Magnetic properties of a spin system in a longitudinal magnetic field

Wei Jiang and Bao-Dong Bai
College of Sciences, Shenyang University of Technology, Shenyang 110023, China and Department of Applied Physics, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China

Veng-Cheong Lo
Department of Applied Physics, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China

Wei Liu
Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

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The hysteresis loops and susceptibility of spin system with the crystal field have been studied within the framework of the effective-field theory with the differential technique. The effects of the external longitudinal magnetic field on the magnetization and susceptibility are discussed in detail. Numerical results are performed and analyzed for the cases of the honeycomb and square lattice. A number of interesting phenomena have been found due to the applied longitudinal magnetic field, such as, the shape of hysteresis loops and susceptibility are dependent on the longitudinal magnetic field and crystal field. The peak of susceptibility of the honeycomb lattice is bigger than that of the square lattice when the parameters are the same in the two systems. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1853210]

I. INTRODUCTION

Experimental investigations of magnetic systems applied to the longitudinal magnetic field, have been studied for many years.[1–3] The results show that the longitudinal magnetic field has a strong influence on magnetic properties of the system. Theoretically, few works have been extended to the Ising system by taking into account the longitudinal magnetic field. Wei[4] has discussed the magnetic properties of mixed-spin Ising systems in a longitudinal magnetic field. The thermal behaviors of magnetizations, susceptibilities, and phase transition are examined. They found some interesting results due to the applied external field. The magnetic properties of the mixed spin-1/2 and spin-1 Ising ferromagnetic system with a crystal-field interaction in the absence and presence of an external magnetic field are studied by using the cluster variation method.[5] Thermal variations of order parameters are investigated and the metastable and unstable branches of the order parameters are obtained besides the stable states. The influence of the external magnetic field on the system is also examined. On the other hand, in our previous works,[6–9] we have discussed the phase transition, magnetization, and specific heat of the higher spin Ising model with both the transverse magnetic field and crystal-field in the absence an external magnetic field. As far as we know, the high spin Ising systems with the crystal-field in external longitudinal field have not been studied. Particularly, less attention has been devoted to the hysteresis loops of the spin system theoretically.

In this paper, we studied the effects of the longitudinal magnetic field on magnetic properties of the spin system with the crystal-field. The formulation was based on the effective-field theory with the differential operator technique. In Sec. II, the theoretical formulation is shown. In Sec. III, numerical results for the polarization and susceptibility are presented in detail.

II. FORMULATIONS

The spin system with the crystal-field in a longitudinal magnetic field is described by the Hamiltonian

$$H = -J\sum_{\langle i,j\rangle} S_i^z S_j^z - D\sum_i (S_i^z)^2 - h\sum_i S_i^z, \tag{1}$$

where S_i^z and S_j^z are the components of quantum spin-S operator at site i and j. The first summation is carried out only over nearest-neighbor pairs. D is the crystal-field. J is the exchange interaction. h represents the longitudinal magnetic field.

Within the effective-field theory with correlations and differential operator technique, we can investigate the magnetization for the present system with a coordination number z. We will study the honeycomb ($z=3$) and square ($z=4$) lattices for spin-3/2. The magnetization for the system is given as in Refs. 6–9 by

$$M = \langle S_i^z\rangle = \langle \exp(E_i \nabla)\rangle F(x)|_{x=0} = \left[\cosh(J\eta\nabla) + \frac{M}{\eta}\sinh(J\eta\nabla)\right]^z F(x)|_{x=0}, \tag{2}$$

$$\eta^2 = \langle (S_i^z)^2\rangle = \langle \exp(E_i \nabla)\rangle G(x)|_{x=0} = \left[\cosh(J\eta\nabla) + \frac{M}{\eta}\sinh(J\eta\nabla)\right]^z G(x)|_{x=0}, \tag{3}$$

where $\nabla = \partial/\partial x$ is the differential operator. The expressions

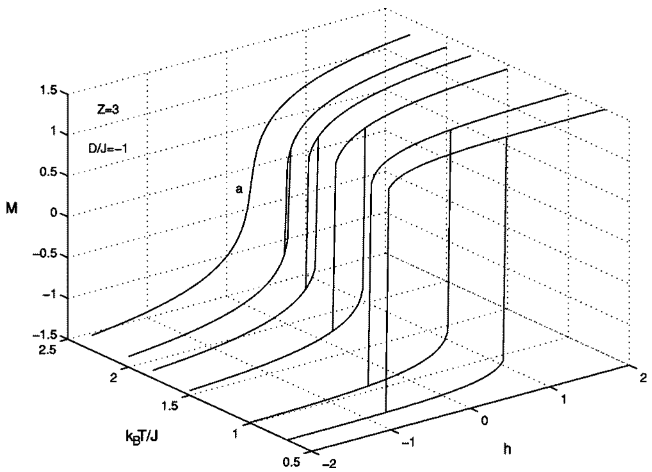

FIG. 1. The hysteresis loops for the honeycomb lattice of spin-3/2 system in three-dimensional space $(h, k_BT/J, M)$, when the crystal-field is selected as $D/J=-1$.

of the functions $F(x)$ and $G(x)$ can be, respectively, described as

$$F(x) = \frac{3\sinh\left[\frac{3}{2}\beta(x+h)\right] + \exp(-2D\beta)\sinh\left[\frac{1}{2}\beta(x+h)\right]}{2\cosh\left[\frac{3}{2}\beta(x+h)\right] + 2\exp(-2D\beta)\cosh\left[\frac{1}{2}\beta(x+h)\right]}, \quad (4)$$

$$G(x) = \frac{9\cosh\left[\frac{3}{2}\beta(x+h)\right] + \exp(-2D\beta)\cosh\left[\frac{1}{2}\beta(x+h)\right]}{4\cosh\left[\frac{3}{2}\beta(x+h)\right] + 4\exp(-2D\beta)\cosh\left[\frac{1}{2}\beta(x+h)\right]}. \quad (5)$$

Here, $\beta=1/k_BT$, k_B is the Boltzmann constant, and T is the absolute temperature. The longitudinal susceptibility for the system can be determined from the relation

$$\chi = \partial M/\partial h. \quad (6)$$

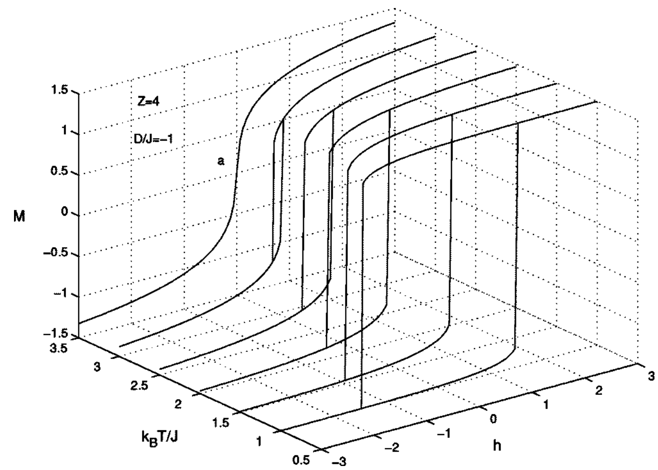

FIG. 3. The hysteresis loops for the square lattice of spin-3/2 system in three-dimensional space $(h, k_BT/J, M)$, when the crystal-field is selected as $D/J=-1$.

III. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we shall present numerical results for the hysteresis loops and susceptibility of the spin-3/2 with crystal-field on the honeycomb and square lattices by applying longitudinal magnetic field. The magnetizations are a function of temperature, exchange interaction, crystal-field and longitudinal magnetic field and depending on the value of temperature and longitudinal magnetic field. The hysteresis loops are plotted in Figs. 1–4. The curves in Figs. 1–4 represent the case of the honeycomb lattice $(Z=3)$ and square lattice $(Z=4)$, respectively. From our calculation, we can find that when we applied the longitudinal magnetic field $(h>0$ or $h<0)$, the absolute magnetizations decrease slowly from their saturation magnetizations to remaining magnetizations with increasing temperatures. The remaining magnetizations are bigger with increasing of the longitudinal mag-

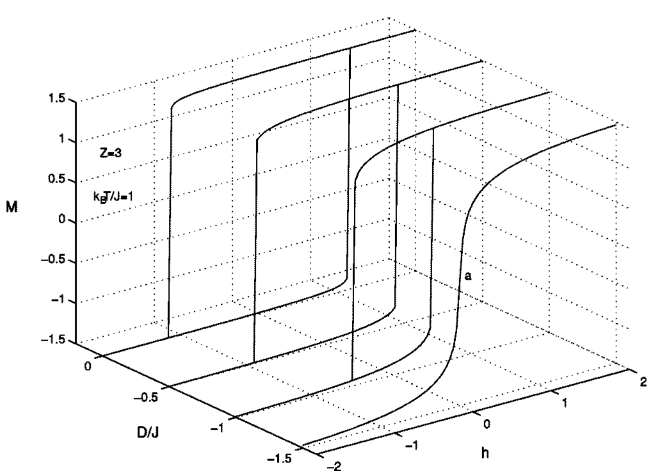

FIG. 2. The hysteresis loops for the honeycomb lattice of spin-3/2 system in three-dimensional space $(h, D/J, M)$, when the temperature is selected as $k_BT/J=1$.

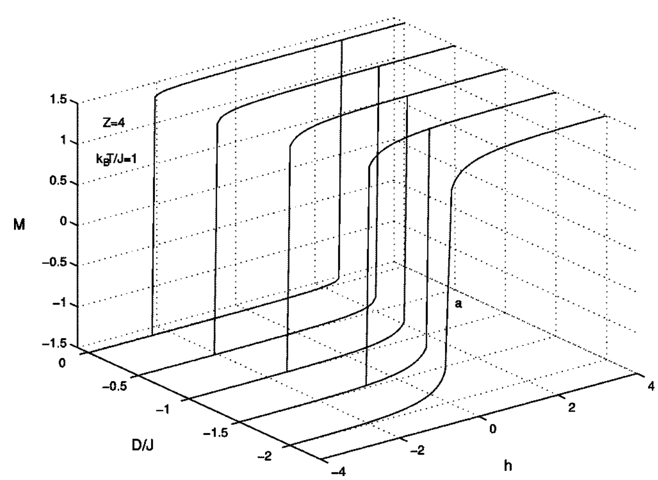

FIG. 4. The hysteresis loops for the square lattice of spin-3/2 system in three-dimensional space $(h, D/J, M)$, when the temperature is selected as $k_BT/J=1$.

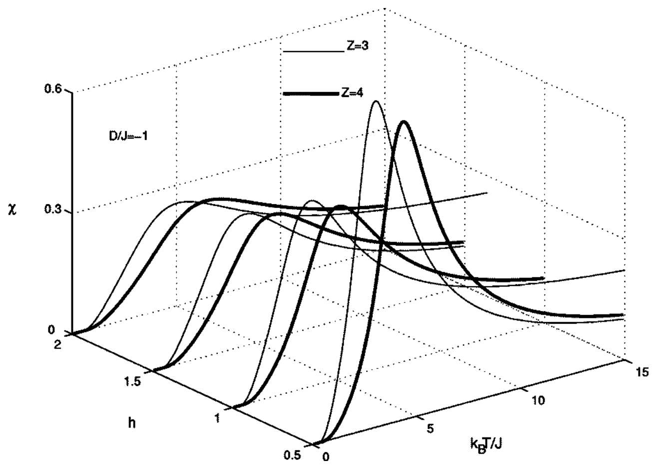

FIG. 5. The susceptibility for the spin-3/2 system in three-dimensional space $(k_BT/J,h,\chi)$, when the crystal-field is selected as $D/J=-1$. The solid curves and bold curves represent the case of the honeycomb and square lattices, respectively.

netic field. We can also see that the magnetization curves symmetric for both positive and negative longitudinal magnetic field. These results are quite different from those of previous works[6–9] in which without applying longitudinal magnetic field. Notice that when the crystal-field is fixed as $D/J=-1$, as seen from Figs. 1 and 3. The type of hysteresis loops become narrower with increasing temperature below the transition temperature. Then the hysteresis loop disappears when the temperature is higher than the transition temperature; the curves labeled *a* are such the cases in Figs. 1 and 3. When the temperature is selected as $k_BT/J=1$, the type of hysteresis loops become narrower with increasing the absolute value of the crystal-field. Then the hysteresis loop disappears when the absolute value of the crystal-field is large enough, the curves labeled *a* are such the cases in Figs. 2 and 4. It is interesting to compare the effects of the longitudinal magnetic field on the magnetization of the honeycomb and square lattice. When the parameters (temperature, crystal-field) are the same, the hysteresis loop of square lattice is larger than that of the honeycomb lattice.

In Fig. 5, we plot the numerical results of the susceptibility for the spin-3/2 system with the crystal-field on the honeycomb (solid curves), square (bold curves) lattices in three-dimensional space $(k_BT/J,h,\chi)$, when the crystal-field is selected as $D/J=-1$. It can be seen that the curves of susceptibility rapidly increase and express the peak at the transition temperature and then rapidly decrease with the increasing of temperature. The stronger the longitudinal magnetic field, the smaller is the susceptibility, reflecting the fact that the magnetization is weaker. From Fig. 5, we can also see that the peak of susceptibility of the honeycomb lattice is bigger than that of the square lattice when the parameters are the same in the two systems.

IV. CONCLUSIONS

In this work, within the framework of the effective-field theory based on the differential technique, we have studied the magnetic properties of the spin-3/2 system with the crystal-field applied external magnetic field. The influence of the longitudinal magnetic field on the hysteresis loops and susceptibilities have been discussed in detail. The type of hysteresis loops can be changed that depend on the temperature and value of crystal-field. The stronger the longitudinal magnetic field, the smaller the susceptibility, reflecting the fact that the magnetization is weaker. On the other hand, the conventional mean field theory is simple and many useful results for various spin systems have been obtained. Because it neglects all the spin–spin correlations, it is still far from satisfactory. The EFT with correlations considered partially the spin–spin correlations, and has been successfully applied to a variety of spin Ising problems, which is superior to conventional mean field theory.

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