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# Nonequilibrium dynamics of a spin-3/2 Blume-Capel model with quenched random crystal field

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ABSTRACT

The relaxation and complex magnetic susceptibility treatments of a spin-3/2 Blume-Capel model with quenched random crystal field on a two-dimensional square lattice are investigated by a method combining the statistical equilibrium theory and the thermodynamics of linear irreversible processes. Generalized force and flux are defined in irreversible thermodynamics limit. The kinetic equation for the magnetization is obtained by using linear response theory. Temperature and also crystal field dependencies of the relaxation time are obtained in the vicinity of phase transition points. We found that the relaxation time exhibits divergent treatment near the order–disorder phase transition point as well as near the isolated critical point whereas it displays cusp behavior near the first-order phase transition point. In addition, much effort has been devoted to investigation of complex magnetic susceptibility response of the system to changing applied field frequencies and it is observed that the considered disordered magnetic system exhibits unusual and interesting behavior. Furthermore, dynamical mean field critical exponents for the relaxation time and complex magnetic susceptibility are calculated in order to formulate the critical behavior of the system. Finally, a comparison of our observations with those of recently published studies is represented and it is shown that there exists a qualitatively good agreement.



## 1. Introduction

Investigation of disorder effects on the critical phenomena has a long history and there have been a great many of theoretical studies focused on disordered magnetic materials with quenched randomness where the random variables of a magnetic system such as random fields [1,2] or random bonds [3,4] may not change its value over time. On the other hand, quenched crystal field diluted ferromagnets constitute another example of magnetic systems and equilibrium properties of this type models have been investigated under multifarious approximation methods [5–8]. Besides, effects of disorder on magnetic systems have been systematically studied, not only for the theoretical interests but also for the identifications with experimental realizations [9–11]. It has been shown by renormalization group arguments that first-order transitions are replaced by continuous transitions, consequently tricritical points and critical end points are depressed in temperature, and a finite amount of disorder will suppress them [12].

Since the time in which Ising model [13] was invented there exists a limited number of studies including the dynamic nature of the system under the influence a small perturbation. Even though the physical investigations regarding these systems bring about a lot of mathematical difficulties, the nonequilibrium systems are in the focus of scientists because they have an unusual and interesting dynamic behavior. It is known that examination of physical properties of the nonequilibrium systems allows us to analyze various dynamical concepts. One of them is the relaxation time of a considered system which exhibits a divergence near the critical and multicritical points and gives remarkable information about dynamic properties. As far as we know, on the theoretical picture, the relaxation behavior of a limited number of systems has been investigated by making use of Onsager reciprocity theorem [14,15]. This type of investigation was first performed by Tanaka et al. [16] near the continuous phase transition point for the spin-1/2 Ising model by means of Onsager reciprocity theorem. Next, AB-type ferromagnetic and antiferromagnetic models have been investigated by Barry [17], Barry and Harrington [18] using the similar formulation, respectively. Additionally, in Ref. [18], dynamic initial parallel susceptibility expression is analyzed near the Néel temperature for considered applied field frequencies. Recently, spin-1 Ising model has been analyzed by Erdem and Keskin within the framework of

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the entropy production [19,20] and it is found that one of the relaxation times diverges at the continuous phase transition point while the other relaxation time remains finite. The relaxation process of the pure spin-3/2 Blume–Emery–Griffiths (BEG) model with bilinear and biquadratic exchange interactions has been analyzed near the critical [21] and multicritical points [22]. In addition, thermal variations of the relaxation time of a metamagnetic Ising model have been investigated by Gulpinar et al. [23]. Very recently, following the same methodology, spin-1 Blume-Capel (BC) model with quenched random crystal field has been studied in detail and it is observed that the relaxation time has a jump discontinuity at the first-order phase transition point whereas it diverges in the neighborhood of multicritical points such as tricritical, critical end point and bicritical end points [24]. Moreover, from the experimental point of view, a great many of experimental studies have been dedicated to the better understanding of dynamic critical phenomena in magnetic systems [25–29].

On the other side, it is known that the dynamic or ac susceptibility measurement, in which a time varying oscillating magnetic field is carried out to a sample, is a powerful method for analyzing the dynamic evolution of the considered real magnetic system. It is obtained from the dynamic response of the system to time dependent magnetic field and many studies have been performed regarding the magnetic relaxation of cooperatively interacting systems such as nanoparticles [30–32], spin glasses [33], high $T_c$ systems [34] and magnetic fluids [35]. From the theoretical point of view, in Ref. [36], Acharyya and Chakrabarti probed thoroughly the real and imaginary parts of magnetic susceptibility in the neighborhood of phase transition temperature of a spin-1/2 Ising model under the time dependent oscillating external magnetic field by using Monte Carlo (MC) simulation with periodic boundary conditions. Additionally, Erdem investigated the magnetic relaxation in a spin-1 Ising model near the second-order phase transition point where time derivatives of the dipolar and quadrupolar order parameters are treated as fluxes conjugate to their appropriate generalized forces in the sense of irreversible thermodynamics [37], next, the same author has analyzed the frequency dependence of the complex susceptibility for the same system [38]. In addition to these, with the helping of Nelson's method, a systematic investigation containing frequency, momentum and temperature dependent response function has been achieved for Ising-type system below the critical temperature [39]. Very recently, a comprehensive study including the equilibrium and nonequilibrium antiferromagnetic and ferromagnetic susceptibilities of a metamagnetic Ising system in the vicinity of order–disorder transition point has been done by benefiting from Mean Field Approximation (MFA) [40].

Apart from these, the effects of impurities on driving-rate-dependent energy loss in a ferromagnet under the time dependent magnetic field have been analyzed by Zheng and Li [41] by using several well defined models within the frameworks of MFA and MC, and they found using MFA that, the hysteresis loop area is a power law function of the linear driving rate as $A - A_0 \propto h^{\beta}$, where $A_0$,$h$ and $\beta$ are the static hysteresis loop area, the linear driving rate and scaling exponent of the system, respectively. Very recently, the quenched site and bond diluted kinetic Ising models under the influence of a time dependent oscillating magnetic field have been analyzed by making use of effective field theory [42,43] on a two-dimensional honeycomb lattice. In Ref. [42], the global phase diagrams including the reentrant phase transitions are presented by the authors for site diluted kinetic Ising model, and they showed that the coexistence regions disappear for sufficiently weak dilution of lattice sites. Following the same methodology, the authors have concentrated on the influences of quenched bond dilution process on the dynamic behavior of the system. After some detailed analysis, it has been found that the impurities in a bond diluted kinetic Ising model give rise to a number of interesting and unusual phenomena such as reentrant phenomena and the impurities to have a tendency to destruct the first-order transitions and the dynamic tricritical point [43]. Furthermore, it has also been shown that dynamically ordered phase regions get expanded with decreasing amplitude which is more evident at low frequencies.

As far as we know, the nonequilibrium properties of the quenched disordered systems such as crystal field (and also bond or site) diluted ferromagnets under the influence of a small magnetic field perturbation have not yet been investigated for higher spin models. These types of disorder effects constitute an important role in the real magnetic material science, since the quenched disorder effects may induce some important macroscopic influences on the material. Therefore, we believe that the investigation of the effects of quenched randomness on the nonequilibrium properties of the Ising model and its derivations still need particular attention. Hence, in this work based on MFA, we intend to study the nonequilibrium properties of a spin-3/2 BC model by introducing the quenched crystal field dilution effects. Here, we used a method combining statistical equilibrium theory and the thermodynamics of irreversible processes to analyze the magnetic relaxation behavior and dynamic complex susceptibility of a spin-3/2 BC model with quenched crystal field randomness. In this context, by means of the MFA to obtain magnetic Gibbs free-energy, a generalized force and a generalized current are determined within the framework of irreversible thermodynamics in the neighborhood of equilibrium states. After that, the kinetic equation for the time dependent magnetization is obtained and a relaxation time is derived and also thermal and crystal field variations are examined in the neighborhood of critical and isolated critical points. In addition, we calculated the complex magnetic susceptibility expression and analyzed near the isolated critical as well as second order phase transition points for selected Hamiltonian parameters. It can be said that the considered disordered magnetic system exhibits unusual and interesting behavior. The aforementioned features will be discussed in detail in later sections.

The remaining part 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

In this section, we give the formulation of present study for a two-dimensional square lattice. The Hamiltonian of the spin-3/2 BC model is given by

$$\hat{H} = -J\sum_{\langle ij \rangle} S_i S_j + \sum_i \Delta_i S_i^2, \tag{1}$$

where the first term is a summation over the nearest neighbor spins with $S_i = \pm 3/2, \pm 1/2$ and $\Delta_i$, in the second term, represents random crystal field which is distributed according to a given probability distribution function

$$G(\Delta_i) = \tfrac{1}{2}(\delta(\Delta_i - \Delta(1+\alpha)) + \delta(\Delta_i - \Delta(1-\alpha))), \tag{2}$$

here $\alpha \geq 0$, and half of the lattice sites subject to a crystal field $\Delta(1+\alpha)$ and the remaining lattice sites have a crystal field $\Delta(1-\alpha)$. In order to examine the nonequilibrium properties of the considered magnetic system, first we have to focus on the equilibrium properties following the definition given in Ref. [44]. In this context, we have derived the Gibbs free energy ($G = U - TS - BNm$)