The step effect of hysteresis loop in FM/AFM mixed magnetic system

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Abstract. By using statistical analysis and Monte Carlo simulation, we investigate the nature of step effect in the hysteresis loop with ± J Ising model and Heisenberg model respectively. The results indicate that it is the strong anisotropy, weak magnetic dipolar interaction, and low temperature that together induce the step effect of ferromagnetic (FM) and antiferromagnetic (AFM) mixed magnetic system, and the results are in good agreement with experiments phenomenally. That makes us view spin glass and magnetic sensor from a new aspect.

1. Introduction

Recently the exchange bias properties of FM/AFM mixed magnetic systems [1-4] are widely discussed because of its significance to understanding some interesting magnetic phenomena. On account of zero magnetization in virgin state, the site-diluted antiferromagnets [5-8] have attracted many researchers’ interests. In 1997, Viitala and coworkers [9] have observed steplike magnetization curves with the nearest-neighbor Ising model. Then Vogel et al. [10] have also acquired hysteresis curves in ± J Ising square lattices and triangular lattices. Subsequently, Slalas-Solis et al. [11] added anisotropy to the Edwards-Anderson model, and found ladders of irregular step width and height. That is in accordance with the properties of real systems qualitatively.

In some excellent experiments there appears similar phenomena like the step effect. For example, Kushauer et al. [12] found the magnetization avalanches in dilute layered antiferromagnets of Fe₉Mg₁₋ₓCl₂ at low temperatures. Zhang and co-workers [13] also reported a similar result in the layered cluster compound NbFeTe₂.

In the present paper, we will give a detailed account of the step effect, and the outline is as follows. In section 2, physical origin of step effect is investigated in FM/AFM Ising lattice. And in section 3, we study the influence of anisotropy and dipolar interaction on this effect in FM/AFM Heisenberg lattice. Finally, section 4 is the part of analysis and discussion for the simulation results.

2. The step effect of hysteresis loop in FM/AFM Ising square lattice

Let us consider a two-dimensional (2D) Ising square lattice of \( N = L \times L \) sites. The Hamiltonian can be written as

\[
H = \sum_{\langle i,j \rangle} J_{ij} S_i S_j - H \sum_i S_i
\]
where $S_i$ is spin of site $i$. $J_{ij}$ denotes the exchange constant between $S_i$ and $S_j$ and $H$ is the external magnetic field. The FM and AFM sites for $(FM)_x(AFM)_{1-x}$ lattice are prepared by a stochastic distribution, and periodic boundary conditions are assumed. The results are shown in figure 1. It is obvious that each hysteresis curve with different concentration $x$ is divided into four parts, which is similar to Vogel’s work [10]. We also investigate the rate of spin up and spin down during the whole cycle, which indicates that the AFM points always flip firstly and influences the spin patterns. To make the underlying principle clear, we discuss the corresponding spin patterns in following parts.

Figure 1. Hysteresis curves for $60\times60$ $(FM)_x(AFM)_{1-x}$ Ising lattice at $T=0.01$.

From the view of statistics, for $(FM)_x(AFM)_{1-x}$ Ising square lattice, the probability of the isolated FM point is $x(1-x)^4$ and for AFM point, it is $x^4(1-x)$. Obviously, for a saturated system, the change of Zeeman energy induced by the overturn of isolated FM spin is $2H$ and the increment of exchange energy is $-8$. On account of the energy, isolated FM points flip to down at $H \leq 4$, so do the isolated AFM points. At $H = 4^-$ the magnetization per site is

$$M_i = 1 \to 1 - 2\left[x(1-x)^4 + x^4(1-x)^4\right].$$

Figure 2. Hysteresis curves of Monte Carlo (broken line) and statistic (continuous line).

For the isolated FM or AFM pair, in the same way, the probability of FM pair is $x^2(1-x)^6$ and for AFM pair, it is $x^6(1-x)^2$. For an $N$-sited system, the number of isolated pairs is $Nz/2 = 2N$ for coordination number $z=4$. So the number per site is 2, i.e., the probability becomes $2x^2(1-x)^6$ /site. And $2x^6(1-x)^2$ is for AFM pair. So the isolated FM pairs will flip down at $H \leq 3$. The above calculation is applicable for AFM pairs. Then the magnetization per site is

$$M_2 = M_1 - 8\left[x^2(1-x)^6 + x^6(1-x)^2\right]$$

at $H = 3^-$. More analysis results are listed in figure 2.

We can easily find there exists difference. In order to acquire more convicitive illustration, we investigate the spin patterns for an $60\times60$ Ising lattice with concentration $x=0.9$. It can be concluded that the AFM points begin to flip down at $H = 4$ with the reduction of magnetic field from saturation. It is necessary to pay special attention to AFM pairs in which the two spins don’t flip simultaneously. Neither do the other spin configurations. That may be

Figure 3. Diagrammatic sketch of spin patterns (solid row denotes FM spin and the hollow row denotes AFM spin).
the genuine of the discrepancy shown in figure 2. Further we give a new statistical analysis. In figure 3(b), as one AFM spin reverses, the other doesn’t do until $H = 2$ because of the energy. It is different from the above result $H = 3$. Similarly, in figure 3(c), the overturn of the three AFM sites is also not at the same time. At $H = 4$ the two bilateral spins can reverse, but the middle turns till $H = 0$. It is surely applicable for 4-sited group. In figure 3(e), the middle one reverses at $H = -2$. If it reverses firstly as shown in figure 3(f), magnetic field required will be $H = 2$.

Then we can conclude that the critical magnetic field for the isolated sites is $H = 4, 2, 0, -2, -4$. It can be verified as follows: for a lattice with coordination number $Z$, the exchange energy of one site is one of the summations of the number $Z$ with 1 or -1. For $Z = 4$, it is $0, +2, +4$. Once it reverses, the increment of exchange energy is $0, +4, +8$ and to Zeeman energy, it is $\pm 2H$. Therefore we can attain the critical field $H_C = 0, +2, +4$. For $Z = 3$, the critical field is $H_C = 1, +3$; and for $Z = 6$, it is $H_C = 0, +2, +4, +6$. For $Z = 8$, it is $H_C = 0, +2, +6, +8$ and so on. We can conclude that at $H = Z$ the width of steps is $\Delta H = 2$.

On existing knowledge, we can predict that the steps will be weakened with the magnitude of the spin increasing, while we acquire the same results for $(FM)_{0.5}(AFM)_{0.5}$ Ising lattice, through using Gaussian distribution with the mean random number 1 and standard deviation $\sigma$, as shown in figure 4.

3. Monte Carlo simulation of FM/AFM Heisenberg lattice

In order to give a more detailed illustration the influence of anisotropy and dipolar interaction is investigated at low temperature. Let us consider Heisenberg model for the $N = L \times L$ square lattice and magnetic field $H$ along the axis of $z$ is applied. The Hamiltonian of such a system is in the form,

$$H = \sum_{\langle i,j \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j + D \sum_{i,j}^5 \frac{3 (\vec{S}_i \cdot \vec{r}_{ij}) (\vec{S}_j \cdot \vec{r}_{ij})}{r_{ij}^5} - K \sum_i (\vec{S}_i \cdot \vec{u}_i)^2 - H \sum_i S_i^z$$

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure4.png}
\caption{Hysteresis curves in Ising lattice with different $\sigma$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5.png}
\caption{Hysteresis curves in Heisenberg lattice with different anisotropy constant.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure6.png}
\caption{Hysteresis curves in Heisenberg lattice with different dipolar interaction.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure7.png}
\caption{Hysteresis curves in Heisenberg lattice with different temperature.}
\end{figure}
where $\vec{S}_i$ and $\vec{S}_j$ are the total spins of the $i$-th and $j$-th site respectively, separated by distance $\vec{r}_{ij}$, and $S^z_i$ is the $z$ component. As above mentioned, $J_{ij}$, $D$, and $K$ are exchange coefficient, dipolar interaction and anisotropy constant respectively. The first term on the right of the above equation is exchange energy and the second is dipolar energy. Then the third is anisotropy energy and the last term is Zeeman energy. Generally, we consider the nearest neighbors exchange interaction. Because dipolar interaction is a long-rang interaction, the summation is over all neighbors confining to $L$.

On one hand, figure 5 shows the result for $(FM)_{0.1}(AFM)_{0.9}$ lattice with $K=1.0, 1.5, 2.0, 2.5$ and $D=0$. And we can see that the decreasing of $K$ makes the hysteresis loop smooth. That illustrates that step effect exists with strong anisotropy. On the other hand, we study the properties of $(FM)_{0.5}(AFM)_{0.5}$ lattice with $K=2.5$ and $D=10^{-4}, 10^{-5}$ as shown in figure 6. It indicates that the steps are also weakened with the dipolar interaction increasing. So we can say it is the weak dipolar interaction that induces the step effect. Then the temperature effect is simulated for $(FM)_{0.9}(AFM)_{0.1}$ lattice with the size $100 \times 100$ and $K=1.0$. The results are shown in figure 7. It is obvious that curves become smooth with temperature increasing, which has the same tendency with the Ising result of Vogel et al. [10].

4. Conclusions

In conclusion, by statistical analysis and Monte Carlo simulation we investigate the nature of step effect in FM/AFM mixed magnetic system with $\pm J$ Ising model and Heisenberg model. The result is that step effect is originated from the strong anisotropy, weak dipole interaction, and low temperature altogether. Our results are in good agreement with those experimental ones. That makes us view the spin glass and magnetic sensor from a new aspect.

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