University of Thi-Qar Journal of Science (UTJsci)
E-ISSN: 2709-0256, P-ISSN: 1991-8690, Vol.12 , No. 1, June. 2025

Compensation Phenomenon and Hysteresis Loops of a Mixed Spin Ferrimagnetic System

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Received:2025-04-02, Revised: 2025-05-11, Accepted: 2025-05-24, Published: 2025-06-27

***Abstract*— A ferrimagnetic mixed-spin simple cubic system consisting of spin-3/2 and spin-9/2 constituents on two interpenetrating sublattices was investigated using the molecular mean-field approximation based on the Blume-Capel Ising model. The influence of crystal fields and external magnetic fields on magnetic ordering was systematically analyzed by solving the coupled self-consistent equations for sublattice magnetizations. Crystal field anisotropy significantly modifies the magnetic exchange interactions, where specific values of DA/|J| = -13.5 and DB/|J| = -6.75 induce compensation phenomena through differential thermal responses of the sublattices. At these critical values, the system exhibits zero net magnetization while maintaining long-range ferrimagnetic order (mA = -mB ≠ 0). The application of external magnetic fields generates distinct hysteresis behaviors, including multi-step magnetization processes with triple-loop configurations that systematically transform with increasing temperature. These hysteresis patterns undergo progressive changes from multi-loop structures to singular central loops before complete dissipation at higher temperatures, reflecting the complex interplay between crystal field anisotropy, exchange interactions, and thermal fluctuations. The results demonstrate how crystallographic anisotropy parameters can be tuned to control both compensation temperatures and hysteresis characteristics in mixed-spin ferrimagnetic systems.**

***Keywords*— Mixed spin ferrimagnet; Mean-field approximation; Ferrimagnetic anisotropies; Hysteresis behaviour.**

I. INTRODUCTION

Ferrimagnetic materials represent the predominant class of magnetically essential substances utilized across various technological applications. The implementation of mixed Ising models has demonstrated substantial efficacy in facilitating the thermomagnetic characterization of numerous complex material systems, particularly those classified as molecular-based magnetic compounds [1-6]. Ising models and their various modifications constitute fundamental frameworks of investigation within statistical mechanics. These theoretical constructs are distinctively characterized by magnetization instability phenomena induced by thermalfluctuations, which consequently manifest as superparamagnetic behavior in the corresponding physical systems [1-2]. N. De La Espriella et al [1]. Various researchers have conducted comprehensive investigations utilizing Mean Field (MF) theoretical approaches and Monte Carlo (MC) computational simulations have been systematically implemented to elucidate the critical behavior characteristics, magnetic compensation phenomena, and hysteresis properties intrinsic to ferrimagnetic systems comprising spin-3/2 and spin-7/2 constituents within a theoretical framework incorporating antiferromagnetic coupling interactions between nearest-neighbor sites. M. Karimou et al [7] implemented standard Monte Carlo simulation protocols based on the Metropolis algorithmic methodology in conjunction with mean-field theoretical formulations to determine the magnetic property characteristics of an Ising bilayer film structure consisting of two superposed ferromagnetic square lattice configurations, designated as A and B, containing magnetic atomic species with respective spin quantum numbers of 7/2 and 5/2. Their investigative research examined the consequences of external magnetic field constraints, documenting the intermittent generation of hysteresis loop configurations. In related research, H. Bouda et al. conducted extensive investigations into analogous magnetic phenomena.[8] have conducted comprehensive investigations into the effects of single-ion anisotropy parameters and external magnetic field application on magnetization characteristics. Furthermore, they presented a detailed ground-state phase diagram elucidating the thermodynamic properties of the mixed-spin (7/2, 3/2) ferromagnetic Ising system. The magnetic properties elucidated through this investigation were systematically analyzed to provide clarification and empirical support for specific characteristic behaviors for the compounds, and in general [9]. It has been prepared complexes using the methodological approach employed in this investigation following protocols previously established in the literature [9-10]. This work is organized as follows: in section 2, we discussed the basic framework of the relevant theory, giving the Hamiltonian operator of a simple cubic

https://doi.org/10.32792/utq/utjsci/v12i1.1370

lattice. In Section 3, the results and discussions were discussed. Finally, the conclusion is presented in Section 4.

II. FORMALISM

It worths to note that the Hamiltonian operator characterizes the interaction dynamics between nearest neighbors of a simple cubic ferrimagnetic system constituted of two interpenetrating sublattices, designated as A and B, characterized by a heterogeneous spin distribution of spin-3/2 and spin-9/2 within the Ising model framework. Under the effects of external magnetic and crystal fields, **the Hamiltonian is given by:**

$$H = -J\sum\langle i,j\rangle s_i^A s_j^B - D_A \sum_i (s_i^A)^2 - D_B \sum_j (s_j^B)^2 - h[\sum_i s_i^A + \sum_j s_j^B] \quad (1)$$

$D_A/|J|, D_B/|J|$ are the magnetic anisotropic field effects exerted upon spin configurations of A-atoms and spins of B-atoms, respectively. J is the nearest-neighbor exchange interaction. Maxwell-Boltzmann statistics is appropriate because the present magnetic systems consist of localized, and hence distinguishable spins will be in the classical regime. let us consider the Hamiltonian operator of the proposed system contains spins s_i^A taking the values of $\pm$ 3/2, $\pm$ 1/2 , and spins s_j^B taking the values of $\pm$9/2, $\pm$ 7/2, $\pm$ 5/2, $\pm$ 3/2 , $\pm$ 1/2, as in Eq.(1), respectively, that one has :

$$m_{S_i^A \frac{3}{2}} = \frac{1}{2}\frac{3\,sinh(1.5\beta\mu_A) + e^{-2\beta D_A}\,sinh(0.5\beta\mu_A)}{cosh(1.5\beta\mu_A) + e^{-2\beta D_A}\,cosh(0.5\beta\mu_A)} \quad (2)$$

and,

$$m_{S_j^B = 9/2} = \frac{1}{2}\frac{9\,sinh(4.5\beta\mu_B) + 7e^{-8\beta D_B}\,sinh(3.5\beta\mu_B) + 5e^{-14\beta D_B}\,sinh(2.5\beta\mu_B) + 3e^{-18\beta D_B}\,sinh(1.5\beta\mu_B) + e^{-20\beta D_B}\,sinh(0.5\beta\mu_B)}{cosh(4.5\beta\mu_B) + e^{-8\beta D_B}\,cosh(3.5\beta\mu_B) + e^{-14\beta D_B}\,cosh(2.5\beta\mu_B) + e^{-18\beta D_B}\,cosh(1.5\beta\mu_B) + e^{-20\beta D_B}\,cosh(0.5\beta\mu_B)} \quad (3)$$

To evaluate free energy of the proposed system ($S_i^A = 3/2$, $S_j^B = 9/2$), A systematic method for deriving the mean-field theory for a given microscopic Hamiltonian is based on the Bogoliubov inequality. As [13,14],

$$f \le \Phi = f_o + \langle H - H_o \rangle_o \quad (4)$$

where f represents the free energy formulation of the proposed system, H_o a variational Hamiltonian dependent upon adjustable parameters is formulated to facilitate optimization of the free energy boundary conditions as prescribed by the Bogoliubov inequality theorem. The free energy $f_0$and variational parameters μ_A and μ_B denote the corresponding free energy formulation of the trial Hamiltonian H_o .The notation $\langle ... \rangle_0$ represents the statistical average evaluated within the ensemble characterized by H_o. The mean-field free energy formulation was established through systematic minimization of the free energy functional with respect to the variational parameters incorporated within the trial Hamiltonian construct. f with respect to the explicitly defined variational parameter set $\mu_{A/B}$, therefore this methodology yields the optimal approximation to the actual free energy function for H_o. So, one can consider a simplest possible choice of the tial Hamiltonian as:

$$H_o = -\sum_i[\mu_A s_i^A + D_A (s_i^A)^2] - \sum_j[\mu_B s_j^B D_B (s_j^B)^2] \quad (5)$$

with, s_i^A taking spin magnitudes associated with A-sublattice atomic constituents, and corresponding to spin magnitudes characteristic of B-sublattice atomic components S_j^B. D_A, D_B, are the ferrimagnetic anisotropies of two-sublattices examined, and the variational parameters respectively,. The approximated free energy formulation is derived by energy minimization of the right-hand side of Equation (4) with respect to the variational parameters. This energy minimization process applies the Bogoliubov inequality to find the optimal configuration that minimizes the system's free energy, Equation (4) can be expressed as,

$$\Phi = \frac{\Phi}{N} = \frac{k_B T}{2}\Big\{ln\Big[2e^{-2D_{J,S}\,k_B T}cosh\Big(\frac{1}{2}\mu_s k_B T\Big) + 2e^{-4D_{J,S}\,k_B T}cosh\Big(\frac{3}{2}\mu_s k_B T\Big)\Big] + ln\Big[2e^{-6D_{J,S}\,k_B T}cosh\Big(\frac{5}{2}\mu_s k_B T\Big) + 2e^{-8D_{J,S}\,k_B T}cosh\Big(\frac{7}{2}\mu_s k_B T\Big) + 2e^{-10D_{J,S}\,k_B T}cosh\Big(\frac{9}{2}\mu_s k_B T\Big)\Big] + 2e^{-6D_{J,S}\,k_B T}cosh\Big(\frac{5}{2}\mu_s k_B T\Big) + 2e^{-8D_{J,S}\,k_B T}cosh\Big(\frac{7}{2}\mu_s k_B T\Big)\Big\} + \frac{1}{2}J_{m_A} m_B \quad (6)$$

wherein N represents the total number of lattice sites. By energy minimization of Eq.(6) with respect to μ_A and μ_B.This process yields self-consistent expressions for the mean-field. (as indicated in Eqs. (2), (3)). To calculate the values of μ_A , and μ_B one used,

$$\mu_A = zJm_B \tag{7}$$

where z represents the nearest-neighbor coordination number characterizing the crystallographic arrangement of the lattice structure, and,

$$\mu_B = zJm_A \tag{8}$$

A compensation point may manifest where the total longitudinal magnetization per site vanishes due to the precise mutual cancellation of the opposing sublattice magnetization parameters, despite the persistence of the ordered magnetic state per site [15,16], that:

$$M = \frac{1}{2}(m_A + m_B) \tag{9}$$

M equals zero when ($m_A = -m_B \neq 0$).

where M represents the total magnetization

III. RESULTS AND DISCUSSION

A mixed spin-3/2 and spin-9/2 Blume-Capel Ising theoretical framework exhibits ten distinct phases across various parametric valuesof{ m_A, m_B, K_A, K_B }, i.e., the structurally ordered ferrimagnetic phase domains:

$$O_1 \equiv \left\{-\frac{3}{2},\frac{9}{2},\frac{9}{4},\frac{81}{4}\right\}, or \left\{\frac{3}{2},-\frac{9}{2},\frac{9}{4},\frac{81}{4}\right\}$$

$$O_2 \equiv \left\{-\frac{1}{2},\frac{9}{2},\frac{1}{4},\frac{81}{4}\right\}, or \left\{\frac{1}{2},-\frac{9}{2},\frac{1}{4},\frac{81}{4}\right\};$$

$$O_3 \equiv \left\{-\frac{3}{2},\frac{7}{2},\frac{9}{4},\frac{49}{4}\right\}, or \left\{\frac{3}{2},-\frac{7}{2},\frac{9}{4},\frac{49}{4}\right\}$$

$$O_4 \equiv \left\{-\frac{1}{2},\frac{7}{2},\frac{1}{4},\frac{49}{4}\right\}, or \left\{\frac{1}{2},-\frac{7}{2},\frac{1}{4},\frac{49}{4}\right\};$$

$$O_5 \equiv \left\{-\frac{3}{2},\frac{5}{2},\frac{9}{4},\frac{25}{4}\right\}, or \left\{\frac{3}{2},-\frac{5}{2},\frac{9}{4},\frac{25}{4}\right\}$$

$$O_6 \equiv \left\{-\frac{1}{2},\frac{5}{2},\frac{1}{4},\frac{25}{4}\right\}, or \left\{\frac{1}{2},-\frac{5}{2},\frac{1}{4},\frac{25}{4}\right\};$$

$$O_7 \equiv \left\{-\frac{3}{2},\frac{3}{2},\frac{9}{4},\frac{9}{4}\right\}, or \left\{\frac{3}{2},-\frac{3}{2},\frac{9}{4},\frac{9}{4}\right\};$$

$$O_8 \equiv \left\{-\frac{1}{2},\frac{3}{2},\frac{1}{4},\frac{9}{4}\right\}, or \left\{\frac{1}{2},-\frac{3}{2},\frac{1}{4},\frac{9}{4}\right\};$$

$$O_9 \equiv \left\{-\frac{3}{2},\frac{1}{2},\frac{9}{4},\frac{1}{4}\right\}, or \left\{\frac{3}{2},-\frac{1}{2},\frac{9}{4},\frac{1}{4}\right\}$$

$$O_{10} \equiv \{-\frac{1}{2},\frac{1}{2},\frac{1}{4},\frac{1}{4}\}, or \{\frac{1}{2},-\frac{1}{2},\frac{1}{4},\frac{1}{4}\};$$

and the parameters K_A and K_B are defined as:

$$K_A = \left\langle (s_i^A)^2 \right\rangle, \qquad K_B = \left\langle (s_j^B)^2 \right\rangle \tag{10}$$

The distribution of these ten ferrimagnetic phase domains is illustrated in the ground state phase diagram as a function of crystal field parameters DA/|J| and DB/|J|. This diagram reveals critical boundaries between different magnetic orderings and provides insight into the system's fundamental behavior that influences both compensation phenomena and hysteresis characteristics

Now, let us examine the magnetic characteristics of the proposed system under varying crystal field conditions, through which distinctive magnetic behavioral patterns can be observed in this investigation. Fig.2 illustrates the temperature dependence of sublattice magnetizations as a function of absolute temperature, in the absence of external magnetic field influence, for various parametric values of $D_A/|J|$.

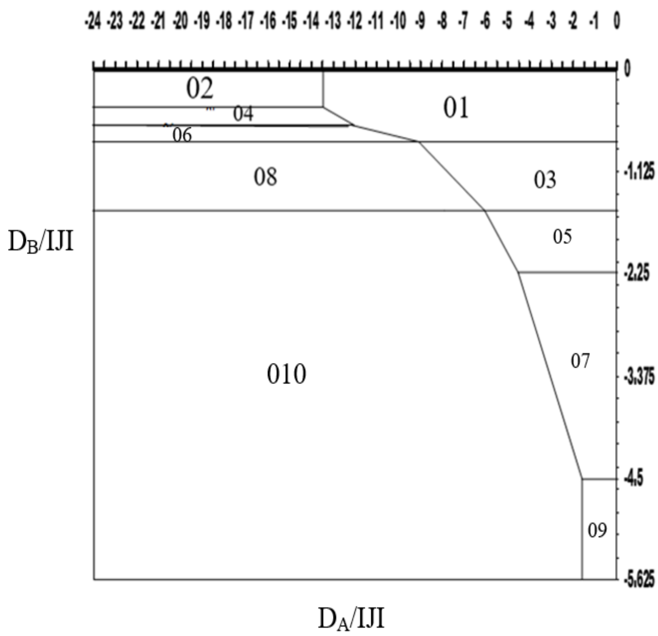

Fig.1: Ground stat phase diagram of mixed spin-9/2 and spin-3/2 Ising ferrimagnetic system on a simple cubic lattice (z=6)

Now, let us examine the magnetic characteristics of the proposed system under varying crystal field conditions, through which distinctive magnetic behavioral patterns can be observed in this investigation. Fig.2 illustrates the temperature dependence of sublattice magnetizations as a function of absolute temperature, in the absence of external magnetic field influence, for various parametric values of $D_A/|J|$.

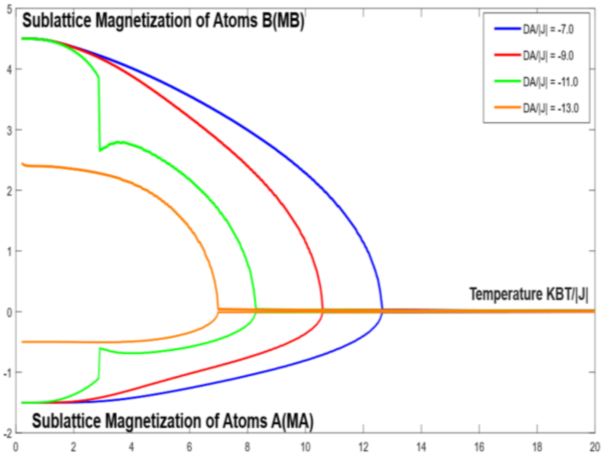

Fig.2:Temperature-dependent sublattice magnetizations of a ferrimagnetic mixed-spin Ising system with a fixed value of $D_B/|J|$= -0.625, when z=6.

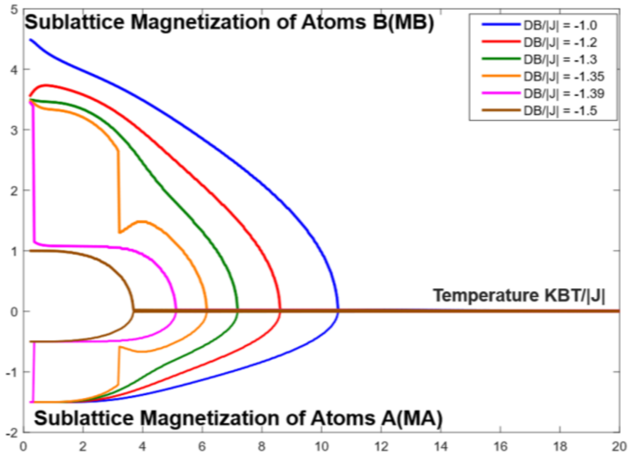

Fig.5: Temperature-dependent sublattice magnetizations of a ferrimagnetic mixed-spin Ising system with a fixed value of $D_A/|J|$= -6.5, when z=6

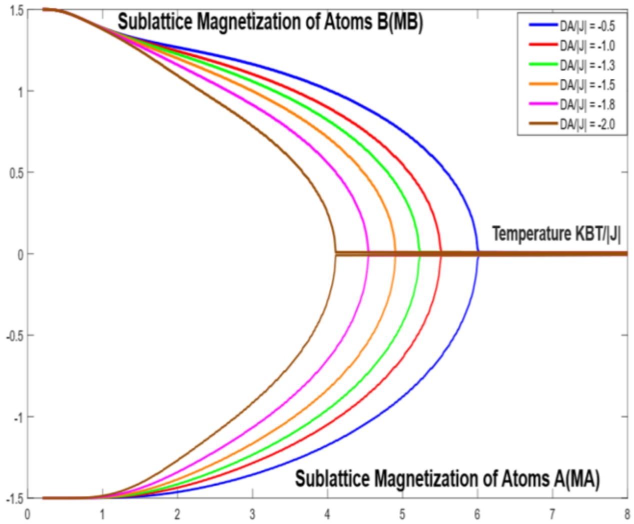

Fig.3:Temperature-dependentsublattice magnetizations of a ferrimagnetic mixed-spin Ising system with a fixed value of $D_B/|J|$=-3.5, when z=6

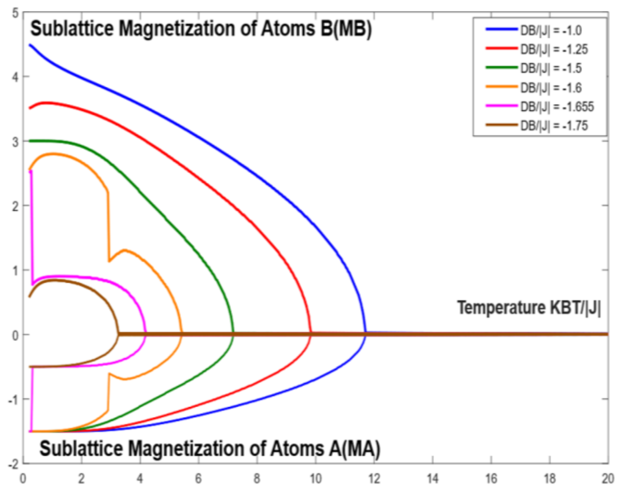

Fig.4: Temperature-dependent sublattice magnetizations of a ferrimagnetic mixed-spin Ising system with a fixed value of $D_A/|J|$=-5.5, when z=6

It has been investigated the influence of spin crystal field parameters $D_A/|J|$ with a constant value of $D_B/|J|$, on the ferrimagnetic properties of the system under investigation. Specifically, when the magnetic anisotropy parameter values $D_B/|J|$=-0.625, is maintained at a constant value, the sublattices exhibit distinctive magnetization distribution patterns within the parametric domain of (-13.0 ≤ $D_A/|J|$ ≤ -7.0), as seen in Fig.2. The sublattice magnetization experiences a first-order phase transition characterized by an abrupt transition to either zero magnitude or an alternative value. Specifically, the sublattice magnetization demonstrates rapid diminution to zero coincident with system phase transition, establishing a critical boundary demarcating the ferrimagnetic or antiferromagnetic ordered states from the disordered paramagnetic phase [14-16]. Additionally, first-order phase transitions manifest when the magnetization parameter exhibits discontinuous variation, precipitating the formation of novel phase configurations at (3, -1.5) and (1, -0.5) for $D_A/|J|$=-5.5 and $D_B/|J|$=-1.5, similarly, for $D_A/|J|$=-6.5 and $D_B/|J|$=-1.5, as the transitions are illustrated in Figs, 4 and 5, respectively. However, within the range $-2.0 \le D_A/|J| \le -0.5$, and $D_B/|J| = -3.5$, the sublattice magnetizations m_B show second-order critical transition temperatures as evidenced in Fig.3. A particularly noteworthy aspect of the investigation involves the examination of the characteristic properties of the proposed system whereby a compensation temperature can be realized (T_k) for the $A-$ atoms and $B-$ atoms when they are under the effect of specific critical values of crystal field parameters D_A, D_B , respectively. The system under investigation demonstrates distinctive characteristic behaviors in the thermal evolution of magnetization that are contingent upon the specific magnetic anisotropy parameter values D_B for a particular value of D_A, that it is possible to have many compensation points at $k_B T/|J| = 0$ and $k_B T/|J| \neq 0$, respectively. The investigation revealed a systematic response characteristic of the system facilitating the induction of multiple compensation temperature phenomena when the parametric value of $D_A/|J|=-13.5$, with a fixed value of $D_B/|J|=-6.75$, of the crystallographic positions occupied by B-sublattice atoms. The data clearly demonstrates in Fig.6 It is worth noting that our results agree with the research results by Deviren et al. [14] and Feraoun and Kerouad [16] that when the compensation temperatures' appearance and outcomes are impacted by crystallographic anisotropy.Additionally, the results are encouraging and show a good agreement with the results that B. Deviren et al. investigated in [14]. Entropic mechanisms which measure the level of disorder in the magnetic lattice structure, are responsible for the magnetic compensation phenomenon . UnderThermal elevation, experimental observations showed that magnetic spin colonies of sublattice A atoms had better inter-alignment in the crystal lattice than magnetic spins of sublattice B atoms, leading to differential temperature responses that impact the system as a whole. By systematically altering the parameters of magnetic anisotropy, an inverse moment A counter-directional moment configuration evolves, reaching its critical manifestation at a specific threshold of magnetic contrast where the precise condition $m_A = -m_B$ is achieved. At this critical juncture, the system's total magnetization approaches zero magnitude despite the persistence of long-range ferromagnetic order within the structure. This specific thermal condition represents the definitive characteristic that identifies the compensation temperature phenomenon. This characteristic phenomenological behavior exhibits a strong theoretical alignment with the Néel framework, specifically corresponding to the N-type classification as documented in the relevant scientific literature [14-17].

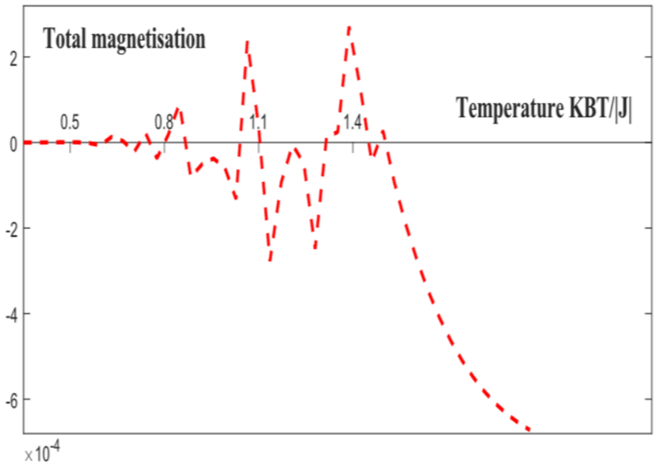

Fig.6:Temperature-dependences of the total magnetization M for the mixed ferrimagnet z = 6, when the value of $D_A/|J|= -13.5$, and $D_B/|J| = -6.75$

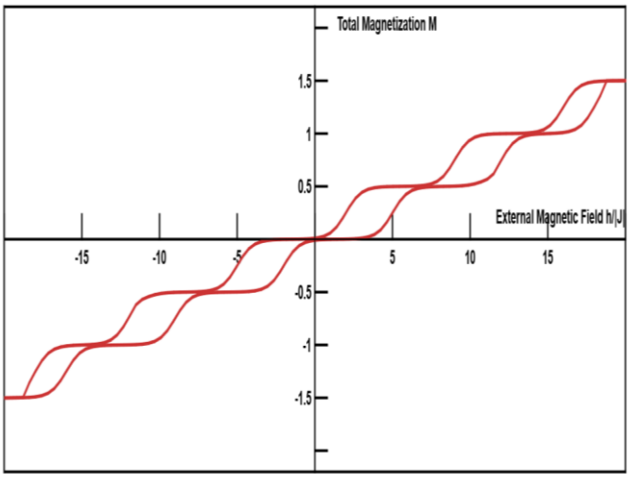

Fig.7. Temperature dependences of the hysteresis loop behavior when $k_B T/|J| = 0.5$, $D_A/|J|= -1.5$, and $D_B/|J| = -3.5$, for mixed-spin ferrimagnet z=6.

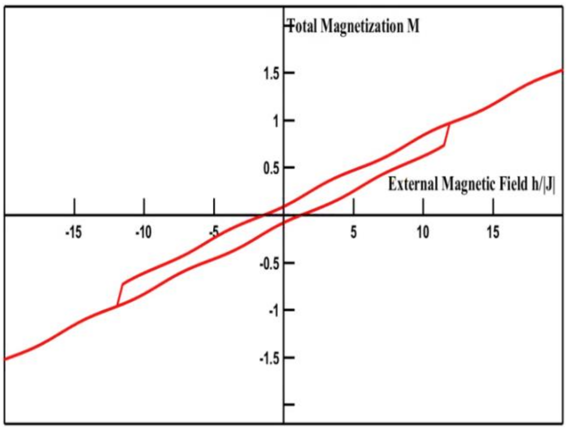

Fig.8.Temperature dependences of the hysteresis loop behavior when $k_B T/|J| = 1.5$, $D_A/|J|= -1.5$, and $D_B/|J| = -3.5$, for mixed-spin ferrimagnet z=6.

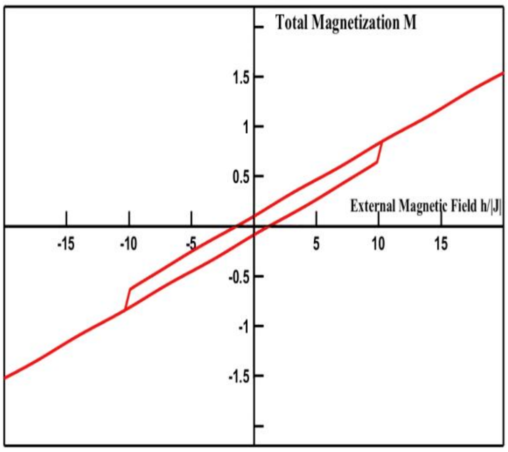

Fig.9.Temperature dependences of the hysteresis loop behavior when $k_B T/|J| = 2.5$, $D_A/|J|= -1.5$, and $D_B/|J| = -3.5$, for mixed-spin ferrimagnet z=6.

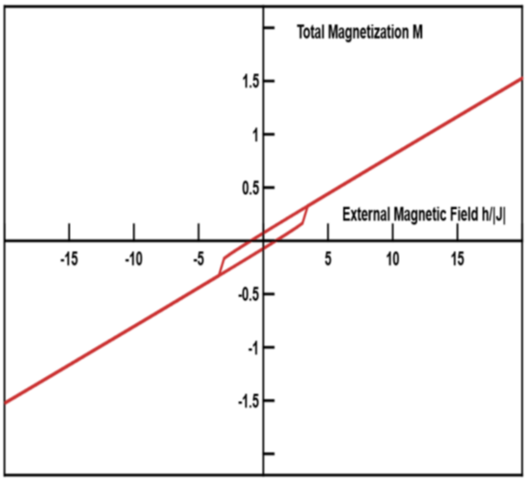

Fig.10.Temperature dependences of the hysteresis loop behavior when $k_BT/|J| = 3.5$, $D_A/|J|$= -1.5, and $D_B/$ |J| = -3.5, for mixed-spin ferrimagnet z=6

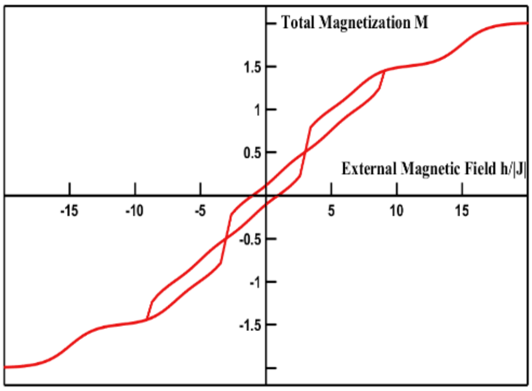

Fig.11.Temperature dependences of the hysteresis loop behavior when $k_BT/|J| = 1.0$, $D_A/|J|$= -6.0, and $D_B/$ |J| = -2.0, for mixed-spin ferrimagnet z=6.

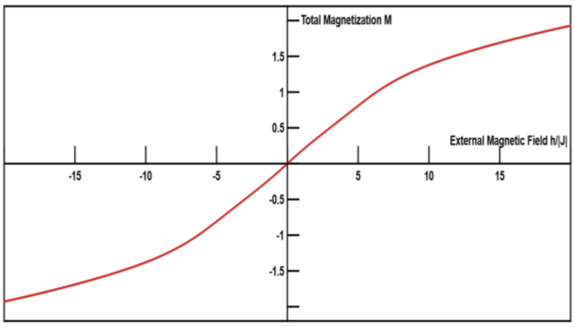

Fig.12.Temperature dependences of the hysteresis loop behavior when $k_BT/|J| = 1.5$, $D_A/|J|$= -6.0, and $D_B/$ |J| = -2.0, for mixed-spin ferrimagnet z=6.

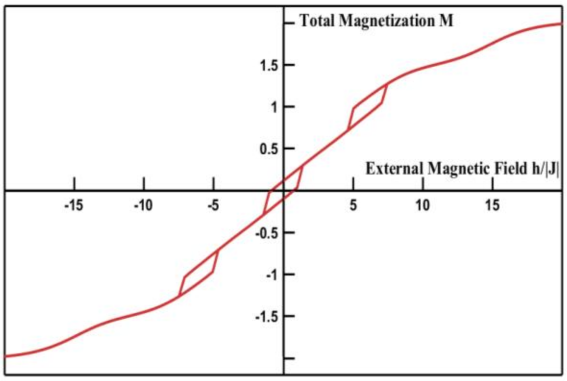

Fig.13.Temperature dependences of the hysteresis loop behavior when $k_BT/|J| = 2.5$, $D_A/|J|$= -6.0, and $D_B/$ |J| = -2.0, for mixed-spin ferrimagnet z=6.

The manifestation of hysteresis phenomena constitutes an effective methodological approach for characterizing the response dynamics of the proposed system when exposed to externally applied magnetic field disturbances [7]. Crystal-field interaction phenomena and externally imposed magnetic field perturbations on spin orientation configurations were methodically integrated within the theoretical framework of this comprehensive investigation. Besides, multi-hysteresis loops pattern has beenwas observed in Figs. 7,8,9, and 10, respectively, for $D_A/|J|$= -1.5, and $D_B/$ |J| = -3.5, in the range of temperature $0.5 \le k_BT/|J| \le 3.5$. Multi-hysteresis behavior in the proposed system changes from the multi-loop configuration undergoes a progressive transformation toward a singular central loop before complete dissipation with increasing thermal conditions. The system under investigation demonstrates a tripartite hysteresis pattern characterized by a primary central loop flanked by two peripheral loops that systematically diminish in magnitude as the temperature increases within the specified crystal field parameter regime. field $-6.0 \le D_A/|J| \le -2.0$. As temperature increases, the hysteresis configuration exhibits a progressive reduction in loop multiplicity, ultimately converging to a singular central loop as documented in Figs 7, 8, 9, and 10, respectively, for the designated anisotropy parameter values. In all analytical representations, the remanent magnetization exhibits exact correspondence with the saturation magnetization magnitude of the complete film structure. Notably, observations indicate that when T=1.5, $D_A/|J|$= -5.0, and $D_B/$ |J| = -3.0, the multiplicity occurrence once again starts and then leading to triple hysteresis loops in the range $1.0 \le k_BT/|J| \le 2.5$, for $D_A/|J|$= -6.0, and $D_B/$ |J| = -2.0, as seen in Figs. 11,12, and 13, respectively. However, when $k_BT/|J| = 2.5$, for $D_A/|J|$= -6.0, and $D_B/$ |J| = -2.0, hysteresis phenomena undergo complete suppression, with the corresponding magnetization profiles illustrated in Fig. 13. Simultaneously, a systematic examination of the magnetic characteristics of the system under investigation has been implemented across multiple parametric domains of $D_A/|J|$ and $D_B/|J|$ at specified thermal conditions. This hysteresis loop configuration demonstrates notable morphological similarity to those previously documented in the investigation conducted by N. De La Espriella et al [1]. It worths to notice that results are significantly different when z=8, particularly regarding the Curie temperature and compensation temperature. Such investigation would require a separate study due to the fundamental differences in lattice structure. These results demonstrated the critical role of lattice coordination in determining hysteresis characteristics in mixed-spin ferrimagnetic systems.

IV. Conclusions

In this study, the mean field approximation methodology systematically was used to implement the research endeavors to elucidate the magnetic property characteristics and behavioral phenomena of a ferrimagnetic mixed-spin (3/2,9/2) Blume-Capel Ising model. The paper focused on the examination of crystalline field effects and externally applied magnetic field influences on the magnetic compensation phenomena and hysteresis patterns, respectively. The results demonstrated that the proposed system displays compensation behaviors for $DA/|J|=-13.5$, with results showing specific magnetic behavior at $DB/|J|=-6.75$ Similar compensation behavior was also observed for $DB\ /|J|=-5.75$ under these $DA/|J|$ conditions, respectively. Significantly, our investigation reveals that the ferrimagnetic anisotropy applied to individual sublattices exert characteristic influence on the induction of compensation points within this proposed system. Comparative analysis with previous investigations, specifically those documented in Refs. [1-8]. wherein the authors studied a heterogeneous spin-7/2 and spin-3 system through implementation of Monte-Carlo simulation methodologies with a Hamiltonian formalism that incorporates nearest-neighbor exchange interactions and crystalline field anisotropy effects, reveals notable consistencies. It is particularly significant that at reduced temperatures, exchange interactions disrupt the symmetry under external field inversion, manifesting as exchange bias [18]. Furthermore, when sublattices exhibit heterogeneous crystal field values, absolute temperature variations precipitate the emergence of multiple hysteresis configurations of the proposed system specifically demonstrating triple and hextuple hysteresis loops at low temperatures.

Acknowledgment

I would like to thank all those who motivated me to accomplish this study.

CONFLICT OF INTEREST

Author declares that he has no conflict of interest.

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