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An effective field theory study of layering transitions in Blume–Capel thin films in the presence of quenched random crystal fields

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HIGHLIGHTS

- We study the surface magnetism in thin magnetic films using effective field theory.
- The presence of random crystal fields has been considered in the system.
- Disorder has been sampled from dilute and trimodal probability distributions.
- For diluted fields, a novel feature emerges in the presence of enhanced surfaces.
- The variation of the special point R_c as a function of system parameters has been clarified.

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ABSTRACT

In the presence of quenched random crystal fields, phase transitions in magnetic thin films described by the spin-1 Blume–Capel model have been investigated using effective field theory (EFT). Crystal field disorder has been sampled by introducing dilute and trimodal random crystal fields. For dilute crystal fields, in the highly anisotropic limit ($D \to \infty$), we have found that the critical value of the surface to bulk ratio of exchange interactions (R_c) at which the second-order transition temperature becomes independent of the film thickness is a spin-dependent property of thin magnetic films. Moreover, as a percolation problem, we have performed detailed calculations in the limit $D \to -\infty$, and it has been shown that a novel feature emerges in the presence of enhanced surfaces. Besides, for trimodal random crystal fields, the variation of the special point R_c as a function of the random field parameters has been elucidated. Finally, in the limit $D \to \infty$, based on the numerical data provided by EFT, we have introduced an analytical expression for the variation of R_c as a function of the randomness parameter p of the trimodal distribution.

1. Introduction

The investigation of critical phenomena in ferromagnetic thin film systems has a long history [1], and these magnetic systems are of great technological significance [2], while they also present problems of fundamental interest [3–5]. In magnetic systems with thin film geometry, due to their reduced coordination number, the surface atoms may have a lower symmetry in comparison with that of the inner atoms; meanwhile, the exchange interactions between the surface atoms may be different from those between the corresponding bulk counterparts, leading to a phenomenon known as surface enhancement in which the surface may exhibit an ordered phase even if the bulk itself is disordered. This phenomenon has also been observed experimentally [6–8].

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Due to the presence of modified exchange couplings at the surface, magnetic thin film systems may exhibit an extraordinary phase transition at which the surface transition temperature is higher than that of the bulk, whereas in the ordinary case the transition temperature of the film is mainly determined by the bulk region. In order to investigate the thermal and magnetic properties of thin films, models based on an Ising-type spin Hamiltonian are well suited, since many thin films such as those in the Fe/Ag(100) system [9] exhibit a strong uniaxial anisotropy. A great many theoretical efforts have shown that there exists a critical value of surface to bulk ratio of exchange interactions R_c, above which the surface effects are dominant and the transition temperature of the entire film is determined by the surface magnetization, whereas below R_c the transition characteristics of the film are governed by the bulk magnetization. The critical value R_c is known as the special point at which the transition temperature of the film becomes independent of the thickness, and the numerical value of this point has been examined within various theoretical techniques for the spin-1/2 case [10–20]. On the other hand, the problem has also been extended to higher spins using a number of techniques [21–27].

Among these works, the effects of different interaction parameters on the variation of the special point R_c have been widely examined. For instance, within the framework of effective field theory (EFT), Peliti and Saber [17] have examined the phase transitions of a spin-1/2 Ising film in a transverse field. They considered a uniform transverse field in the bulk and at the surface layers of the film, and they concluded that the critical value R_c shifts towards higher values with increasing transverse field. Sarmento and Tucker [18] took the work one step forward by considering different transverse fields at the surface and in the bulk of the film. According to their results, a transverse field in the surface layer causes the R_c value to move to a higher value, whereas in the presence of a bulk transverse field R_c decreases to a lower value. Moreover, using extensive Monte Carlo (MC) simulations, the effect of surface exchange enhancement on ultrathin spin-1 films has been studied by Tucker [23], and it was concluded that the R_c value is spin dependent. Hence, whatever the approach used (i.e. EFT or MC), in the highly anisotropic limit $D \to \infty$ (where D denotes the crystal field interactions), the critical parameters of a spin-1 film should converge to those corresponding to a spin-1/2 film which were reported in Ref. [24].

The critical phenomenon peculiar to thin film magnetism, namely the existence of a critical surface coupling R_c at which the transition temperature of the film becomes independent of the film thickness, has been examined in detail for pure magnetic films. However, the characteristic behavior of the system is dramatically affected in the presence of disorder. Theoretically, the presence of quenched randomness in layered magnetic systems has been considered within various methods involving various types of disorder [28–39]. The foremost observations reported in these works can be briefly summarized as follows. In Ref. [28], transverse Ising thin films with diluted surfaces have been studied with the help of mean field theory (MFT) and EFT. It has been shown that the value of the special point R_c becomes large rapidly as the surface sites are diluted with nonmagnetic impurities. Similar behavior has also been reported in Ref. [30]. Using EFT, the effect of the presence of amorphous surfaces on the critical behavior of a ferromagnetic Ising film has been studied by Saber et al. [33]. According to their results, the amorphization causes the R_c value to move to higher values. A ferromagnetic Ising film in a random transverse field has been investigated by Moutie et al. [34]. They concluded that the surface and bulk probabilities of the random transverse fields act on R_c in opposite ways. The effect of a variable surface crystal field on the magnetic order–disorder layering transitions of a spin-1 thin film has been investigated by Bahmad et al. [35,36] using MFT and MC simulations. They reported the existence of tricritical behavior and reentrant phenomena. In one of the most recent works based on EFT, Akıncı [37] reported that, in the presence of random longitudinal magnetic fields, the width σ of the Gaussian random fields makes no significant change in R_c value of a ferromagnetic Ising thin film. On the other hand, Kaneyoshi [38,39] has considered ultrathin films in a transverse field with bond and site dilutions at the surfaces. He showed that, depending on the type of the dilution process (i.e. site or bond), the system may exhibit different characteristic behavior.

Conventional EFT approximations include spin–spin correlations resulting from the usage of the Van der Waerden identities, and provide results that are superior to those obtained within the traditional MFT. Although the thermal fluctuations are partially considered in the formalism, the EFT method offers rich physical phenomena which present qualitatively similar results in comparison with those obtained by some sophisticated techniques such as MC simulations. On the other hand, as far as we know, less attention has been paid to the critical behavior of spin-1 Blume–Capel (BC) films in the presence of random crystal fields (RCFs) in the literature [40]. Therefore, the aim of the present paper is to elucidate the phase transition properties of spin-1 BC thin film systems in the presence of quenched RCFs. The organization of the paper is as follows. In Section 2, we briefly present the formulations. The results and discussions are presented in Section 3, and finally Section 4 contains our conclusions.

2. Formulation

We consider a ferromagnetic thin film with thickness L (see Fig. 1) described by the conventional Blume–Capel Hamiltonian [41]

$$\mathcal{H} = -\sum_{\langle ij\rangle} J_{ij} S_i S_j - \sum_i D_i (S_i)^2, \tag{1}$$

where $J_{ij} = J_s$ if the lattice sites i and j belong to one of the two surfaces of the film; otherwise, we have $J_{ij} = J_b$, where J_s and J_b denote the ferromagnetic surface and bulk exchange interactions, respectively. The first term in Eq. (1) is a summation over the nearest-neighbor spins with $S_i = \pm 1$, 0, and the second term represents the crystal field energy on the lattice. D_i is the random crystal field strength, which is distributed on the lattice sites according to given specific probability distributions.