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On the hysteresis behaviors of the higher spin Ising model

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HIGHLIGHTS

- The hysteresis behaviors of spin-S Blume–Capel model have been investigated.
- Multiple hysteresis behavior observed.
- The effect of temperature and crystal field on hysteresis loops investigated.

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ABSTRACT

Hysteresis characteristics of the general Spin-S ($S > 1$) Blume–Capel model have been studied within the effective field approximation. Particular emphasis has been paid on the large negative valued crystal field region and it has been demonstrated for this region that, Spin-S Blume–Capel model has $2S$ windowed hysteresis loop in low temperatures. Some interesting results have been obtained such as nested characteristics of the hysteresis loops of successive spin-S Blume–Capel model. Effect of the rising crystal field and temperature on these hysteresis behaviors have been investigated in detail and physical mechanisms have been given.

1. Introduction

Higher spin Ising model ($S > 1$) is very important for understanding of the real magnetic materials. Although S-1/2 problems are the most widely studied in the literature on the theoretical side, it is a well known fact that S-1/2 systems are highly idealized systems. For instance none of the known ferromagnetic/antiferromagnetic atom in the periodic table has 1/2. When the atoms brought together in a solid, different spin values emerge due to the overlapping of the atomic orbitals of the constituent atoms. Indeed, there are numerous molecules that have very high spins in the ground state, for instance S-6 [1], S-8, S-10 [2]. Besides, the most of the magnetic materials are represented by higher spin systems. For instance bimetallic Prussian blue analogs $CsNi^{II}[Cr^{III}(CN)_6] \cdot (H_2O)$ can be represented by S-3/2, S-1, S-2 atoms on the lattice [3]. Although it is very important to investigate higher spin systems, there is a downward trend with the rising spin value in the theoretical literature. This is due to the fact that, rising computational time for simulations and rising mathematical difficulties for approximation schemes for greater spin values.

Ising model including the crystal field or the single-ion anisotropy was introduced as a S-1 Blume–Capel (BC) model [4,5]. Later on, it was generalized to the higher spin problems and solved within the mean field approximation (MFA) [6]. Some variants of the model exist such as spin-S model with biquadratic exchange interaction and it was solved within the cluster variation method [7,8]. Also, transverse Ising model with higher spin has been solved within the effective field theory (EFT) [9–11]. Quenched disorder effects such as site dilution has been also investigated for spin-S BC model with EFT [12,13] and random crystal field problem within the pair approximation [14]. Some other techniques such as Monte Carlo

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(MC) simulation exist for the higher spin BC model [15]. This short literature was for the general spin-S models. If we look at the specific spin valued BC model, we see downward trend with rising spin values.

S-3/2 BC model have been introduced earlier to explain the phase transitions in $DyVO_4$ [16,17] and tricritical properties of the ternary fluid mixtures [18]. This model has been solved by various methods such as EFT [19–22], two spin cluster approximation [23], thermodynamically self consistent theory [24], finite size scaling [25], MC and density matrix renormalization group technique [26], renormalization group technique (RG) [27]. Antiferromagnetic BC model has already been worked within the MFA [28], cluster variation method [29], transfer matrix technique [30], transfer-matrix finite-size-scaling calculations and MC [31]. Besides, S-3/2 BC model with bilinear and biquadratic interactions has been investigated [32–34]. If we look at different geometries we can see that S-3/2 model within different geometries have also been worked such as Bethe lattice [35–37], multilayer [38,39], cylindrical Ising nanotube [40], hexagonal Ising nanowire [41] and semi infinite geometry [42]. Some generalizations of the S-3/2 Ising model have already been constructed and solved. S-3/2 Ising model with transverse field [43–51], and transverse crystal field [52,53] are among them. Quenched disorder effects, which is another important topic is widely worked out for the S-3/2 Ising model. Effect of the discrete random longitudinal field distribution (bimodal distribution) [54–58] and random crystal field distribution [59–61], random bond distribution [62–64], bond dilution [65], site dilution [66,67] problems have been worked out. Note that, EFT has been used in most of these quenched disorder works.

S-2 Ising model is also important due to the experimental realizations. For instance the spin values of Fe II ions are 2 and it is experimentally found that these ions have anisotropy [68]. Also for the disordered $Fe_{(1-q)}Al_q$ alloys, it has been demonstrated that the effective spin value of iron is 2 and 5/2 for Fe 2+ and Fe 3+ ions, respectively [69]. Fe–Al alloys has been modeled and solved by EFT [70]. As in S-3/2 models, EFT is dominant method for the aim of determining critical and thermodynamical properties of the S-2 Ising model. EFT is successfully applied to the S-2 Ising model with transverse field [71–74], transverse crystal field [75], discrete distributed random field [76,77], random crystal field [78], site dilution problems [79,80] and the model with biaxial crystal field [81]. MFA has also been applied to the S-2 Ising model with transverse field [82,83] and random crystal field [84]. S-2 Ising model on the Bethe lattice is the example of the S-2 Ising model with different geometry [85,86].

S-5/2 Ising model has many experimental realizations as mentioned in [87]. This model has been solved within the EFT [88]. Also S-5/2 Ising model with transverse field [89], and quenched site dilution [90] problems were solved with EFT. Some other methods exist such as mean field renormalization group technique for the S-5/2 Ising model with random transverse field [91].

Besides, a broad literature has been formed about the dynamical hysteresis behaviors. For instance dynamical spin-1 BC model [92] and spin-3/2 BC model [93] have been worked out within the mean-field theory based on Glauber-type stochastic dynamics.

As seen from this short literature summary, many attempts have been made for the thermodynamical properties of the Spin-S model. But there is less attention paid on the hysteresis behaviors. The aim of this work is to determine the hysteresis properties of the Spin-S BC model and to obtain some general results especially about the multiple hysteresis behaviors. EFT for higher spin Ising model has been used in order to investigate hysteresis behaviors of the spin-S BC model. First attempts of the constructing formulation can be found in Ref. [94] and decoupling approximation has been constructed in [95]. The most advanced version of the formulation can be found in a review article [96].

Very recently, it has been shown by the author that, crystal field diluted S-1 BC model could exhibit double and triple hysteresis behaviors at large negative values of the crystal field and the physical mechanisms behind these behaviors have been explained [97]. Also it has been demonstrated that isotropic Heisenberg model could not exhibit these types of behaviors [98]. The aim of the paper is obtain general results about the multiple hysteresis behaviors of the higher spin valued systems. For this aim, the paper is organized as follows: In Section 2 we briefly present the model and formulation. The results and discussions are presented in Section 3, and finally Section 4 contains our conclusions.

2. Model and formulation

The Hamiltonian of the spin-S BC model with uniform longitudinal magnetic field is given by

$$\mathcal{H} = -J \sum_{\langle i,j \rangle} s_i s_j - D \sum_i s_i^2 - H \sum_i s_i, \tag{1}$$

where s_i is the z component of the spin operator and it takes number of $2S+1$ different values such as $s_i = -S, -S+1, \ldots, S-1, S$, $J > 0$ is the ferromagnetic exchange interaction between the nearest neighbor spins, D is the crystal field (single ion anisotropy), H is the external longitudinal magnetic field. The first summation in Eq. (1) is over the nearest-neighbor pairs of spins and the other summations are over all the lattice sites.

We can construct the EFT equations by starting with generalized Callen–Suzuki [99] identities, which are generalized versions of the identities for the S-1/2 system [100,101] and given as

$$\langle s_0^i \rangle = \left\langle \frac{Tr_0 s_0^i \exp\left(-\beta \mathcal{H}_0\right)}{Tr_0 \exp\left(-\beta \mathcal{H}_0\right)} \right\rangle, \tag{2}$$