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The phase diagrams and compensation behaviors of mixed spin Blume–Capel model in a trimodal magnetic field

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Abstract

The phase diagrams and compensation behaviors of mixed spin-$1/2$ and spin-1 Blume–Capel model in a trimodal magnetic field are investigated in the framework of the effective field theory on simple cubic lattice. The change of negative crystal field and trimodal concentration can affect the TCP, the second-order phase and the magnetic field degeneration at ground state in T–H space. In T–D space, the trajectory of the TCP takes on the acre curve and there exist the two TCPs under certain condition. In addition to giving one or two compensation temperature points in M–T space, the mixed spin Blume–Capel model also provides one or two novel compensation magnetic field points in M–H space. Some results are not revealed in previous works.

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Keywords: Phase diagram; Compensation behavior; Mixed spin Blume–Capel model; Trimodal magnetic field

1. Introduction

The phase diagrams and compensation behaviors of the mixed spin Ising model have been a subject of extensive investigation for a long time. The different mixed spin Ising models are treated by using various techniques, such as mean-field approximation [1,2], effective field theory with correlations [3,4], renormalization group [5,6], Monte Carlo simulation [7–10], a precise numerical solution [11–13] and so on. Some studies indicate that the mixed spin BCM in the absence or presence of the magnetic field can show a number of important critical behaviors, such as reentrant phenomenon and tricritical point [14–18]. We need to mention here that the phase diagrams of the mixed spin system under a unique magnetic field condition are not given. However, the phase diagrams can be obtained if the magnetic field satisfies a bimodal or trimodal distribution. Key problem lies on the presence of magnetic field symmetric disorder distribution and not on the exact form of disorder distribution. Recently, Benayad et al. have discussed the thermodynamical properties of trimodal magnetic field mixed spin transverse Ising model [19].

Another appealing problem is ferrimagnetic properties of the mixed spin Ising model. It is known that, in a ferrimagnet, there is one or multi-compensation temperature points at which the resultant magnetization vanishes below its Curie temperature [20–23]. It is important to have the compensation temperature points, because of the high coercivity around the points. From the material science point of view, such an investigation may be helpful for the thermomagnetic recording and magneto-optical readout applications [24]. In fact, some experimental studies have shown the stability of one or two compensation temperature points [25–27]. More recently, one of the present authors has given magnetizations and compensation behaviors of the bond and crystal field dilution mixed spin Blume–Capel model

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(BCM) in a magnetic field [28]. In that work, the author defined primarily a new compensation magnetic field H_K and found one magnetic compensation point at which the resultant magnetization vanishes below its saturation magnetic field.

In this work, we consider the phase diagrams and compensation behaviors of the mixed spin-1/2 and spin-1 BCM in a trimodal magnetic field. The calculated results show that the change of negative crystal field and trimodal concentration can affect the TCP, the second-order phase and the magnetic field degeneration at ground state in T–H space. In T–D space, the trajectory of the TCP takes on the acre curve and there exist the two TCPs. On the other hand, in addition to giving one or two compensation temperature points in M–T space, the present system also provides one or two novel compensation magnetic field points in M–H space. To our knowledge, some results have not been revealed in previous works. Here we employ an effective field theory (EFT) and a cutting approximation to discuss these problems.

2. Theory

For a mixed spin Blume–Capel model in a trimodal external field, the Hamiltonian is given by

$$H = -J\sum_{\langle ij\rangle}\sigma_i^z S_j^z - D\sum_j (S_j^z)^2 - \sum_i H_i\sigma_i^z - \sum_j H_j S_j^z. \quad (1)$$

The underlying lattice is composed of two interpenetrating sublattices A and B. One is occupied by spin-1/2 with spin moment σ_i^z at site i, while other one is occupied by spin-1 with spin moment S_j^z at site j. The first summation is carried out only all the 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. Here J defines the exchange interaction between the nearest-neighbour sites. D is the parameter of the crystal field, assumed to be negative. H_α ($\alpha = i$ or j) represents the longitudinal magnetic field acting on the sublattices A and B and satisfies trimodal probability distribution.

$$P(H_\alpha) = p\delta(H_\alpha) + \frac{1}{2}(1-p)\left[\delta(H_\alpha + H) + \delta(H_\alpha - H)\right], \quad (2)$$

where p indicates the trimodal magnetic field concentration in sublattice A and B. Within the EFT, the averaged magnetizations in sublattices A and B are given by

$$\sigma = \langle(\sigma_i^z)\rangle = \left\langle \prod_{j=1}^{z}\left[(S_j^z)^2\cosh(J\nabla) + S_j^z\sinh(J\nabla) + 1 - (S_j^z)^2\right]\right\rangle F(x)|_{x=0}, \quad (3)$$

$$m = \langle(S_j^z)\rangle = \left\langle \prod_{i=1}^{z}\left[\cosh\left(\frac{1}{2}J\nabla\right) + 2\sigma_i^z\sinh\left(\frac{1}{2}J\nabla\right)\right]\right\rangle G(x)|_{x=0}, \quad (4)$$

while the quadrupolar moment is given by

$$q = \langle(S_j^z)^2\rangle = \left\langle \prod_{i=1}^{z}\left[\cosh\left(\frac{1}{2}J\nabla\right) + 2\sigma_i^z\sinh\left(\frac{1}{2}J\nabla\right)\right]\right\rangle H(x)|_{x=0}, \quad (5)$$

where $\nabla = \partial/\partial x$ is a differential operator, $\langle\cdots\rangle$ indicates the canonical thermal average. The functions $F(x)$, $G(x)$ and $H(x)$ are defined by

$$F(x) = \int P(H_i)f(x, H_i)\,dH_i, \quad (6)$$

$$G(x) = \int P(H_j)g(x, H_j)\,dH_j, \quad (7)$$

$$H(x) = \int P(H_j)h(x, H_j)\,dH_j, \quad (8)$$

while

$$f(x, H_i) = \frac{1}{2}\tanh\left[\frac{\beta}{2}(x + H_i)\right], \quad (9)$$

$$g(x, H_j) = \frac{2\sinh[\beta(x + H_j]}{2\cosh[\beta(x + H_j)] + e^{-\beta D}}, \quad (10)$$

$$h(x, H_j) = \frac{2\cosh[\beta(x + H_j]}{2\cosh[\beta(x + H_j)] + e^{-\beta D}}. \quad (11)$$

If we try to treat exactly the multispins correlation presented in Eqs. (3)–(5), the problem is mathematically intractable. A cutting approximation is usually adopted

$$\langle\sigma_i^z\sigma_j^z\cdots\sigma_k^z\rangle \approx \langle\sigma_i^z\rangle\langle\sigma_j^z\rangle\cdots\langle\sigma_k^z\rangle, \quad (12)$$

$$\langle S_i^z(S_j^z)^2\cdots S_k^z\rangle \approx \langle S_i^z\rangle\langle(S_j^z)\rangle^2\cdots\langle S_k^z\rangle, \quad (13)$$

for $i \neq j \neq \cdots \neq k$. Then Eqs. (3)–(5) may be rewritten as

$$\sigma = \left[q\cosh(J\nabla) + m\sinh(J\nabla) + 1 - q\right]^z F(x)|_{x=0}, \quad (14)$$

$$m = \left[\cosh\left(\frac{1}{2}J\nabla\right) + 2\sigma\sinh\left(\frac{1}{2}J\nabla\right)\right]^z G(x)|_{x=0}, \quad (15)$$

$$q = \left[\cosh\left(\frac{1}{2}J\nabla\right) + 2\sigma\sinh\left(\frac{1}{2}J\nabla\right)\right]^z H(x)|_{x=0}. \quad (16)$$

If we expand the right-hand side of Eqs. (14)–(16) and combine them, the self-consistent equation of the magnetization σ in sublattice A is given by

$$\sigma = a\sigma + b\sigma^3 + c\sigma^5\cdots, \quad (17)$$

where

$$a = 2z^2 L_1\langle\sinh(J\nabla)\rangle\left[Q_1\langle\cosh(J\nabla)\rangle + 1 - Q_1\right]^{z-1}F(x)|_{x=0}, \quad (18)$$

$$\begin{aligned} b = {}& \frac{4}{3}z^2(z-1)(z-2)L_2\langle\sinh(J\nabla)\rangle\left[Q_1\langle\cosh(J\nabla)\rangle + 1 - Q_1\right]^{z-1}F(x)|_{x=0} \\ &+ \frac{4}{3}z^4(z-1)(z-2)L_1^3\left[\langle\sinh(J\nabla)\rangle\right]^3\left[Q_1\langle\cosh(J\nabla)\rangle + 1 - Q_1\right]^{z-3}F(x)|_{x=0} \end{aligned}$$