Dynamical properties of temperature chaos and memory effect

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In the frustrated interaction systems, the nature of ordered configuration can be intrinsically temperature dependent. There, the idea of effective coupling of decorated and frustrated bond plays an important role. The idea of effective coupling is verified in the study of equilibrium properties. We will study how the effective coupling is realized in the dynamical processes, e.g. the relaxation time after a change of temperature. We also study the memory phenomena which have been found in the spin glass.

§1. Introduction

Researches on the spin glass have been made in both-sides side of a theory and an experiment for the past dozens of years. An interesting dynamical characteristic called aging phenomena have appeared\cite{1}-\cite{9}. There are following features in the aging phenomena. The first is memory effect. It is observed by the experiments of temperature cycling\cite{1}-\cite{6}. In these experiments, temperature change is carried out at a fixed speed, and at a certain temperature $T_1$ the temperature is fixed for a time $t_w$ (waiting time). During which the dynamical susceptibility reduces to a certain value. After that, the temperature is changed again up to $T_2$ ($T_1 > T_2$), and then it is swept back to $T_1$ at the same speed. The value of susceptibility observed at $T_1$ is reproduced, this phenomenon is called memory effect. The second is rejuvenation. It is found in the same protocol where the memory effect is observed. When the temperature is reduced below $T_1$, the susceptibility increases again. This means that the system is more disordered, although the temperature is decreased, which is called rejuvenation. This phenomenon indicates that ordering pattern is temperature dependent, which is called temperature chaos.

Although interesting phenomena have been observed in experiments, there are only few explanations for these phenomena from microscopic viewpoint. Yoshino et al.\cite{10} and Miyashita et al.\cite{11} studied a mechanism of the memory effect. The latter introduced a microscopic mechanism of the temperature dependence and an idea of “memory spot”, by which they demonstrated the memory effect. But in their study, the change of the effective temperature is assumed by hand. Thus, in this paper, we will study a microscopic bond configuration which realizes the change of the effective coupling automatically, and try to realize the memory effect. We study a model with a certain combination of bond which is called “decoration bond”\cite{12}.

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§2. Model and Numerical experiment protocol

We introduce a decoration bond in order to realize temperature dependence of the effective coupling, and study microscopic mechanism of the dynamics of the memory effect. As shown in Fig. 1(a), we prepare a system which is a $10 \times 10$ square lattice. Each bond of the lattice, which we call “system bond”, consists of a set of bonds depicted in Fig. 1(b). The effective coupling of the bond $K_{\text{eff}}$ is defined by $e^{K_{\text{eff}} \sigma_1 \sigma_2} \propto \text{Tr}_{\{s\}} e^{-\beta \mathcal{H}}$. Concretely, for Fig. 1(b), we have

$$K_{\text{eff}} = m \cdot \left( \frac{1}{2} \log \left[ \frac{\cosh \beta (J_1 + J_2)}{\cosh \beta (J_1 - J_2)} \right] - \beta J_3 \right), \quad \left( \beta = \frac{1}{k_B T} \right), \quad (2.1)$$

where $m$ is the number of sets of the decoration bond in a system bond.

Because $K_{\text{eff}}$ of this single decoration bond does not exceed, the transition value $K_c$ of the two dimensional Ising model. For this reason, we arrange ten sets of the decoration bond (see Fig. 1(c)). The total effective coupling exceeds $K_c$. So that, it is expected that ferromagnetic order appears at $T_1$ and antiferromagnetic order at $T_2$. We consider that an effective interaction contributes to the temperature selectivity nature of an aging phenomenon. Temperature dependence of $K_{\text{eff}}$ is nonmonotonic. In other words, it shows a reentrant phenomenon. Using $J_1 = 0.6$, $J_2 = -0.7$, $J_3 = 0.28$ (positive constant denotes a ferromagnetic coupling), the effective coupling exceeds $K_c$ as depicted in Fig. 1(d). For this reason, at $T_1$ the system is ordered ferromagnetically, and at $T_2$ the system is ordered antiferromagnetically.

However, in fact, at low temperature side ($T_2$), the order expected from $K_{\text{eff}}$ does not appear in a short time. A kind of freezing appears if the values of decoration bonds are not chosen appropriately. About this problem, we will discuss in the next section. Next, we introduce a configuration for a memory spot, which is drawn by the thick line in Fig. 1(a). It serves as a local strong interaction to keep memory.

![Fig. 1](image_url)
§3. Dynamical aspects and Results

3.1. Mechanism of slowing down

It turned out a sequence of ferromagnetic order $\rightarrow$ antiferromagnetic order $\rightarrow$ ferromagnetic order is brought thanks to the effective coupling which is induced by the decoration bonds. However, as pointed out in the previous section, the expected order does not in a short time. Fig. 2 shows a 0 of decoration spins which does not relaxed easily, although the center spin can flip free by in the lattice of a single bond. We defined an effective time $t_{\text{eff}}$ by calculating a probability of a flip of this “free system spin”. In Fig. 2, between the center spin (−) and the + spins, the internal field on the decoration spin is $J_1 - J_2 = J_1 + |J_2| = 1.3$, and the decoration spins are ordered in + direction with a high probability $p = \exp(1.3\beta)/(1 + \exp(1.3\beta))$. The expectation value of the internal field from the + spins $H^+$ is $\langle H^+ \rangle = m \times (1 - 2p)(J_1 + |J_2|)$. On the other hand, between the center spin and the − spins, the internal field on the decoration spin is $-J_1 - J_2 = -J_1 + |J_2| = 0.1$, and the decoration spins are ordered in + direction with a low probability $p' = \exp(0.1\beta)/(1 + \exp(0.1\beta))$. The expectation value of the internal field from the + spins $H^−$ is $\langle H^− \rangle = -m \times (1 - 2p)(-J_1 + |J_2|)$. Thus the internal field on the center spin tends to be negative and the center spin is stabilized to be the present value. If the center spin is initially +, the state is stabilized in the same scenario. The center spin (−) can flip when $H^+ + H^− \leq 0$, the probability of which is very small. We defined an effective time $t_{\text{eff}}$ by considering flipping probability of this free system spin. In the present situation, $t_{\text{eff}}$ is estimated to be about 357 at $T_2$, which caused slowdown of the relaxation by about 357 times. If we use the same strength for $J_1$ and $J_2$, the ratio of $p$ and $p'$ becomes large and $t_{\text{eff}} \simeq 613$.

It should be noted that, if we use a longer decoration bond, the domain wall presents near the center of bond and the system spins are screened by favorable neighborhood spins and strongly stabilized, which causes extremely long relaxation.

3.2. Memory spot to realize the memory effect

In this subsection, we will demonstrate this memory of a ordering pattern. We consider a large system consisting of $5 \times 5$ of the unit clusters. Fig. 1(a) coupled by a weak decoration bond($J' = 0.2J$). After a new order develops at $T_2$, the order at $T_1$ is erased, and when the temperature comes back to $T_1$, the original order is usually not reproduced. However, if the memory spot is introduced, the order is reproduced. In Fig. 3, ferromagnetic order formed at 20000MCS. After that, temperature is changed to $T_2$. There, the ferromagnetic order is destroyed, and antiferromagnetic order begins to form. However, as we explains above, the development of antiferro-
magnetic order is very slow. At 40000MCS, the antiferromagnetic order completed at each cluster. And after the temperature is increased to $T_1$. There, the antiferromagnetic order is destroyed and ferromagnetic order appears in the same pattern as the previous one. This process demonstrates the memory effect. In each cluster, the ferromagnetic order spreads from each memory spot. It will be an interesting future problem to find some design to realize two or more memories.

Fig. 3. From 0 to 20000 MCS, the temperature is $T_1 = 3$ at which $K_{eff} > K_c$, as a result, the ferromagnetic order appears. Next, From 20000 to 40000 MCS, the temperature is $T_2 = 1$ at which $K_{eff} < -K_c$. As a result, the antiferromagnetic order appears. At last, the configuration returns to that at 20000 MCS due to the memory spot.

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