The Magnetic Properties of a Mixed Spin-1 and Spin-$\frac{3}{2}$ Ferrimagnetic Ising System in a Random Longitudinal Field

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Using an effective field theory based on the use of a probability distribution technique that accounts for the self-spin-correlation function, a ferrimagnetic mixed spin-1 and spin-$\frac{3}{2}$ Blume-Capel model in a random longitudinal field is investigated. The existence and dependence of a compensation point on the random field and on the anisotropy strength is investigated. A tricritical behavior is observed for given values of the parameters of the system.

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I. INTRODUCTION

During the last few years much effort has been directed towards the study of critical phenomena in mixed-spin Ising systems consisting of spin-$\frac{1}{2}$ and spin-s atoms with $s > 1/2$. They are of great interest, because new and possibly useful properties are expected. The system has less translational symmetry than its single-spin counterparts, since it consists of two interpenetrating inequivalent sublattices, and is well adapted to study a certain type of ferrimagnetism, namely molecular-based magnetic materials which are of current interest [1–3]. The mixed spin system has also been discussed for the regular ferrimagnetic case [4–6], and in an amorphous binary solid [7], in order to explain the experimental results in the ferrimagnetic amorphous oxides in which Fe^{3+} ions are included [8–9]. Recently, several theoretical studies of the mixed spin-1 and spin-$\frac{3}{2}$ Ising model have been carried out [10–14] using different techniques.

In contrast to ferromagnets and antiferromagnets, in ferrimagnets there is an important possibility of the existence, under certain conditions, of a compensation temperature T_{comp}, at which the resultant magnetization vanishes below the transition temperature T_c. The appearance of compensation points is due to the fact that the magnetic moments of the sublattices compensate each other completely at T=T_{comp}. The existence of such a phenomenon may be very useful in many technological applications, such as thermomagnetic writing and erasing at the compensation point, because of the high coercivity around it. It has been found that the coercivity diverges at the compensation point [15]; and at this point only a small driving field is required to reverse the sign of the magnetization. It has been also found that, for given conditions [16], there are some systems which can possess more than one compensation point. Because of potential device applications, many ferrimagnets have been extensively investigated [17–25], and some of them possess a compensation point temperature which may vary in the vicinity of room temperature.

On the other hand, considerable progress has been made in the understanding of the random field Ising model (RFIM) [26–34]. One of the interesting phenomena in the RFIM is the occurrence of a tricritical behavior. The RFIM has been examined by the use of various techniques, such as mean field theory [35], Monte Carlo simulations [36–38], renormalization-group calculations [28, 39], the Beth-Peirels approximation [40], and effective-field theories [41, 42]. It is worth noting that the analysis of the RFIM has been almost restricted to the simple spin-$\frac{1}{2}$ systems, some interest has also been directed to the understanding of more complicated systems in the presence of random fields (i.e., the transverse Ising model [43, 44], the amorphous Ising ferromagnets [45], the site-diluted Ising model [46–47], the semi-infinite Ising model [48, 49], the Blume-Capel model [50] and the spin-s Ising model [51]). It has been shown that we can find in these systems a very rich critical behavior and many interesting phenomena can appear (i.e., reentrant behavior or the existence of tricritical points).

The purpose of this paper is to study the mixed spin-1 and spin-$\frac{3}{2}$ Blume-Capel model in a random longitudinal field distributed according to a bimodal distribution in particular, we are going to investigate the effect of the random field on the compensation temperature. This study is done using effective field theory. The equations are derived using a probability distribution method [52] based on the use of exact Van der Warden identities [53]. As far as we know, such a study has not been carried out.

II. FORMALISM

The model we investigate is the mixed spin-1 and spin-$\frac{3}{2}$ Ising system in a random longitudinal field, described by the Hamiltonian

$$H = -J \sum_{\langle ij \rangle} S_{iz}^A S_{jz}^B - D_0 \sum_i \left(S_{iz}^A\right)^2 - D \sum_j \left(S_{jz}^B\right)^2 - \sum_i h_i S_{iz}^A - \sum_j h_j S_{jz}^B, \tag{1}$$

where S_{iz}^A is the z-component of the spin-1 operator, on the A atoms, S_{jz}^B is the z-component of the spin-$\frac{3}{2}$ operator on the B atoms. The first summation is carried out only over nearest-neighbor pairs of spins on different sublattices and $J(J<0)$ is the nearest-neighbor exchange interaction. D_0 and D are the single-ion anisotropy on the A and B atoms respectively, $h_i(h_j)$ are the random external fields acting on the spin-1 and spin-$\frac{3}{2}$, respectively, distributed according to a bimodal distribution:

$$p(h_i) = \frac{1}{2}[\delta(h_i - h) + \delta(h_i + h)]. \tag{2}$$

The purpose of this paper is to study the phase diagrams of such a system, using the effective field theory based on the use of a probability distribution technique that correctly accounts for the single site kinematic relations [52, 54]. This method provides results which are superior to those obtained within the mean field approximation. For the system under consideration, the application of this method leads to the sublattice order parameters:

• For the sublattice A(spin-1)

$$m_1 = << F_1(J\sum_i S^B_{jz}, D_0, h_i) >>_r = << \frac{2\sinh\left(\beta(X_1 - h_i)\right)}{2\cosh\left(\beta(X_1 - h_i)\right) + \exp\left(-\beta D_0\right)} >>_r, \quad (3)$$

$$q_1 = << G_1(J\sum_i S^B_{jz}, D_0, h_i) >>_r = << \frac{2\cosh\left(\beta(X_1 - h_i)\right)}{2\cosh\left(\beta(X_1 - h_i)\right) + \exp\left(-\beta D_0\right)} >>_r, \quad (4)$$

where $X_1 = J\sum_i S^B_{jz}$.

• For the sublattice B(spin$-\frac{3}{2}$)

$$\begin{aligned} m_{\frac{3}{2}} &= << F_{\frac{3}{2}}(J\sum_j S^A_{iz}, D, h_j) >>_r \quad (5)\\ &= << \frac{3\sinh(\frac{3}{2}\beta(X - h_j)) + \exp(-2\beta D)\sinh\left(\frac{1}{2}\beta(X - h_j)\right)}{2\cosh\left(\frac{3}{2}\beta(X - h_j)\right) + 2\exp\left(-2\beta D\right)\cosh\left(\frac{1}{2}\beta(X - h_j)\right)} >>_r,\\ q_{\frac{3}{2}} &= << G_{\frac{3}{2}}(J\sum_j S^A_{iz}, D, h_j) >>_r \quad (6)\\ & << \frac{9\cosh(\frac{3}{2}\beta(X - h_j)) + \exp(-2\beta D)\cosh\left(\frac{1}{2}\beta(X - h_j)\right)}{4\cosh\left(\frac{3}{2}\beta(X - h_j)\right) + 4\exp\left(-2\beta D\right)\cosh\left(\frac{1}{2}\beta(X - h_j)\right)} >>_r,\\ r_{\frac{3}{2}} &= << H_{\frac{3}{2}}(J\sum_j S^A_{iz}, D, h_j) >>_r \quad (7)\\ & << \frac{27\sinh\left(\frac{3}{2}\beta(X - h_j)\right) + \exp(-2\beta D)\sinh\left(\frac{1}{2}\beta(X - h_j)\right)}{8\cosh\left(\frac{3}{2}\beta(X - h_j)\right) + 8\exp\left(-2\beta D\right)\cosh\left(\frac{1}{2}\beta(X - h_j)\right)} >>_r, \end{aligned}$$

where $X = J\sum_j S^A_{iz}$. m_1, q_1 and $m_{\frac{3}{2}}$, $q_{\frac{3}{2}}$, $r_{\frac{3}{2}}$ are the order parameters of the sublattices A and B, respectively, $\beta = \frac{1}{k_BT}$ (we take $k_B = 1$ for simplicity), T is the absolute temperature, and $< ... >$ indicates the usual canonical ensemble thermal average for a given configuration,$< ... >_r$ denotes the random field average.

In a mean-field approximation, one would simply replace these spin operators by their thermal values. However, it is at this point that a substantial improvement to the theory is made by noting that the spin operators have a finite set of base states, with the result that the averages over the functions $F_{\frac{3}{2}}$, $G_{\frac{3}{2}}$, $H_{\frac{3}{2}}$ and F_1, G_1 can be expressed as an average over a finite polynomial of spin operators belonging to the neighboring spins. This procedure can be effected by the combinatorial method and correctly accounts for the single site kinematic relations. Up to this point, the right-hand sides of Eqs. (3–7) will contain multiple spin-correlation functions. To perform thermal averaging on the right-hand sides of Eqs. (3–7), one now follows the general approach described in Ref. [52]. Thus, with the use of the integral representation method of the Dirac distribution δ, Eqs. (3–7) can be written as

$$m_{\frac{3}{2}} = < \int d\omega F_{\frac{3}{2}}(\omega, D, h_j)\frac{1}{2\pi}\int [dt\exp(iwt)\prod_i < \exp(itJS^A_{iz}) >] >_r, \quad (8)$$

$$q_{\frac{3}{2}} = < \int d\omega G_{\frac{3}{2}}(\omega, D, h_j)\frac{1}{2\pi}\int [dt\exp(iwt)\prod_i < \exp(itJS^A_{iz}) >] >_r, \quad (9)$$

$$r_{\frac{3}{2}} = < \int d\omega H_{\frac{3}{2}}(\omega, D, h_j)\frac{1}{2\pi}\int [dt\exp(iwt)\prod_i < \exp(itJS^A_{iz}) >] >_r, \quad (10)$$

$$m_1 = < \int d\omega F_1(\omega, D_0, h_i)\frac{1}{2\pi}\int [dt\exp(iwt)\prod_j < \exp(itJS^B_{jz}) >] >_r, \quad (11)$$

$$q_1 = < \int d\omega G_1(\omega, D_0, h_i)\frac{1}{2\pi}\int [dt\exp(iwt)\prod_j < \exp(itJS^B_{jz}) >] >_r . \quad (12)$$

We now introduce the probability distributions of the spin variables
• spin-1

$$P(S^A_{jz}) = \frac{1}{2}[(q_1 + m_1)\delta(S^A_{jz} - 1) + (1 - 2q_1)\delta(S^A_{jz}) + (q_1 - m_1)\delta(S^A_{iz} + 1)], \quad (13)$$

• spin-$\frac{3}{2}$

$$\begin{aligned} P(S^B_{iz}) = \frac{1}{48}[&(-3 - 2m_{\frac{3}{2}} + 12q_{\frac{3}{2}} + 8r_{\frac{3}{2}})\delta(S^B_{iz} + \frac{3}{2}) + 3(9 + 18m_{\frac{3}{2}} - 4q_{\frac{3}{2}} - 8r_{\frac{3}{2}}) \\ &\delta(S^B_{iz} + \frac{1}{2}) + 3(9 - 18m_{\frac{3}{2}} - 4q_{\frac{3}{2}} + 8r_{\frac{3}{2}})\delta(S^B_{iz} - \frac{1}{2}) + \\ &(-3 + 2m_{\frac{3}{2}} + 12q_{\frac{3}{2}} - 8r_{\frac{3}{2}})\delta(S^B_{iz} - \frac{3}{2})]. \end{aligned} \quad (14)$$

Using these expressions in Eqs. (8–12) and performing the random field average, we get the following equations for the order parameters of the spin-1 and spin-$\frac{3}{2}$, respectively.
• For the sublattice A

$$\begin{aligned} m_1 = &\frac{1}{48^N}\sum_{i=0}^{N}\sum_{j=0}^{N-i}\sum_{k=0}^{N-i-j} C_i^N C_j^{N-i} C_k^{N-i-j} 3^{j+k}(-3 - 2m_{\frac{3}{2}} + 12q_{\frac{3}{2}} + 8r_{\frac{3}{2}})^i \quad (15) \\ &(9 + 18m_{\frac{3}{2}} - 4q_{\frac{3}{2}} - 8r_{\frac{3}{2}})^j(9 - 18m_{\frac{3}{2}} - 4q_{\frac{3}{2}} + 8r_{\frac{3}{2}})^k(-3 + 2m_{\frac{3}{2}} + \\ &12q_{\frac{3}{2}} - 8r_{\frac{3}{2}})^{N-i-j-k}\left\{\frac{F_1(X_1, D_0, h) + F_1(X_1, D_0, -h)}{2}\right\}, \end{aligned}$$

$$q_1 = m_1(F_1 \to G_1), \quad (16)$$

where

$$F_1(X_1, D_0, h) = \frac{2\sinh(\beta(X_1 - h))}{2\cosh(\beta(X_1 - h)) + \exp(-\beta D_0)},$$

$$G_1\left(X_1, D_0, h\right) = \frac{2\cosh\left(\beta(X_1 - h)\right)}{2\cosh\left(\beta(X_1 - h)\right) + \exp\left(-\beta D_0\right)},$$

and $X_1 = \frac{J}{2}\left(3N - 6i - 4j - 2k\right)$.

• For the sublattice B

$$\begin{aligned} m_{\frac{3}{2}} &= \frac{1}{2^N}\sum_{\mu=0}^{N}\sum_{K1=0}^{N-\mu} C_\mu^N C_{k1}^{N-\mu} 2^\mu (1-q_1)^\mu (q_1 - m_1)^{k1} (m_1 + q_1)^{N-\mu-k1} \\ & \frac{1}{2}\{F_{\frac{3}{2}}(X, D, h) + F_{\frac{3}{2}}(X, D, -h)\}, \end{aligned} \tag{17}$$

$$q_{\frac{3}{2}} = m_{\frac{3}{2}}\left(F_{\frac{3}{2}} \to G_{\frac{3}{2}}\right), \tag{18}$$

$$r_{\frac{3}{2}} = m_{\frac{3}{2}}\left(F_{\frac{3}{2}} \to H_{\frac{3}{2}}\right), \tag{19}$$

where

$$F_{\frac{3}{2}}\left(X, D, h\right) = \frac{3\sinh\left(\frac{3}{2}\beta(X-h)\right) + \exp\left(-2\beta D\right)\sinh\left(\frac{1}{2}\beta(X-h)\right)}{2[\cosh\left(\frac{3}{2}\beta(X-h)\right) + \exp\left(-2\beta D\right)\cosh\left(\frac{1}{2}\beta(X-h)\right)]},$$

$$G_{\frac{3}{2}}\left(X, D, h\right) = \frac{9\cosh\left(\frac{3}{2}\beta(X-h)\right) + \exp\left(-2\beta D\right)\cosh\left(\frac{1}{2}\beta(X-h)\right)}{4[\cosh\left(\frac{3}{2}\beta(X-h)\right) + \exp\left(-2\beta D\right)\cosh\left(\frac{1}{2}\beta(X-h)\right)]},$$

$$H_{\frac{3}{2}}\left(X, D, h\right) = \frac{27\sinh\left(\frac{3}{2}\beta(X-h)\right) + \exp\left(-2\beta D\right)\sinh\left(\frac{1}{2}\beta(X-h)\right)}{8[\cosh\left(\frac{3}{2}\beta(X-h)\right) + \exp\left(-2\beta D\right)\cosh\left(\frac{1}{2}\beta(X-h)\right)]},$$

and $X = J\left(N - \mu - 2k_1\right)$.

Thus, the total magnetization is given by:

$$M = \frac{m_1 + m_{\frac{3}{2}}}{2}. \tag{20}$$

One has a set of coupled equations for the order parameters $m_{\frac{3}{2}}$, $q_{\frac{3}{2}}$, and $r_{\frac{3}{2}}$ for the spin-$\frac{3}{2}$ atoms and m_1, q_1 for the spin-1 atoms, that can be solved directly by numerical iteration without any further algebraic manipulations. The same equations hold for a general lattice with a coordination number N, so results for different structures may be obtained without carrying out the detailed algebra encountered when employing other techniques.

In the vicinity of the transition temperature, T_c, the quadrupolar moments $q_i \to q_{0i}$, as q_{0i} is the solution of Equations (16, 18) for $m_i \to 0$ and $r_{\frac{3}{2}} \to 0$. To obtain the critical temperature T_C, we expand the right hand-sides of Equations (15, 17, 19), this leads to:

$$m_1 = a_1 m_{\frac{3}{2}} + b_1 r_{\frac{3}{2}} + c_1 m_{\frac{3}{2}}^3 + d_1 r_{\frac{3}{2}}^3 + \ldots, \tag{21}$$

$$m_{\frac{3}{2}} = a_2 m_1 + b_2 m_1^3 + \ldots, \tag{22}$$

$$r_{\frac{3}{2}} = a_3 m_1 + b_3 m_1^3 + \ldots . \tag{23}$$

If we substitute Equations (22, 23), into Equation (21), we obtain an equation for m_1 of the form:

$$m_1 = a m_1 + b m_1^3 + \ldots . \tag{24}$$

The second-order phase transition line is then determined by the condition:
$a = 1$ and $b < 0$.
In the vicinity of this line, the sublattice magnetization m_1 is given by

$$m_1^2 = \frac{1-a}{b}. \tag{25}$$

The right-hand side must be positive; if that is not the case the transition is of the first order, and hence the point at which $a = 1$ and $b = 0$ is the tricritical point.

On the other hand, the compensation temperature $T_{Comp}/|J|$, if it exist in the system, can be obtained by introducing the condition in Eq. (20): $M = 0$ with $T_{comp}/|J| < T_C/|J|$.

III. RESULTS AND DISCUSSION

In this section, we examine the phase diagrams (critical temperature and compensation temperature) of the mixed spin-1 and spin-$\frac{3}{2}$ ferrimagnetic Ising system in a random longitudinal field.

The phase diagrams in the $(D/|J|, T/|J|)$ plane for $D_0/|J| = 0$ for different values of $h/|J|$, and for the coordination numbers $N = 3, 4$, and 6 are shown in Fig. 1 (a), (b), and (c), respectively. It is noted from these figures that the phase diagrams are topologically similar. For $h/|J| < 0.88$ in Fig. 1(a), $h/|J| < 1.30$ in Fig. 1(b) and $h/|J| < 1.88$ in Fig. 1(c), all the transitions are of the second order; the critical temperature increases from a minimal saturation value to reach a maximum one for large positive values of the anisotropy $D/|J|$. The saturation values depends strongly on $h/|J|$; they increase when we decrease $h/|J|$. It is also noted that the critical temperature decreases when the external field $h/|J|$ is increased. For $h/|J| \geq (0.88, 1.30$ and $1.88)$ in Fig. 1 (a), (b), and (c), respectively, the system exhibits a tricritical point, the order of the transition depends on the value of D/J. The critical temperature decreases when we decrease $D/|J|$ to terminate at a tricritical point, whose coordinates depend strongly on the value of $h/|J|$. For example for $h/|J| = 1.30$ in Fig. 1(b), the coordinates of the tricritical points are ($D/|J| = -3.15$, $T_c/|J| = 0.54$). The critical temperature disappears for $h/|J| > 1.8$ in Fig. 1(a), $h/|J| > 2.8$ in Fig. 1(b) and $h/|J| > 3.8$ in Fig. 1(c).

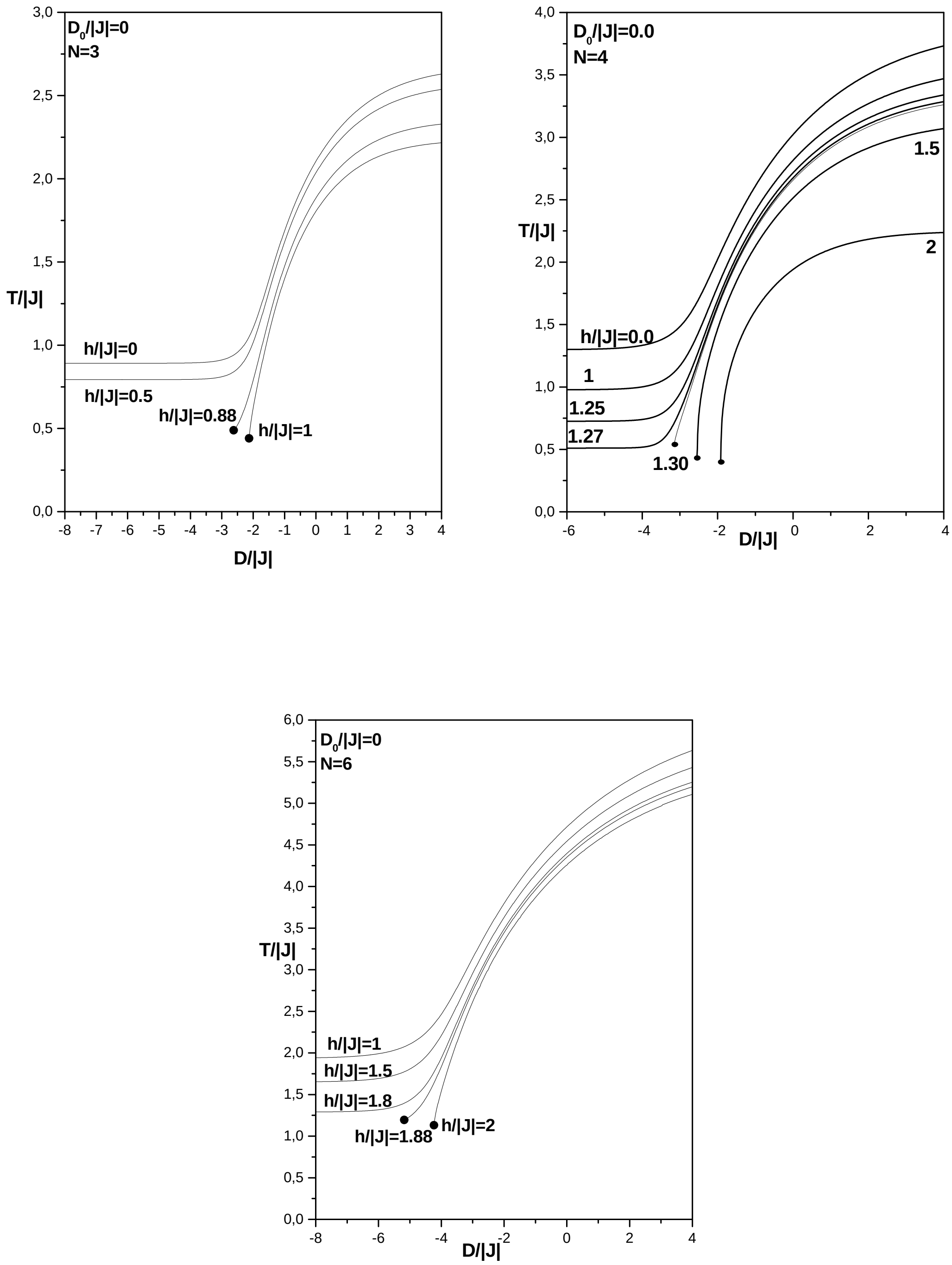

FIG. 1: The phase diagram in the $(T/|J|, D/|J|)$ plane for the mixed spin-1 and spin-$\frac{3}{2}$ Ising ferrimagnetic system for $D_0/|J| = 0$, the number accompanying each curve is the value of $h/|J|$, (a) coordination numbers $N = 3$, (b) $N = 4$, and (c) $N = 6$.

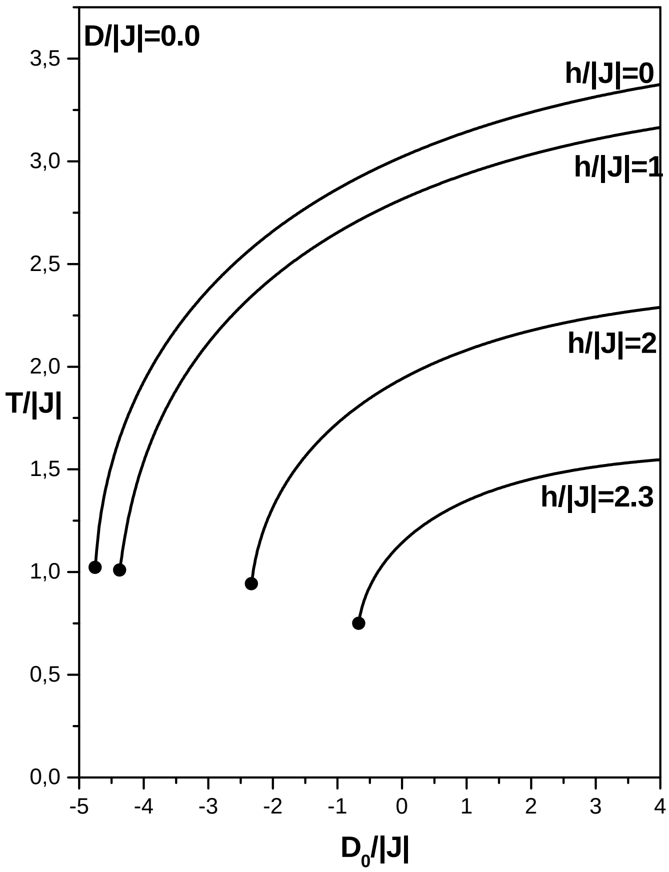

FIG. 2: The phase diagram in the $(T/|J|, D_0/|J|)$ plane for the mixed spin-1 and spin-$\frac{3}{2}$ Ising ferrimagnetic model on square lattice (N=4) for $D/|J| = 0$; the number accompanying each curve is the value of $h/|J|$.

We show in Fig. 2, the phase diagrams in the $(T/|J|, D_0/|J|)$ plane for $D/|J| = 0$ and for different values of $h/|J|(0, 1, 2 \text{ and } 2.3)$. We can see that in this case the system exhibits a tricritical behavior whatever the value of $h/|J|$. The critical temperature decreases with increasing value of $h/|J|$ and disappears when $h/|J| > 2.4$.

To better understand the effect of the random field on the behavior of the system, we have plotted in Fig. 3 the phase diagrams on the $(T/|J|, h/|J|)$ plane for different values of $D_0/|J| = D/|J|$. When we increase $h/|J|$, the transition temperature, which

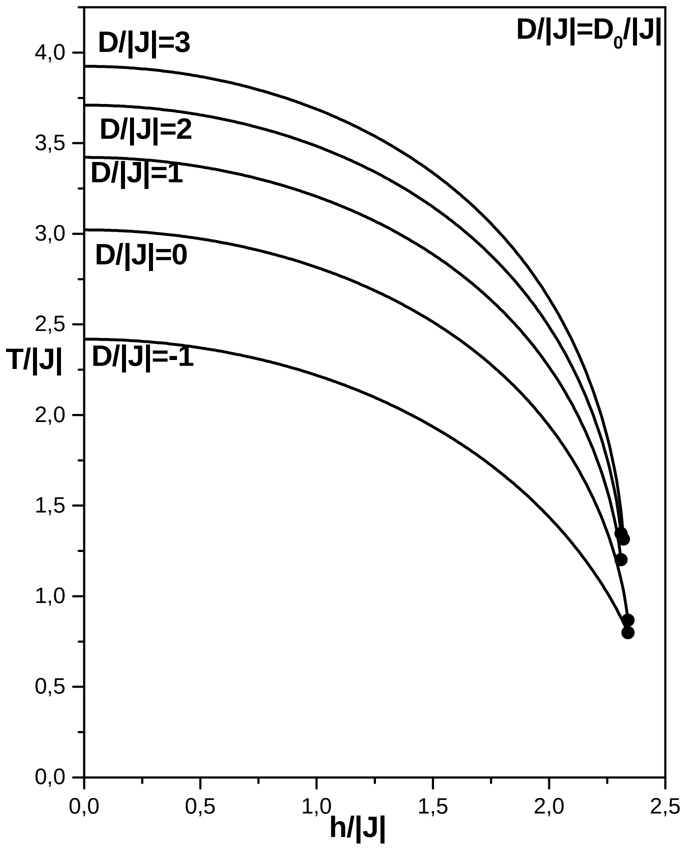

FIG. 3: The phase diagram in the $(T/|J|, h/|J|)$ plane for the mixed spin-1 and spin-$\frac{3}{2}$ Ising ferrimagnetic model on a square lattice (N=4) for $D_0/|J| = D/|J|$, the number accompanying each curve is the value of $D/|J| = D_0/|J|$.

is of the second order for the low values of $h/|J|$, decreases to reach a tricritical point whose coordinates depend on $h/|J|$ and $D/|J|$. It is also seen from this figure that $T_c/|J|$ decreases when we decrease $D/|J|$.

The variation of the compensation temperature $T_{comp}/|J|$ as a function of $D/|J|$ is presented in Fig. 4, for several values of $D_0/|J|$ and $h/|J|$. As can be seen from this figure, the T_{comp} curves emerge from $D/|J| = -2$ at $T = 0K$, and for the values of

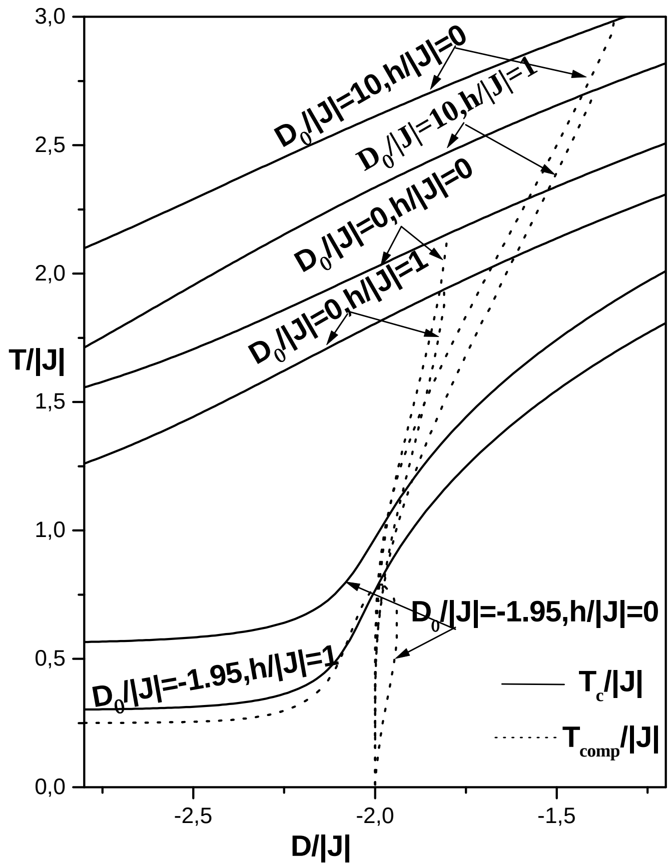

FIG. 4: The phase diagram in $T_c/|J|$ (solid line) and $T_{comp}/|J|$ (doted line) versus $D/|J|$ in a mixed spin-1 and spin-$\frac{3}{2}$ Ising ferrimagnetic model on a square lattice (N=4), for different values of $D_0/|J|$, $h/|J|$.

$D_0/|J| \geq 0$ increase monotonically with $D/|J|$ to terminate at the corresponding phase boundary $T_c/|J|$ (solid lines). As $D_0/|J|$ is reduced, the range of $D/|J|$ over which the compensation point occurs becomes small gradually. Moreover, we can see from this figure that for an appropriate negative value of $D_0/|J|(D_0/|J| = -1.95)$, in a restricted region of $D/|J|(-2, -1.98)$, which is close to $D/|J| = -2$, the compensation temperature lines exhibit bulges, which implies the existence of two compensation points in the system. These results are confirmed in Fig. 5 in which we have plotted the total magnetization $|M|$ of the system

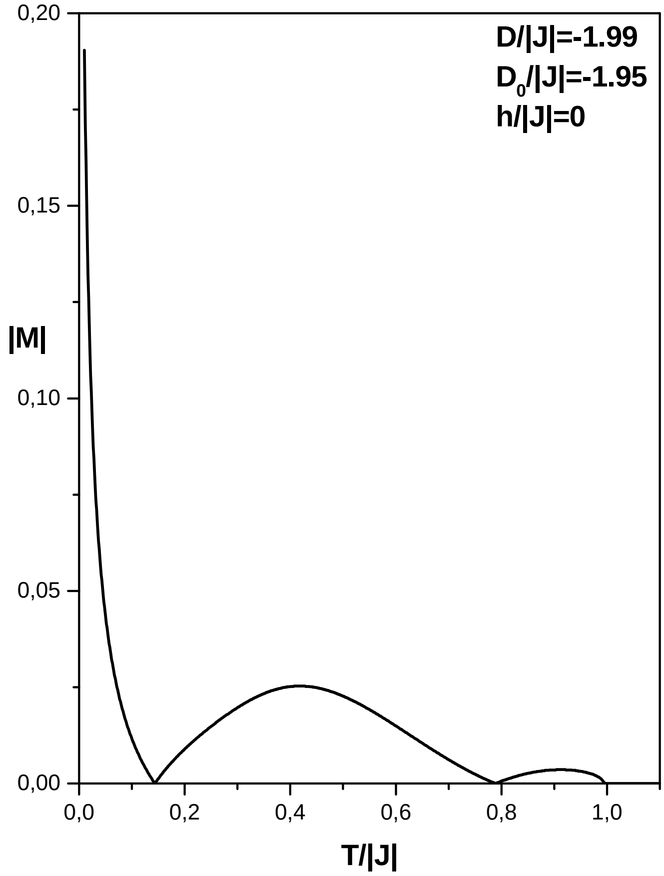

FIG. 5: The temperature dependence of $|M|$ for $D/|J| = -1.99$, $D_0/|J| = -1.95$, and $h/|J| = 0.0$.

with $D/|J| = -1.99$, $D_0/|J| = -1.95$, and $h/|J| = 0$. It is clear from this figure that the system exhibits two compensation points. It is also worth mentioning that the existence of a compensation temperature for the square lattice depends on the values of the anisotropy and the longitudinal field. It is found that the compensation temperature disappears when $h/|J| > 1$.

In order to investigate the variation of the compensation temperature $T_{comp}/|J|$ with $h/|J|$, we have plotted in Fig. 6, the phase diagram in the $(T/|J|, h/|J|)$ plane, for $D/|J| = -1.9$ and for different values of $D_0/|J|$. It is seen that when we increase $h/|J|$, the transition temperature decreases to reach a tricritical point whose coordinates depends on

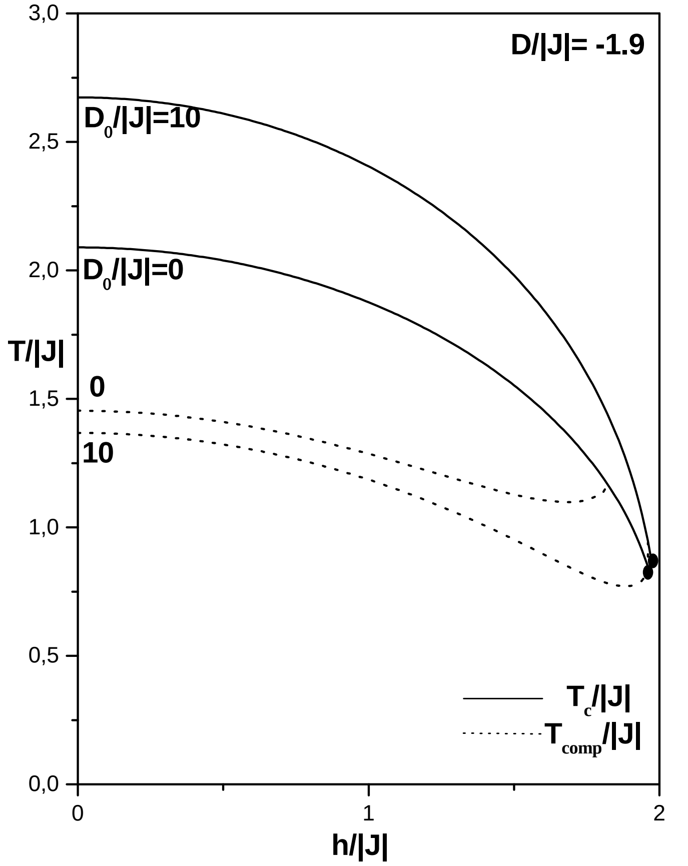

FIG. 6: The phase diagram in $T_c/|J|$ (solid line) and $T_{comp}/|J|$ (doted line) versus $h/|J|$ in a mixed spin-1 and spin-$\frac{3}{2}$ Ising ferrimagnetic model on a square lattice ($N = 4$), for $D/|J| = -1.9$ and for different values of $D_0/|J|$.

$h/|J|$ and $D_0/|J|$. It is also seen from this figure that $T_c/|J|$ decreases when we decrease $D_0/|J|$. Concerning the compensation temperature T_{comp}, it is clear that it exists only when the transition is of the second order. For a given value of $D_0/|J|$, T_{comp} decreases slightly when we increase the value of the longitudinal field $h/|J|$. In contrast to the variation of the critical temperature, the compensation temperature decreases when we increase the value of $D_0/|J|$.

IV. CONCLUSIONS

In this work, we have studied the phase diagrams of a mixed spin-1 and spin-$\frac{3}{2}$ Ising ferrimagnetic system in a random longitudinal field using effective-field theory. We have found that there exists a critical value of $h/|J|$ above which the system exhibits a tricritical point. This tricritical behavior depends also on the single ion anisotropies $D/|J|$ and $D_0/|J|$. Concerning the compensation temperature, we have shown that it exists only when the transition is of the second order, and that for a set of the parameters this system can exhibit two compensation points.

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