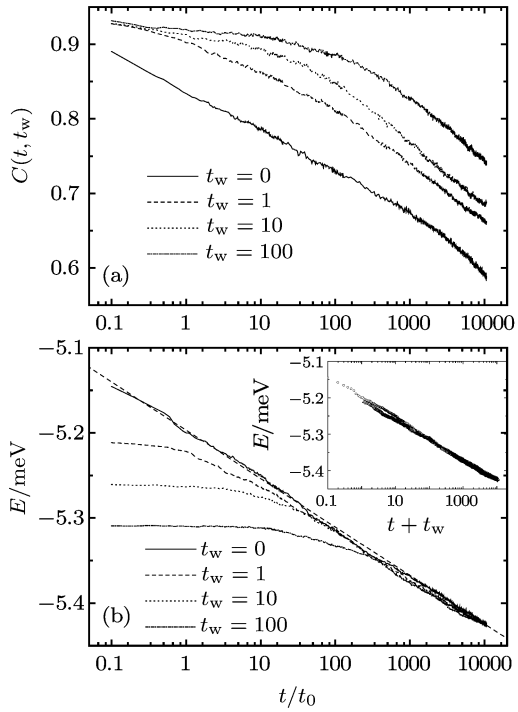


Fig. 3. Curves for autocorrelation (a) and coupling energy per spin (b) versus time. The system is first ZFC cooled to 10 K and waits for 0, 1, 10, 100 t_0. The dash line is the fitted line. The inset shows the plot of E versus $t + t_{\rm w}$.

The memory effect is simulated by the following protocol. The system is ZFC quenched from high temperature to 23 K which is below $T_{\rm g}$. Then the system waits in zero fields for $t_{\rm w}$. After that the system is quenched to 1 K. Then a small field is applied and the system is warmed back homogeneously. We calculate two magnetizations which wait at 23 K for $1t_0$ and $10t_0$ respectively and set the curve with $1t_0$ as the reference. The double magnetizations and the susceptibility difference are shown in Fig. 4. The magnetizations merge with each other at high and low temperatures except at the stop temperature. The difference between double magnetizations dips deeply at 23 K, which manifests the system keeps memory of its waiting history. Similar to the difference between magnetizations, the difference between susceptibilities also dips at 23 K as shown in Fig. 4(b). Moreover, it is clearly shown that the energy relaxations of both systems are identical except for those near 23 K. Near

23 K the system energy with longer waiting drops off abruptly compared with that of the reference. It demonstrates that the relaxation at a certain temperature only strengthens the coupling energy in the corresponding region, but does not affect the energy in other regions. This manifests that the relaxation only happens to certain spins accordingly. Our simulations are consistent with the measurements.[11,24]

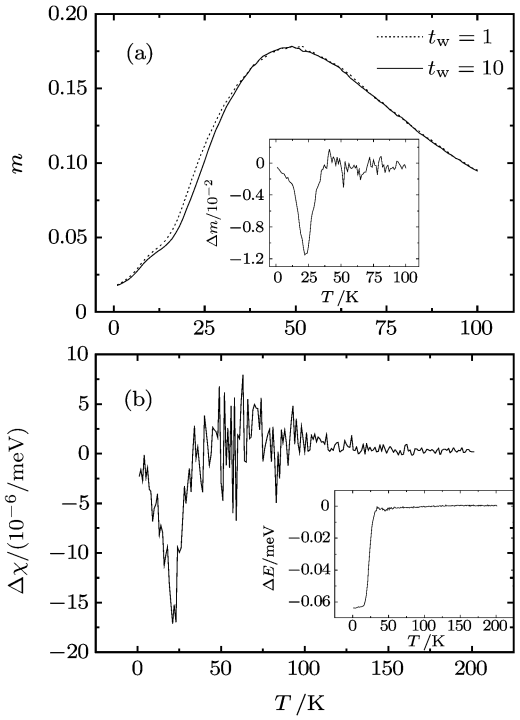


Fig. 4. Curves for ZFC memory of magnetization (a) and difference between susceptibilities (b) versus temperature. The system waits additionally at 23 K for $1t_0$ and $10t_0$ respectively. The applied field is $h = 0.1$ meV. Insets in panels (a) and (b) show the differences in magnetization and in energy between two systems respectively.

4. Discussion

According to the master equation and the energy relaxation we draw our explanations for memory and aging effects. In our simulations the system is composed of random distributed spins. Each spin has its τ to characterize its relaxation according to Neel–Brown law.[25,26] For memory and aging effects the relaxation at temperature T_s happens only to those spins with $\tau \sim t_w$ while those $\tau >> t_w$ or $\tau << t_w$ keeps frozen or paramagnetic. Therefore, energy relaxation at T_s happens only to the corresponding spins. Initially, these spins occupy the up states and the down states with probabilities p_1 and p_2 respectively, and the transition rate from up state to down state is $W_{1\to2}$. The spin flipping must obey the master equation which is written as

$$\mathrm{d}p_1/\mathrm{d}t = -p_1 W_{1\to2} + p_2 W_{2\to1}. \tag{6}$$

In a small field (i.e. when the value of h is small), the above equation has an analytical solution, which is much similar to the solution given in Ref. [27]. For the memory effect, these spins increase the coupling energy from U_1 to U_2 by relaxation at the stop temperature. Assuming that these spins initially occupy two states with the same probabilities, the difference in magnetization between the reference and the waiting can be written as

$$\Delta m = \frac{\mu^2 h}{k_B T}\left(\mathrm{e}^{-t/\tau_1} - \mathrm{e}^{-t/\tau_2}\right), \tag{7}$$

in which $\tau_i = \tau_0 e^{U_i/k_B T}$ $(i = 1, 2)$, with τ_0 being the characteristic constant and usually takes $10^{-9} \sim 10^{-12}$ s, h is the small applied field and μ is the spin moment. Since the measurement time at each temperature point is set to be t_0 and the energy increment ΔU caused by relaxation is far less than the coupling energy, that is, $\Delta U << U_1$ or U_2, at low temperatures, the above equation can be simplified into

$$\Delta m = \frac{\mu^2 h \Delta U t_0}{\tau_0 (k_B T)^2}\mathrm{e}^{-U_1/k_B T}. \tag{8}$$

As T decreases, Δm rapidly approaches to zero. This manifests that the magnetization difference caused by relaxation must disappear with temperature decreasing. At high temperatures, it can be seen from Eq. (7) that $\mathrm{e}^{-t/\tau_i} \approx 0$, thus Δm also approaches to zero. From the above analysis, the magnetization of the waiting must merge with the reference at low and high temperatures, only deviates heavily from its value near the stop temperature, which corresponds to $t_w/\tau \sim 1$.

For the aging effect, the relaxed spins must be confined to those spins with $t_w/\tau \sim 1$ as discussed above. Similarly, the relaxation causes the coupling energy to increase ΔU. The magnetization of the waiting is the sum of the reference and the difference between them. The spins without relaxation contribute logarithmic magnetization,[28] owing to their distributed coupling energy, and the relaxation rate keeps constant in the zero order approximation, i.e., $S^{(0)} = k_B T/\langle U\rangle$, in which $\langle U\rangle$ is the average coupling energy. But the relaxed spins in the waiting glass contribute less magnetization compared with those in the reference. Thus the magnetization difference and the relaxation rate in the first order approximation can be

written as

$$\Delta m = -\frac{\mu^2 h \Delta U}{(k_{\rm B}T)^2} \cdot \frac{t}{\tau} {\rm e}^{-t/\tau}, \tag{9}$$

$$S^{(1)} = \Delta m \cdot (t/\tau - 1). \tag{10}$$

Due to $t_{\rm w}/\tau \sim 1$, this rate is found to peak near $t_{\rm w}$.

Essentially, the aging effect and the memory effect are induced by those well-relaxed spins. When the spin glass relaxes at a certain temperature ($T_{\rm s}$), only the spins with $t_{\rm w}/\tau \sim 1$ increase their coupling energy while the others are not affected. Hence the magnetization is little affected when the system is apart from $T_{\rm s}$. But when it returns to $T_{\rm s}$, the relaxed spins become more robust against flipping, thus make dips both in magnetization and in susceptibility. Similarly, for aging at $T_{\rm s}$, energy relaxation happens only to those spins with $\tau \sim t_{\rm w}$ while those with $\tau << t_{\rm w}$ or $\tau >> t_{\rm w}$ are almost not affected. When the measurement time passes $t_{\rm w}$, those well-relaxed spins cause progressive magnetization dip and eventually make contribution to the maximum of relaxation rate.

5. Conclusion

Using the dynamical Monte Carlo simulation we study the nonequilibrium properties of RKKY interacting spin glass. Our simulations reproduce well-known aging and memory effects observed in experiments. We find that relaxation can lead to coupling strengthening of the corresponding spins, thereby reducing the magnetization near the stop temperature. According to the master equation and the energy relaxation, we draw the dynamical explanations to the aging effect and the memory effect. Since the exploration of spin glass is always a research focus of magnetism and disordered system,[29,30] our simulations maybe benefit the future research.

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