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Magnetizations and compensation behaviors of the bond and crystal field dilution mixed spin Blume–Capel model in an external magnetic field

Shilei Yan[a,b,d,*], Lei Liu[a,c]

[a] Department of Physics, Suzhou University, Suzhou 215006, China
[b] Jiangsu Key Loboratory of Thin Films, Suzhou University, Suzhou 215006, China
[c] Department of Physics, Henan Science and Technology University, Luoyang 471000, China
[d] CCAST (World Loboratory), P.O. Box 8730, Beijing 100080, China

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Abstract

Magnetizations and compensation behaviors of the bond and crystal field dilution mixed spin-$\frac{1}{2}$ and spin-1 Blume–Capel model in an external magnetic field are investigated by using the effective field theory on simple cubic lattice. Magnetization and compensation point dependences of temperature or external magnetic field for different parameters are calculated. We find a new magnetic compensation behavior in $M-H$ space and define a compensation magnetic field H_k. The crystal field and magnetic field have the effect of changing the compensation temperature in $M-T$ space, while the crystal field and bond dilution can affect the compensation magnetic field. There is a magnetization plateau for $H<H_k$ at low temperatures. The magnetic compensation behaviors are not revealed in previous works and predicted by Nèel theory of ferrimagnetism.

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1. Introduction

Mixed spin system has been a subject of extensive investigation for a long time because it can provide many interesting and important phenomena. For instance, the mixed spin-$\frac{1}{2}$ and spin-S ($S=1$ or 2) Ising model with crystal field has shown that there exists tricritical point on the phase diagram with a coordination number larger than $z=4$ [1]. The crystal field or transverse field can induce new magnetic ordering in bond or site dilution mixed Ising model [2–4]. The different mixed spin Ising models are treated by using various techniques, such as mean field approximation [5,6], effective field theory [7,8], pair approximation [9], cluster variational method [10], Monte-Carlo simulations [11–13] and a precise numerical solution [14–16].

Another remarkable problem is ferrimagnetic properties of the mixed spin Ising model. One notes that, in a ferrimagnet, there is one or multi-compensation points at which the resultant magnetization vanishes below its Curie temperature. From the theoretical aspects, in the mixed spin-$\frac{1}{2}$ and spin-1 Ising model, different transverse fields or crystal field can induce the compensation point [5,6,11,16,17,]. Kaneyoshi has reviewed the mutli-compensation points for a decorated square lattice [18]. From the experimental evidences, some studies have shown the stability of a compensation point, such as single film thickness in Tb/Fe films [19], the crystalline $BiDyFe_5O_{12}$ samples [20], and the composition in Dy/FeCo structure [21]. Some of the synthetic compounds such as $AFe^{II}Fe^{III}$

*Corresponding author. Department of Physics, Suzhou University, Suzhou 215006, China. Tel.: +86 512 65111061; fax: +86 512 65111907.
E-mail address: slyan@suda.edu.cn (S. Yan).

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$(C_2O_4)_3$ [$A = N(n\text{–}C_nH_{2n+1})_4$, $n = 3$–5] exist compensation point near 30 K, depending on the kind of a cation A^+ [22]. From the technological applications, it is important to exist compensation point because of the high coercivity around the point. The feature has important applications in the field of magneto-optic recording.

The mixed spin Blume–Capel model (BCM) [23] is one of the most important models in the family of mixed Ising model and is a development of the spin-1 BCM [24]. One notes that various random distributions in the mixed BCM play an important role for description of critical behaviors and magnetic properties. Some authors have studied the critical behaviors of the mixed BCM with random crystal field [25] and the compensation point of the bond dilution mixed BCM [26]. On the other hand, the ferromagnetic spin-1 BCM in an external magnetic field has been treated by mean field theory [27], effective field theory [28] and an iteration technique [29]. Recently, Ekiz has given the magnetic properties of mixed Ising system on the Bethe lattice in an external magnetic field by using exact recursion relations [30]. In this work, we consider the bond and crystal field dilution mixed spin-$\frac{1}{2}$ and spin-1 BCM in an external magnetic field. Magnetizations and compensation point dependences of temperature or external magnetic field for different parameters are calculated. We find a new magnetic compensation behavior in $M-H$ space and define a compensation magnetic field H_k. The crystal field and magnetic field have the effect of changing the compensation temperature in $M-T$, while the crystat field and bond dilution can affect the compensation magnetic field in $M-H$ space. Moreover, there is a magnetization plateau for $H<H_k$ at low temperatures. Additionally, the theoretical procedure is based on the effective field theory (EFT) introduced by Honmura and Kaneyoshi [31].

The outline of this work is as follows. In Section 2, the expressions of the spin-$\frac{1}{2}$ and spin-1 bond and crystal field dilution BCM in an external magnetic field for evaluating magnetizations are presented. In Section 3, magnetizations and compensation behaviors are investigated in detail. We also include the discussions of possible physical reasons in this section. A brief conclusion is given in Section 4.

2. Theory

The Hamiltonian of the bond and crystal field dilution mixed spin-$\frac{1}{2}$ and spin-1 BCM in an external magnetic field can be defined as

$$H = -\sum_{\langle i,j\rangle} J_{ij}\sigma_i^z S_j^z - \sum_j D_j (S_j^z)^2 + H\left(\sum_i \sigma_i^z + \sum_j S_j^z\right). \tag{1}$$

The underlying lattice is composed of two interpenetrating sublattices A and B, where σ_i^z and σ_i^x are spin-$\frac{1}{2}$ Pauli matrices associated with the ith site in sublattice A, while S_j^z and S_j^x are spin-1 Pauli matrices associated with the jth site in sublattice B. The first summation is run only over all nearest-neighbor pairs of spins. The second summation extends over all sites of sublattice B. The third and the fourth summations involve all sites of sublattices A and B. J_{ij} is the exchange interaction between the nearest-neighbor sites, assumed to be $J_{ij}<0$. D_j represents an uniaxial crystal field parameter with the anisotropy (z) axis. H is an external magnetic field and is parallel to the (z) axis. J_{ij} and D_j can satisfy independent dilution distribtuions, respectively,

$$P(J_{ij}) = p\delta(J_{ij} - J) + (1-p)\delta(J_{ij}), \tag{2}$$

$$P(D_j) = t\delta(D_j - D) + (1-t)\delta(D_j), \tag{3}$$

where $p_c<p\leqslant 1.0$ and $0\leqslant t\leqslant 1.0$. Let p denotes the bond dilution concentration and t indicates the crystal field dilution concentration. The starting point of the statistics of the system is exactly Callen's identity [32]. Within the EFT, the averaged magnetizations of sublattices A and B are given by

$$\sigma = \langle\langle \sigma_i^z \rangle\rangle_r = \left\langle\left\langle \prod_{j=1}^{z}\left[(S_j^z)^2 \cos h(J_{ij}\nabla) + S_j^z \sin h(J_{ij}\nabla) + 1 - (S_j^z)^2\right]\right\rangle\right\rangle_r F(x)\big|_{x=0} \tag{4}$$

and

$$m = \langle\langle S_i^z \rangle\rangle_r = \left\langle\left\langle \prod_{i=1}^{z}\left[\cos h\left(\frac{1}{2}J_{ij}\nabla\right) + 2\sigma_i^z \sin h\left(\frac{1}{2}J_{ij}\nabla\right)\right]\right\rangle\right\rangle_r G(x)\big|_{x=0}. \tag{5}$$

The quadrupolar moment q is given by

$$q = \langle\langle (S_i^z)^2 \rangle\rangle_r = \left\langle\left\langle \prod_{i=1}^{z}\left[\cos h\left(\frac{1}{2}J_{ij}\nabla\right) + 2\sigma_i^z \sin h\left(\frac{1}{2}J_{ij}\nabla\right)\right]\right\rangle\right\rangle_r L(x)\big|_{x=0}, \tag{6}$$

where $\nabla = \partial/\partial x$, $\langle \ldots \rangle$ indicates the canonical thermal average, and $\langle \ldots \rangle_r$ denotes the bond dilution average for Eq. (2). The functions $F(x)$ is defined by

$$F(x) = \frac{1}{2}\tanh\left[\frac{\beta}{2}(x+H)\right], \tag{7}$$

where $\beta = 1/k_B T$. The functions $G(x)$ and $L(x)$ are defined by

$$G(x) = \int P(D_j) g(x, D_j)\,\mathrm{d}D_j, \tag{8}$$

$$L(x) = \int P(D_j) l(x, D_j)\,\mathrm{d}D_j \tag{9}$$

while $g(x,D_j)$ and $l(x,D_j)$ are as follows:

$$g(x, D_j) = \frac{2\sinh(\beta(x+H))}{2\cosh(\beta(x+H)) + e^{-\beta D_j}}, \tag{10}$$