The decorated ferrimagnetic Ising model in a random longitudinal field

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The effect of a random longitudinal field, on the magnetic properties of a decorated ferrimagnetic Ising model consisting of two magnetic atoms A and B with spins σ_A=1/2 and S_B=1, is investigated within the framework of an effective field theory based on the use of a probability distribution method. A number of characteristic phenomena, such as the possibility of two compensation points and reentrant behaviour are found .

I. Introduction:

Ferrimagnetism has been extensively investigated in the past both theoretically and experimentally, since important magnetic materials for technological applications, such as garnets and ferrites, are ferrimagnetic. Ferrimagnets have several sublattices with a finite resultant moment and show paramagnetic behaviour above the transition temperature T_C. In contrast with a ferromagnet, there is an interesting possibility of the existence, under certain conditions, of a compensation temperature T_k (T_k<T_C), at which the resultant magnetization vanishes [1,2]. In recent works, the effect of disordered interfaces with alloying type A_p B_{p-1} on the transition temperature and magnetization has been investigated for a bilayer system consisting of two magnetic layers A and B where A and B can possess different bulk properties [3-6]. The effects of a crystal field D and the magnitude of the spin S on the phase diagram (T_C and T_k) have been examined and it was clarified that more than one compensation point can exist in the disordered ferrimagnetic alloy as well as the diluted mixed spin-1/2 and spin-1 ferrimagnetic Ising systems [7-11]. An exact solution of a decorated ferrimagnetic Ising model with a crystal field D was obtained by A. Dakhama [12].

Decorated Ising spin models were originally introduced in literature by Syozi [13] as exactly solvable models in statistical physics. They show several kinds of ferrimagnetic behaviour in the temperature dependence of the resultant magnetization according to the assumed values of parameters. The arrangement of atoms in these models is like that in the normal spinel. However, most of the decorated models studied have been restricted to the

effects of a crystal field on the phase diagram [14-17].

On the other hand, considerable progress has been recently made in the understanding of the random field Ising model (RFIM) [18-26]. One of the interesting phenomena in the RFIM is the occurrence of a tricritical behaviour. The RFIM has been examined by the use of various techniques, such as mean field theory [27], Monte Carlo simulations [28-30], renormalization-group calculations [20,31], Beth-Peirels approximation [32] and effective-field theories [33,34]. It is worth noting that the analysis of the RFIM have been almost restricted to the simple spin-1/2 systems. Only very recently some interest has been directed to the understanding of more complicated systems in the presence of random fields, (i.e. the transverse Ising model [35,36], he amorphous Ising ferromagnet [37], the site-diluted Ising model [38,39], the semi-infinite Ising model [40,41], the Blume-Capel model [42] and spin S Ising model [43]). It has been shown that we can find in these systems a very rich critical behaviour and many interesting phenomena can appear (i.e. the reentrance behaviour or the existence of two tricritical points) .

The purpose of this paper is to investigate, the effect of a longitudinal random field, distributed according a bimodal distribution (1), on the phase diagram and magnetic properties of a decorated two sublattice ferrimagnetic Ising system consisting of two magnetic atoms A and B with spins $\sigma_A=1/2$ and $S_B=1$.

$$P(h_i)=\frac{1}{2}\left[\delta(h_i-h)+\delta(h_i+h)\right] \qquad (1)$$

This study is done using the effective field theory. The equations are derived using a probability distribution method [44] based on the use of exact Van der Warden identities[45]. As far as we know, such a study has not been carried out. In particular, the results obtained here may clarify the fact that the applied longitudinal field can control the compensation points.

II. Theoretical framework:

We consider a two-dimensional decorated ferromagnetic Ising system. The whole lattice is divided into two sublattices L_1 and L_2. Every point of L_1 is always occupied by an A atom with the fixed spin σ_A ($\sigma_A=1/2$). That of L_2, which is composed of one decorating point on every bond of L_1, is always occupied by a B atom with a fixed spin S_B ($S_B=1$). The exchange interaction between A and B atoms is assumed to be antiferromagnetic. Furthermore, we assume that there exist a ferromagnetic exchange interaction between every nearest-neighbour pair of A atoms. For clarification, the two-dimensional decorated system is depicted in fig-1. The hamiltonian of the system

studied here has the form :

$$H = J\sum_{i,j}\sigma_i S_j - J'\sum_{i,j}\sigma_i\sigma_j + \sum_i h_i S_i + \sum_j h_j\sigma_j \quad (2)$$

where J and J' (J>0, J'>0) are the exchange interactions, h_i (h_j) are the random longitudinal fields acting on σ_i(S_j) distributed according to equation (1). The first summations are carried out only over nearest-neighbour pairs of spins .

The theoretical framework used here is the effective field theory based on a single-site cluster theory [44]. In this approach, attention is focused on a cluster consisting of just a single selected spin, labelled 0, and the neighbouring spins with which it directly interacts. To this end, the hamiltonian is split into two parts $H=H_0+H'$ where H_0 includes all terms of H associated with the site 0, namely :

$$H_0^{\sigma} = (J\sum_j S_j - J'\sum_i \sigma_i)\sigma_0 + \sigma_0 h_0 \quad (3)$$

and

$$H_0^{S} = JS_0\sum_i \sigma_i + S_0 h_0 \quad (4)$$

if the spin 0 belong to L_1 or L_2 sublattices respectively .

Because H_0 and H' commute, we have the exact identities :

$$\langle\sigma_0\rangle = \left\langle \frac{\mathrm{Tr}_{\sigma_0}(\sigma_0)\exp(-\beta H_0^{\sigma})}{\mathrm{Tr}_{\sigma_0}\exp(-\beta H_0^{\sigma})} \right\rangle \quad (5)$$

$$\langle S_0^p\rangle = \left\langle \frac{\mathrm{Tr}_{S_0}(S_0^p)\exp(-\beta H_0^{S})}{\mathrm{Tr}_{S_0}\exp(-\beta H_0^{S})} \right\rangle \quad (6)$$

where β=1/T, p=1, 2 correspond to the magnetization and the quadrupolar moment respectively, and the angular braket denotes a canonical thermal average .

The evaluation of the inner traces over the selected spin in equations (5,6) yields :

$$\langle\sigma_0\rangle = \left\langle \frac{1}{2}\tanh(\frac{\beta}{2}(X_1 - h_0)) \right\rangle \quad (7)$$

$$\langle S_0\rangle = \left\langle \frac{2\sinh(\beta(X_2 - h_0))}{2\cosh(\beta(X_2 - h_0)) + 1} \right\rangle \quad (8)$$

and

$$\langle S_0^2\rangle = \left\langle \frac{2\cosh(\beta(X_2 - h_0))}{2\cosh(\beta(X_2 - h_0)) + 1} \right\rangle \quad (9)$$

where :

$$X_1 = -J\sum_{j=1}^{N} S_j + J'\sum_{i=1}^{M}\sigma_i \quad (10)$$

$$X_2 = -J\sum_{i}^{N'}\sigma_i \quad (11)$$

where N and M are the numbers of nearest-neighbours if the central site 0 belong to the sublattice L_1, and N' is the number of nearest-neighbours if the central site 0 belong to the sublattice L_2. For the two dimensional system studied here N=M=4 and N'=2 .

To perform the thermal and configurational averaging on the right hand side of equations(7-9), we follow the general approach described in [44]. First of all, in the spirit of effective field theory, multi-spin correlation functions are approximated by products of single spin averages. We then take advantage of the integral

representation of the Dirac's delta function, in order to write equations (7-9) in the form:

$$\langle\sigma_0\rangle = \int d\omega f_\sigma(\omega, h_0)\frac{1}{2\pi}\int d\lambda\ \exp(i\lambda\omega)$$
$$\times\prod_{m=1}^{N}\langle\exp(i\lambda J S_m)\rangle\prod_{j=1}^{M}\langle\exp(-i\lambda J'\sigma_j)\rangle \quad (12)$$

$$\langle S_0\rangle = \int d\omega f_S(\omega, h_0)\frac{1}{2\pi}\int d\lambda\ \exp(i\lambda\omega)$$
$$\times\prod_{j=1}^{N'}\langle\exp(i\lambda J\sigma_j)\rangle \quad (13)$$

and

$$\langle S_0^2\rangle = \int d\omega g_S(\omega, h_0)\frac{1}{2\pi}\int d\lambda\ \exp(i\lambda\omega)$$
$$\times\prod_{j=1}^{N'}\langle\exp(i\lambda J\sigma_j)\rangle \quad (14)$$

where

$$f_\sigma(x, h_0) = \frac{1}{2}\tanh\left(\frac{\beta}{2}(x - h_0)\right) \quad (15)$$

$$f_S(x, h_0) = \frac{2\sinh(\beta(x - h_0))}{2\cosh(\beta(x - h_0)) + 1} \quad (16)$$

and

$$g_S(x, h_0) = \frac{2\cosh(\beta(x - h_0))}{2\cosh(\beta(x - h_0)) + 1} \quad (17)$$

To evaluate the averages in the right-hand side of equations (12-14), we introduce the probability distributions of the spin variables , namely :

$$P(\sigma)=\frac{1}{2}[(1+2m_\sigma)\delta(\sigma-1/2)+(1-2m_\sigma)\delta(\sigma+1/2)] \quad (18)$$

$$P(S)=\frac{1}{2}[(m_2+m_1)\delta(S-1)+(m_2-m_1)\delta(S+1)]$$
$$+(1-m_2)\delta(S) \quad (19)$$

Where m_σ is the magnetization of the sublattice L_1 and m_1 and m_2 are the magnetization and the quadrupolar moment for the sublattice L_2 .

Using these equations and equations (12-14), we obtain the following set of equations :

$$\langle\sigma_0\rangle = 2^{-(N+M)}\sum_{j=0}^{M}\sum_{k=0}^{N}\sum_{l=0}^{k} C_j^M C_k^N C_l^k 2^{-k}$$
$$\times(1+2m_\sigma)^j(1-2m_\sigma)^{M-j}(1-m_2)^{N-k}$$
$$\times(m_2+m_1)^l(m_2-m_1)^{k-l}$$
$$\times\tanh\left(\frac{\beta}{2}[-J(2l-k)+J'(j-2)]-\frac{\beta}{2}h_0\right) \quad (20)$$

$$\langle S_0\rangle = 2^{-N'}\sum_{i=0}^{N'} C_i^{N'}(1+2m_\sigma)^i(1-2m_\sigma)^{N'-i}$$
$$\times\frac{2\sinh(\beta J(i-1)-\beta h_0)}{2\cosh(\beta J(i-1)-\beta h_0)+1} \quad (21)$$

and

$$\langle S_0^2\rangle = 2^{-N'}\sum_{j=0}^{N'} C_j^{N'}(1+2m_\sigma)^j(1-2m_\sigma)^{N'-j}$$
$$\times\frac{2\cosh(\beta J(i-1)-\beta h_0)}{2\cosh(\beta J(i-1)-\beta h_0)+1} \quad (22)$$

Since the longitudinal field is randomly distributed, we have to perform the random average of h_0 according to the probability distribution function $P(h_0)$ given by (1) the ordering parameters m_σ , m_1 and m_2 are then defined as : $m_\sigma=\langle\langle\sigma_0\rangle\rangle_r$, $m_1=\langle\langle S_0\rangle\rangle_r$ and $m_2=\langle\langle S_0{}^2\rangle\rangle_r$, where $\langle\ \rangle_r$ denotes the random field average .

Thus, doing the random average, and using the multinomial expansion, we obtain :

$$m_\sigma = 2^{-(N+M)} \sum_{j=0}^{M}\sum_{k=0}^{N}\sum_{l=0}^{k}\sum_{i_1=0}^{j}\sum_{i_2=0}^{M-j}\sum_{i_3=0}^{N-k}\sum_{i_4=0}^{l} \times \sum_{i_5=0}^{k-l} C_j^M C_k^N C_l^k C_{i_1}^j C_{i_2}^{M-j} C_{i_3}^{N-k} C_{i_4}^l C_{i_5}^{k-l} \times 2^{-k+i_1+i_2} (-1)^{i_2+i_3+i_5} m_\sigma^{\,i_1+i_2} m_1^{\,i_4+i_5} \times m_2^{\,k+i_3-i_4-i_5} F(-J(2l-k)+J'(j-2),h) \quad (23)$$

$$m_1 = 2^{-N'} \sum_{i=0}^{N'}\sum_{j=0}^{i}\sum_{k=0}^{N'-i} C_i^{N'} C_j^i C_k^{N'-i} 2^{j+k} (-1)^k \times m_\sigma^{\,j+k} F_1[J(i-1),h] \quad (24)$$

$$m_2 = 2^{-N'} \sum_{i=0}^{N'}\sum_{j=0}^{i}\sum_{k=0}^{N'-i} C_i^{N'} C_j^i C_k^{N'-i} 2^{j+k} (-1)^k \times m_\sigma^{\,j+k} F_2[J(i-1),h] \quad (25)$$

where : $F(x,h)=\frac{1}{2}[f_\sigma(x,h)+f_\sigma(x,-h)]$

$F_1(x,h)=\frac{1}{2}[f_S(x,h)+f_S(x,-h)]$

$F_2(x,h)=\frac{1}{2}[g_S(x,h)+g_S(x,-h)]$

We have obtained a set of self consistent equations (23-25) for the order parameters that can be solved directly by numerical iterations .

The averaged total magnetization M of the system is given by :

$$\frac{M}{N_A} = m_\sigma + 2m_1 \quad (26)$$

where N_A is the total number of A atoms .

The sublattice magnetization m_1 can be evaluated as :

$$m_1 = -2\, m_\sigma [F_1(J,h)] \quad (27)$$

Thus, the total magnetization M in the system can be expressed as :

$$M = M^0\,[1-4\,F_1(J,h)] \quad (28)$$

where $M^0 = N_A\, m_\sigma$

Below the transition temperature T_C, the M^0 takes a finite value. Accordingly, if the compensation point at which the total magnetization reduces to zero may exist in the system, the compensation temperature T_k can be determined exactly from the condition $M = 0$ for $T_k < T_C$ namely :

$$1 = 4\,F_1(J,h) \quad \text{for } T_k < T_C \quad (29)$$

In the vicinity of the transition temperature T_C, equation (25) can be expressed as :

$$m_2 = m_{20} + m_{22}\, m_\sigma^2 \quad (30)$$

where:

$$m_{2n} = 2^{-N'} \sum_{i=0}^{N'}\sum_{j=0}^{i}\sum_{k=0}^{N'-i} C_i^{N'} C_j^i C_k^{N'-i} 2^{j+k} \times (-1)^k \delta(j+k,n) F_2[J(i-1),h] \quad (31)$$

In order to determine the transition temperature T_C, let us expand the right hand side of equations (23) and (24), using equation (30) we obtain the following equations for m_σ and m_1:

$$m_\sigma = a_{10}\, m_\sigma + a_{01}\, m_1 + a_{21}\, m_\sigma^2 m_1 + a_{12}\, m_\sigma\, m_1^2 + a_{30}\, m_\sigma^3 + a_{03}\, m_1^3 + \cdots \quad (32)$$

$$m_1 = b_{10}\, m_\sigma \quad (33)$$

where the coefficients a_{pq} are given by :

$$a_{pq} = 2^{-(N+M)} \sum_{j=0}^{M}\sum_{k=0}^{N}\sum_{l=0}^{k}\sum_{i_1=0}^{j}\sum_{i_2=0}^{M-j}\sum_{i_3=0}^{N-k}\sum_{i_4=0}^{l} \times \sum_{i_5=0}^{k-l}\sum_{\gamma=0}^{k+i_3-i_4-i_5} C_j^M C_k^N C_l^k C_{i_1}^j \times C_{i_2}^{M-j} C_{i_3}^{N-k} C_{i_4}^l C_{i_5}^{k-l} C_\gamma^{k+i_3-i_4-i_5} \times 2^{-k+i_1+i_2} (-1)^{i_2+i_3+i_5} m_{20}^{\,k+i_3-i_4-i_5-\gamma} \times m_{22}^{\,\gamma} F(-J(2l-k)+J'(j-2),h) \quad (34)$$

and :

$$b_{10} = 2^{-N'} \sum_{i=0}^{N'} \sum_{j=0}^{i} \sum_{k=0}^{N'-i} C_i^{N'} C_j^{i} C_k^{N'-i} 2^{j+k}$$

$$\times\ (-1)^k F_1[J(i-1), h]\delta(j+k, 1) \qquad (35)$$

If we substitute equation (33) in equation (32), we obtain an equation for m_σ of the form:

$$m_\sigma = a\, m_\sigma + b\, m_\sigma^3 + \cdots \qquad (36)$$

with : $a = a_{10} + b_{10}\, a_{01}$

and $b = a_{21}\, b_{10} + a_{12}\, b_{10}^2 + a_{30} + a_{03}\, b_{10}^3$

The second-order phase transition line is then determined by the condition :

$$a = 1 \quad \text{and} \quad b < 0 \qquad (37)$$

In the vicinity of this line, the sublattice magnetization m_σ is given by :

$$m_\sigma^2 = \frac{1-a}{b} \qquad (38)$$

The right-hand side must be positive, if it 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 .

III. Results and discussions:

We are now able to study the magnetic properties (compensation and transition temperatures and magnetization curves) of the two-dimensional decorated ferrimagnetic Ising model in a random longitudinal field .

First, let us examine the variations of the compensation and transition temperatures versus the magnitude of the longitudinal field H/J for several values of the ratio α of the exchange interactions J' and J (α=J'/J) . The results are shown in fig-2 . The doted line denotes the compensation temperature T_k/J which is obtained from equation (29), while the solid lines denotes the critical temperature T_C/J which is obtained from equation (37). It is shown that both T_k/J and T_c/J decrease from their maximum values which correspond to H/J=0 to vanish at some critical values of H/J, which depend on α. All the transition are of second order and our system doesn't exhibit a tricritical point. We can see that T_k/J (solution of eqt 29) is independent of α From the curve of the compensation temperature T_k/J, it is also seen that the system may exhibit one compensation point for $0 \le H/J < 1.0$, while it can exhibit two compensation points for $1.0 \le H/J < 1.77$.

Concerning the phase diagrams ,depending on the value of α, the system can have different type of phase diagrams, for $0<\alpha<0.5$, we have a standard phase boundaries, that is T_C/J decreases from it's maximum value (which corresponds to H/J = 0) to vanish at a critical value of H/J (curve a). For $0.5\le\alpha\le1.66$, the system exhibit a reentrant behaviour (curve d). We have also noticed that it is possible within this theory to have a double-reentrant behaviour in the phase diagram (see curve e), that is, for a fixed value of H/J, the system have three critical temperatures. So, we can say that depending on the values of α and H/J, the system considered here, may

present zero, one or two compensation points depending on whether the condition $T_k<T_C$ is verified :

* For $0\leq H/J<1$ and for $0\leq \alpha \leq 2.86$, there is no compensation phenomena, but for $\alpha>2.86$ we found one compensation point .

* For $1.0\leq H/J<1.77$, if $\alpha<1.0$ there is no compensation phenomena, for $1.0\leq\alpha\leq 2.86$ the system exhibit one compensation point and for $\alpha>2.86$ we can have two compensation points .

Now, in order to prove whether the predictions of T_k obtained from fig-2 in the decorated two -dimentional ferrimagnetic system in a random field are correct or not, it is necessary to study the temperature dependence of the total magnetization (eq.26). The thermal variation of M in the system can be obtained by solving the coupled equations for m_σ , m_1 and m_2 of section 2 numerically. The numerical results are presented in figures (3-5), selecting typical values of α and H/J. In fig-3, we have plotted the thermal variations of M for two couples of $(\alpha,H/J)$. It is seen that curve (a) have the standard type of variation of M, that is, it decrease from it's saturation value at T=0 to vanish at T_C ,and in curve (b), we have a situation in which the system exhibit one compensation point and two phase transitions (reentrant phenomena). Fig-4 presents three cases: the case where the system may have one compensation point and one critical temperature (curve a), the case where we have two compensation points and one critical temperature(curve b) and the case where we have only two critical temperatures (curve c). In fig-5, we present two other types of thermal variations of M, curve (a) show the type with one compensation point and three critical temperatures (double-reentrant behaviour), and curve (b) has a characteristic behaviour showing a minimum and two maximums below T_k . All of these results are consistent with the predictions derived from fig-2 .

IV. Conclusion:

In this work, we have investigated the magnetic properties (phase diagrams and magnetization curves) of the two sublattice decorated Ising ferrimagnetic system composed of two magnetic atoms A and B with $\sigma_A=1/2$ and $S_B=1$ in a random longitudinal field . We have shown that the system may exhibit many unexpected features in the phase diagrams, depending on the values of α and H/J. In particular, we have shown, that it is possible to have two compensation points, reentrant behaviour and even a double-reentrant behaviour in the phase diagrams. It is also shown that the thermal variation of M for curve (a) in fig-5 exhibited a minimum and

two maximums below T_k. Thus, we may conclude by saying that the system investigated here is a fruitful system from both the theoretical and the materials science point of view. We hope that the present study will stimulate experimental and theoretical work on the system considered here .

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Figure caption:

Figure-1: The two-dimensional decorated spin system consisting of two kinds of magnetic atoms A and B with spin values $S_A = 1/2$ and $S_B = 1$ on the sublattices L_1 and L_2 where the A atoms (white points) form the square lattice (or L_1) .

Figure-2: The phase diagrams in the T – H , plane for the decorated ferromagnetic system. The dashed line represents the compensation temperature. The solid line represents the transition temperature obtained for selected values of the ratio α :
a) $\alpha = 0.0$, **b)** $\alpha = 0.5$, **c)** $\alpha = 1.0$, **d)** $\alpha = 1.5$, **e)** $\alpha = 2.0$, **f)** $\alpha = 3.0$, **g)** $\alpha = 4.0$.

Figure-3: The temperature dependence of the total magnetization M for the two-dimentional ferrimagnetc system for selected values of α and H/J :

a) $\alpha = 1.0$ and H/J=0.5 , **b)** $\alpha = 1.5$ and H/J=1.4 .

Figure-4: The temperature dependence of the total magnetization M for the two-dimentional ferrimagnetc system for selected values of α and H/J :

a) $\alpha = 4.0$ and H/J=0.5 , **b)** $\alpha = 4.0$ and H/J=1.2 , **c)** α= 1.0 and H/J=1.2 .

Figure-5: The temperature dependence of the total magnetization M for the two-dimentional ferrimagnetc system for selected values of α and H/J :

a) $\alpha = 1.8$ and H/J=1.6 , **b)** $\alpha = 1.7$ and H/J=1.43 .

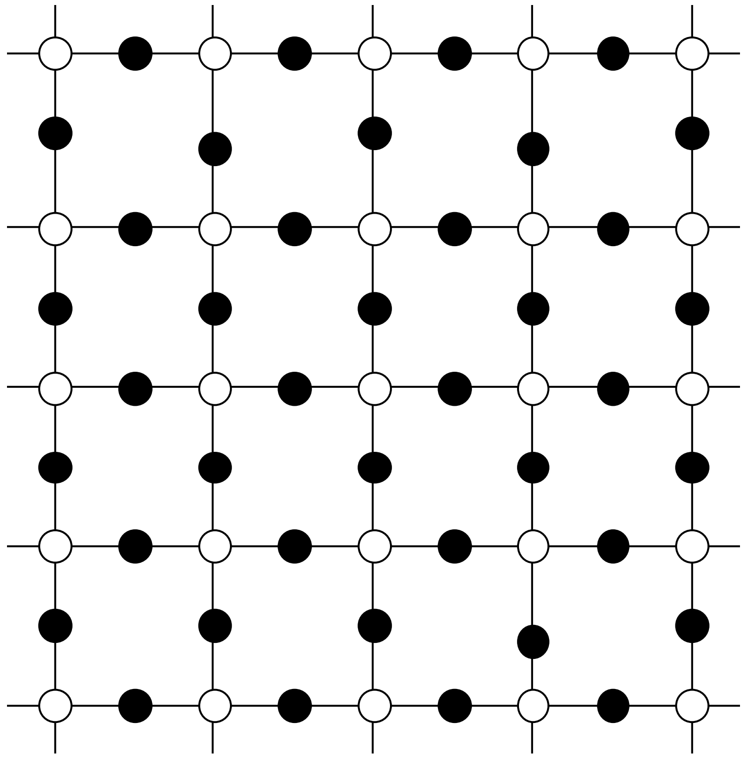

Fig. 1

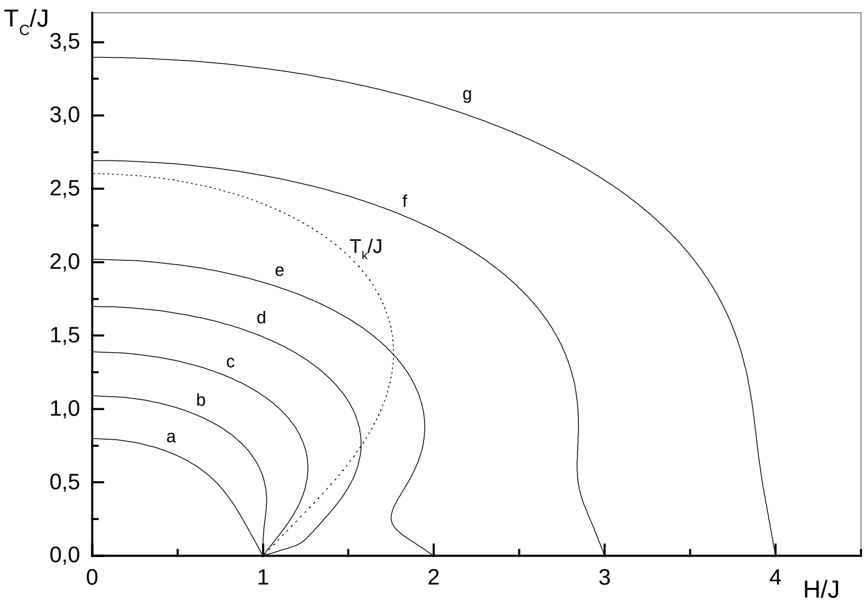
T_C/J
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0
1
2
3
4
H/J
g
f
T_k/J
e
d
c
b
a

Fig.2

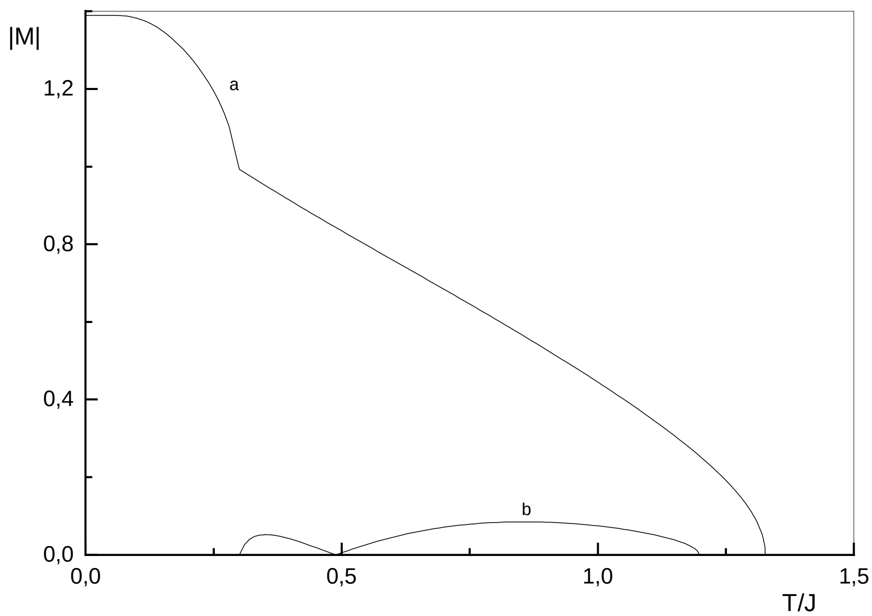
|M|
1,2
0,8
0,4
0,0
0,0
0,5
1,0
1,5
T/J
a
b

Fig.3

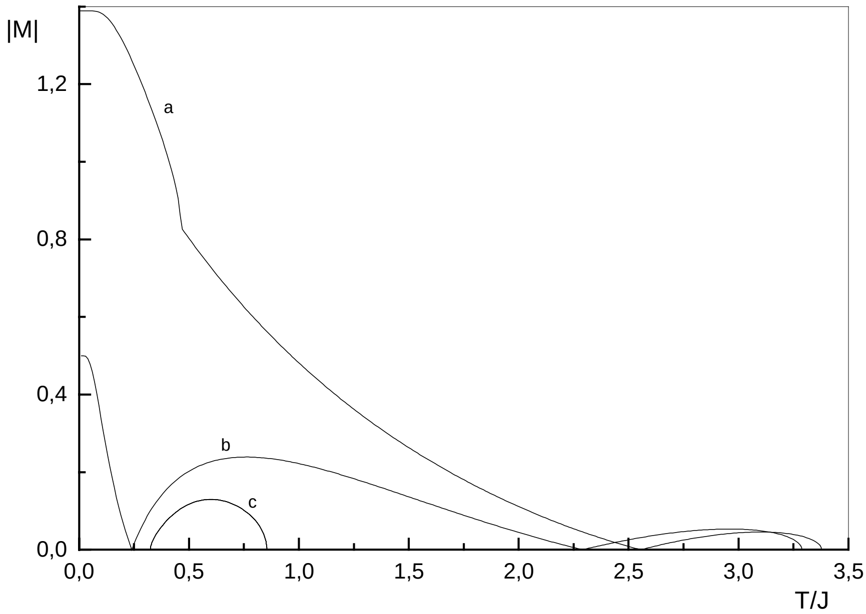
|M|
1,2
0,8
0,4
0,0
a
b
c
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
T/J

Fig.4

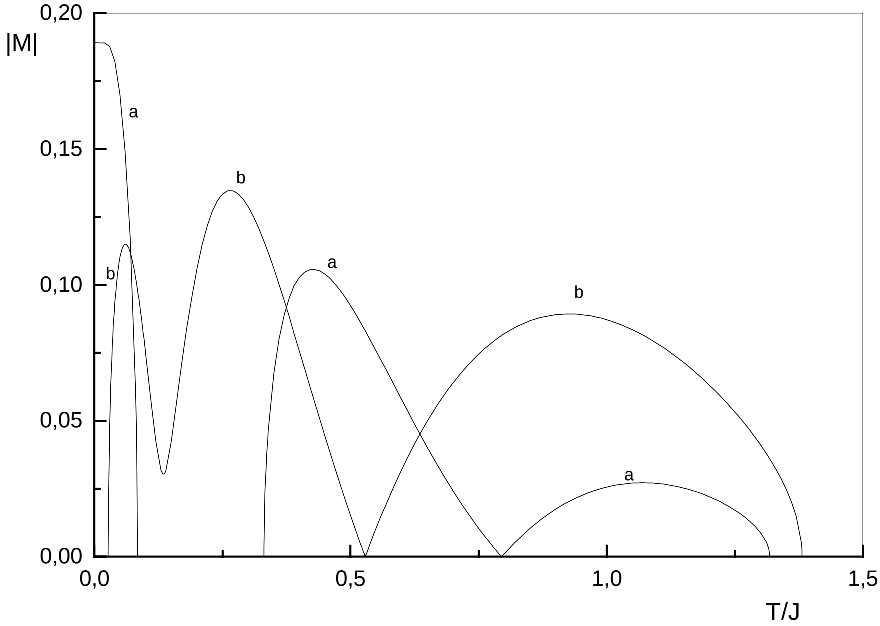
0,20
|M|
0,15
0,10
0,05
0,00
a
b
b
a
b
a
0,0
0,5
1,0
1,5
T/J

Fig.5