Time dependent magnetic field effects on the $\pm J$ Ising model

Erol Vatansever$^{a,b}$, Umit Akinci$^a$, Hamza Polat$^{a,†}$

$^a$Department of Physics, Dokuz Eylul University, TR-35160 Izmir, Turkey
$^b$Dokuz Eylul University, Graduate School of Natural and Applied Sciences, TR-35160 Izmir, Turkey

Abstract

Nonequilibrium phase transition properties of the $\pm J$ Ising model under a time dependent oscillating perturbation are investigated within the framework of effective field theory for a two-dimensional square lattice. After a detailed analysis, it is found that the studied system exhibits unusual and interesting behaviors such as reentrant phenomena, and the competition between ferromagnetic and antiferromagnetic exchange interactions gives rise to destruct the dynamic first order phase transitions as well as dynamic tricritical points. Furthermore, according to Néel nomenclature, the magnetization profiles have been found to obey Q-type, L-type and P-type classification schemes under certain conditions. Finally, it is observed that the treatment of critical percolation with applied field amplitude strongly depends upon the frequency of time varying external field.

Keywords: Dynamic phase transitions; Quenched random bond $\pm J$ Ising model; Effective-field theory

1. Introduction

Investigation of disorder effect problems which may be originated from random interactions between spins or from a random dilution of the magnetic ions with non-magnetic species on the magnetic materials has a long history, and there have been a great many studies focused on disordered magnetic materials with quenched randomness where the random variables of a magnetic system may not change its value over time. Actually, all magnetic materials have some small defects, and magnetic properties, i.e phase transition temperature point that separates the ordered phase from disordered phase, of sample varies significantly depending on the type of defects. From the experimental point of view, a number of studies including the site or bond randomness have been devoted to better understanding of magnetic properties of different types of magnetically interacting systems such as Rb$_3$Mn$_2$Mg$_2$F$_4$ [1], Mn$_2$Zn$_{1−p}$F$_3$ [2], Fe$_2$Mg$_{1−p}$Cl$_2$ [3], Cd$_{1−p}$Mg$_p$Te [4], Mn$_2$Zn$_{1−p}$F$_3$ [5], Co(S$_2$Se$_{1−p}$)$_2$ [6], and Co$_2$Zn$_{1−p}$(C$_2$H$_5$NO)$_6$(ClO$_4$)$_2$ [7].

From the theoretical point of view, a great deal of studies have been performed regarding the magnetic properties of disordered magnetic systems, and based on the investigation of static or dynamic phase transition (DPT) properties of such disordered magnetic system, theoretical works can be classified in two basic categories. In the former group, static or equilibrium properties of these type of systems have been analyzed within the several frameworks such as series expansion method [8, 9, 10, 11], Monte Carlo method [12, 13, 14, 15, 16], renormalization group theory [17, 18, 19, 20, 21, 22, 23, 24], replica method [25, 26, 27], effective field theory [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39] and bethe method [40].

The statistical mechanics of nonequilibrium systems is a less well developed and understood field of study than that for equilibrium systems. 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 exotic, unusual and interesting dynamic behaviors. For instance, the universality class of the kinetic Ising model under a time dependent oscillating magnetic field is different from its equilibrium counterparts [41, 42]. It is exciting to say that a magnetic system composed of interacting magnetic moments under the influence of a time dependent magnetic field exhibits two important phenomena: DPT and dynamic hysteresis behavior. Dynamic evolution of the system strongly depends upon the amplitude and frequency of the applied external magnetic field as well as other intrinsic or
extrinsic Hamiltonian parameters. It is possible to mention that nonequilibrium phase transitions originate due to a competition between time scales of the relaxation time of the system and oscillating period of the external field. As far as we know, the ferromagnetic system exists in dynamically disordered phase at high temperatures and for high amplitudes of the periodically varying magnetic field. In this region, the time dependent magnetization is able to follow the external magnetic field with some delay whereas this is not the case for low temperatures and small magnetic field amplitudes. The mechanism shortly described above points out the existence a DPT \cite{41}, and theoretical point of view, a number of studies concerning the DPTs as well as hysteresis properties of different type systems under the time dependent perturbation have been performed by using well known methods such as Monte Carlo simulation \cite{43, 44, 45, 46, 47, 48, 49, 50}, effective field theory \cite{51, 52, 53}, mean field theory \cite{41, 46, 54, 55} as well as hard spin mean field theory \cite{56}.

In addition to the theoretical published works mentioned above, the DPTs and also hysteretic behaviors can be observed experimentally due to recent developments in experimental techniques. It is beneficial to give a few examples regarding these properties such as epitaxial Fe/GaAs(001) and Fe/InAs(001) ultrathin films \cite{57}, finemetal thin films \cite{58}. [Co(4A°)/Pt(7A°)] multi-layer system with strong perpendicular anisotropy \cite{59}, Co films on a Cu (001) surface \cite{60}, thin polycrystalline Ni\textsubscript{80}Fe\textsubscript{20} films \cite{61}, Fe\textsubscript{80}Zn\textsubscript{58}F\textsubscript{2} \cite{62}, epitaxial Fe/GaAs(001) thin films \cite{63}, epitaxial single ferromagnetic fcc NiFe(001), fcc Co(001), a nd fcc NiFe/Cu/Co(001) layers \cite{64} as well as ultrathin ferromagnetic Fe/Au(001) films \cite{65}. Based upon the detailed experimental investigations, it has been discovered that experimental nonequilibrium dynamics of considered real magnetic systems strongly resemble the dynamic behavior predicted from theoretical calculations of a kinetic Ising model. From this point of view, it is possible to see that there exists an impressive evidence of qualitative consistency between theoretical and experimental investigations.

On the other hand, in the latter group there exists a limited number of nonequilibrium studies concerning randomness effects. For instance, by making use of both mean field theory and Monte Carlo simulation method, it has been shown that the hysteresis loop area of a ferromagnet including impurities under a time dependent magnetic field is a power law function of the linear driving rate as $A \sim \lambda^h \beta^\beta$, where, $A$, $h$ and $\beta$ are the static hysteresis loop area, the linear driving rate and scaling exponent of the system, respectively \cite{66}. Very recently, DPT and also hysteretic properties such as remanence, coercivity and loop area of the random quenched site kinetic Ising model have been probed based on the effective field theory with single-site correlations and it is observed that the coexistence region, where dynamically ordered and disordered phase coexist depending on selected Hamiltonian parameters, disappear for sufficiently weak dilution of lattice sites. It is also propounds that the considered disordered system indicates the existence of essentially three, particularly four layers of dispersion curves \cite{67, 68}. Following the same methodology, quenched random bond diluted Ising model, where the spin-spin exchange interaction has a probability $p$ and $1-p$ of taking on values $J$ and 0, respectively, has been analyzed by benefiting from Glauber type stochastic model \cite{69}, and particular attention has been devoted the better understanding of effects of bond randomness on the global phase diagrams constructed in related planes and on the microscopic origin of the magnetic system \cite{70, 71}. After a complete detailed analysis, the studied system shows that the first order phase transitions as well as dynamic tricritical points (DTCPs) disappear while the reentrant phenomena exists depending on the value of quenched bond dilution parameters $p$ \cite{70}. It is also emphasized that frequency dispersions of hysteresis loop area, remanence and coercivity strongly depend on the quenched bond randomness, as well as applied field amplitude and oscillation frequency \cite{71}. Furthermore, it is beneficial to emphasize that Monte Carlo simulation studies concerning the nonequilibrium behaviors and universality aspects of different type Ising spin glasses systems take part in literature \cite{72, 73, 74, 75}. Even though there exists a limited number of studies including the disorder effects under the time dependent oscillating magnetic field, the dynamic nature of the $\pm J$ Ising model which would exhibit an exotic and unusual dynamic behaviors has not yet been investigated. From this point of view, in this work, we intend to probe the effects of the random bond dilution process on the kinetic Ising model in the presence of a time-dependent oscillating external magnetic field by using the effective field theory with correlations based on the exact Van der Waerden identity for a spin-1/2 system.

The remainder of the study is as follows: The dynamic equation of motion and dynamic order parameter (DOP) of the kinetic $\pm J$ Ising model are described in Sect. 2. The numerical results and related discussions are given in Sect. 3 and finally Sect. 4 contains our conclusions.
2. Formulation

We consider a two dimensional ±J Ising model defined on a square lattice, and the considered system is subjected to a periodically oscillating magnetic field. The time dependent Hamiltonian describing our model of magnetic system can be written as

$$\mathcal{H} = - \sum_{(ij)} J_{ij} S_i S_j - \sum_{i=1}^N H_i(t) S_i$$  \hspace{1cm} (1)

where \(S_i = \pm 1\) is the Ising spin variables and first sum in Eq. (1) is over the nearest neighbor pairs of spins. We assume that the nearest neighbor interactions are randomly diluted on the lattice according to the probability distribution function

$$P(J_{ij}) = p\delta(J_{ij} - J) + (1-p)\delta(J_{ij} + J).$$ \hspace{1cm} (2)

The time dependent magnetic field is as following

$$H_i(t) = h \cos(\omega t)$$ \hspace{1cm} (3)

here, \(h\) and \(\omega\) are amplitude and angular frequency of the external field, respectively. In order to describe the dynamical evolution of the system, we follow a Glauber-type stochastic process \[69\] at a rate of \(1/\tau\) which represents the transitions per unit time, and the dynamical equation of motion can be obtained by using the master equation as follows:

$$\tau \frac{d\langle S_i \rangle}{dt} = -\langle S_i \rangle + \left( \tanh \left[ \frac{E_i + H_i(t)}{k_B T} \right] \right)$$ \hspace{1cm} (4)

where \(E_i = \sum_j J_{ij} S_j\) is the local field acting on the lattice \(i\), and \(k_B\) and \(T\) denote the Boltzmann constant and temperature, respectively. If we apply the differential operator technique \[72, 77\] in Eq. (4) by taking into an account the random configurational averages we get

$$\frac{dm}{dt} = -m + \left( \prod_{i=1}^{q=4} \left| A_{ij} + S_i B_{ij} \right| \right) F(x)_{i=0}$$ \hspace{1cm} (5)

here, where \(A_{ij} = \cosh(J_{ij} \nabla)\), \(B_{ij} = \sinh(J_{ij} \nabla)\) and \(m = \langle \langle S_i \rangle \rangle\) indicates the average magnetization, \(\nabla = \frac{\partial}{\partial x}\) is the differential operator, and the inner \(\langle\cdots\rangle\) and the outer \(\langle\cdots\rangle\) brackets represent thermal and configurational averages, respectively. When the right-hand side of Eq. (5) is expanded, the multispin correlation functions appear. The simplest approximation, and one of the most frequently adopted is to decouple these correlations according to

$$\langle\langle S_i S_j \cdots S_r \rangle\rangle \approx \langle\langle S_i \rangle\rangle \langle\langle S_j \rangle\rangle \cdots \langle\langle S_r \rangle\rangle,$$ \hspace{1cm} (6)

for \(i \neq j \cdots \neq r \). By making use of Eq. (6), the right hand side of Eq. (5) can be easily expanded and then, the following dynamic effective field equation of motion for the magnetization of the ±J Ising model can be found as

$$\frac{dm}{dt} = -m + \sum_{i=0}^q \ell_i m^i$$ \hspace{1cm} (7)

where the coefficients \(\ell_i\) can be readily determined by employing the mathematical relation \(\exp(a \nabla) F(x) = F(x + a)\). Eq. (7) is a kind of initial value problem, and generally, the solutions act a stable function after a certain transition regime. In addition to these, the studied magnetic system exhibit two type solutions, and the first one is called symmetric solution that obeys the following property:

$$m(t) = -m(t + \pi/\omega).$$ \hspace{1cm} (8)

In this type of solution, the time dependent magnetization oscillates around zero value which corresponds to dynamically paramagnetic phase (P). The second one is asymmetric solution where the magnetization oscillates around a nonzero value which indicates the existence a dynamically ferromagnetic phase (F). According to our solutions, the observed behavior of the magnetization is independent of the choice of the initial value of magnetization. On the other hand, depending on Hamiltonian parameters and also initial value of time dependent magnetization, there exist coexistence regions (F+P phases) in the phase diagrams in temperature versus field amplitude plane.

The time average magnetization over a full cycle of the external magnetic field acts as DOP which is defined as follows \[79\]

$$Q = \omega \frac{\pi}{2} \int_0^{\pi} m(t) dt$$ \hspace{1cm} (9)

where \(m(t)\) periodic and stable function.

3. Results and Discussion

In this section, we will focus our attention on the DPT properties of ±J Ising model under a time dependent magnetic field source. Here, we discuss how the bond randomness affects the dynamic evolution of studied system in the vicinity of dynamically order and disorder transition temperature. On the other hand, it is known fact that it is not possible to obtain the free energy for kinetic models in the presence of time-dependent external fields. Hence, in order to determine the type of DPT (first or second order), it is convenient to check the
temperature dependence of DOP. Namely, if the DOP decreases continuously to zero in the vicinity of critical temperature, this transition is classified as second order, whereas if it vanishes discontinuously, then the transition is assumed to be first order. Keeping in this mind, and after detailed analysis with a great success to construct dynamic phase boundary (DPB) that separates the dynamic ordered phases from the dynamic disordered phases, it is shown that the behavior of the system changes dramatically with varying Hamiltonian parameters. In order to investigate these effects on the dynamic behavior of the considered system, we plot the DPB in various planes.

Fig. 1 (a-d) represents the DPT lines in reduced temperature and applied field amplitude plane \((k_B T_c / J - h/J)\) for varying \(p\) values and selected applied field frequencies such as \(\omega = 0.25(a), 0.5(b), 1.0(c)\) and \(\pi(d)\). Here, the full and dotted lines indicate the continuous and discontinuous phase transition points, respectively, and also the solid circle shows the DTCP. It is observed that a reentrant behavior of second order where the two successive second order phase transitions appears in the relatively low applied field amplitude and low temperature regions for low \(p\) values. Another important result of our study is that an increase in the value of \(\omega\) leads to annihilate the reentrant behavior and also to expand the dynamically ferromagnetic region. On the other hand, with the increasing value of \(p\) the dynamic evolution of the \(\pm J\) Ising system begins to resemble the pure kinetic Ising model, and a dynamically first order reentrant behavior with a coexistence region \((F+P)\) phase appears where the critical properties of the system depends on the initial value of the magnetization. Namely, if initial value of the \(m(t)\) is selected to be zero, the time dependent magnetization oscillates around zero value which corresponds to \(P\) whereas if it is considered to be nonzero, in this time, \(m(t)\) oscillates around a nonzero value, and this type of behavior corresponds to \(F\). It is possible to make an inference that the increasing field frequency causes a growing phase delay between the magnetization and magnetic field and this makes the occurrence of the DPT difficult, as a result of this mechanism the DPB gets wider and also the reentrant behavior disappears at the low temperature and low amplitude regions.

![Figure 1: Phase diagrams of the kinetic \(\pm J\) Ising model in the \((k_B T_c / J - h/J)\) plane for selected bond randomness values with (a) \(\omega = 0.25\), (b) \(\omega = 0.5\), (c) \(\omega = 1.0\) and (d) \(\omega = \pi\). Solid (dotted) lines correspond to second- (first-) order DPTs, and • symbols represent DTCPs.](image)

![Figure 2: Phase diagrams of the kinetic \(\pm J\) Ising model in the \((p - k_B T_c / J)\) plane for varying reduced magnetic field values with (a) \(\omega = 0.25\), (b) \(\omega = 0.5\), (c) \(\omega = 1.0\) and (d) \(\omega = \pi\).](image)
ferromagnetic and antiferromagnetic exchange interactions, energy contribution which comes from spin-spin interactions gets smaller. Hence, the system can undergo a DPT at lower critical temperatures, and also the dynamically ferromagnetic regions get narrower. On the other hand, the case of \( h/J = 0 \) corresponds to static ±J Ising model, in which there is no energy contribution originating from magnetic field. Our investigations calculated for this applied field amplitude indicates that the critical percolation value is \( p_c = 5/6 \). At the critical percolation value the concentration of antiferromagnetic bonds equal to 1/6 \( \approx 0.167 \), and it is worth noting that this value is in good agreement with previously published works [26-31, 12, 13, 14]. Another important finding is that increasing \( h/J \) values reduce the dynamic critical temperature whereas as \( \omega \) increases then the F region gets wider in the related plane.

![Figure 3: Thermal variations of the DOP curves as functions of the selected Hamiltonian parameters \( h/J, \omega \) and \( p \) where the letters on the curves denote the value of the corresponding Hamiltonian parameter.](image)

In Figs. 3(a-d), in order to elucidate the effects of the quenched random bond process on the studied system in detail, we give the thermal variations of DOP corresponding to DPBs depicted in Fig. 1 and Fig. 2 for a combination of Hamiltonian parameters. Based on the upper left and right panels in Fig. 3 it can be easily said that as the active ferromagnetic bond concentration decreases then the system tends to exhibit reentrant behavior of second order. Here, two successive DPTs exist, and the first one occurs from a disordered phase to an ordered phase at relatively low temperature regions, while the other one takes place from an ordered phase to a disordered phase at higher temperature regions for decreasing \( p \) values. It is also possible to mention that the aforementioned situation is valid for both weak and strong frequency (or amplitude) values which can be clearly seen from the upper left and right panels in Fig. 3. One of the most interesting findings is that the competition between ferromagnetic and antiferromagnetic bonds gives rise to the existence of different type magnetization profiles. According to Néel nomenclature [80, 81], it is possible to classify the thermal variation of the magnetization curves in certain categories. Based on this classification scheme, one can see from Fig. 3(b) that considered system exhibits Q-type, L-type and P-type magnetization behaviors depending on Hamiltonian parameters. Furthermore, the variations of the DOP with temperature curves as a function of the applied field frequency are shown in the lower left panel in Fig. 3 for \( p = 0.86 \) and \( h/J = 0.25 \). As shown in this figure, value of the DOP decreases when the frequency approaches the static case. The physical backgrounds underlying the behaviors found in Fig. 3(c) are identical to those emphasized in above discussions. Therefore, we will not discuss these interpretations here. In addition to these, the thermal variations of the DOP at various \( h/J \) values show that depending on the applied field amplitudes the system exhibits second order reentrant phenomena in Fig. 3(d).

![Figure 4: Variation of the bond percolation threshold \( p_c \) as a function of the external magnetic field amplitude \( h/J \) for some selected values of the oscillation frequency \( \omega \). The letters on each curve denote the frequency value of the external field](image)

In the following analysis, let us investigate the varia-
tion of the bond percolation threshold $p_c$ as a function of applied field amplitude $h/J$ with some selected values of $\omega$ which is depicted in Fig. 4. We found that at relatively small oscillation frequency values such as $\omega = 0.25, 0.5$ and 1.0, value of $p_c$ increases gradually then exhibits a plateau which gets wider as $\omega$ increases. Another important findings related to the percolation investigation is that after a certain $h/J(= 2.0)$ value, $p_c$ value increases rapidly and saturates at $p_c = 1.0$. At this point, we should indicate that for $p < p_c$, there is no infinite cluster causing to ordered phase and no phase transition whereas there is an infinite cluster for $p > p_c$ and critical temperature rises from zero. On the other hand, it is possible to say that the critical percolation value $p_c$ strongly depends on a kind of competition effect which originates from the collaboration of the ferromagnetic and antiferromagnetic bond interactions with the applied field frequency against the amplitude of the external field. Moreover, as we mentioned above, the case of $h/J = 0.0$ corresponds to static $\pm J$ Ising model, and the numerical calculations show that percolation value is $p_c = 5/6(\approx 0.833)$ which is independent of $\omega$.

![Figure 5: Bond randomness dependencies of the DOP for fixed temperature and applied field amplitude at various frequencies of field (a). Magnetic field variation of the DOP for considered Hamiltonian parameters (b).](image)

The bond randomness and external field amplitude dependence of the DOP are shown in Fig. 5 (a-b) for a considered combination of Hamiltonian parameters. It is obvious from the Fig. 5 (a) that an increment on the active antiferromagnetic bond concentrations $(1 - p)$ tends to destruct the dynamically ordered phase for value of $k_B T/J = 10^{-3}$ and $h/J = 0.25$. We notice that the aforementioned situation is dependent on applied field frequency, and with the decreasing value of $\omega$, the dynamically order-disorder transition point shifts to lower value of active antiferromagnetic bond concentrations. At this point, we can also mention that there exists a good agreement in a formal manner between our Fig. 5(a) and Fig. 5 for $\alpha = -1$ of Ref. [35] where static properties of a quenched random bond Ising ferromagnet with anisotropic coupling constants are discussed. Moreover, in Fig. 5 (b), it is observed that the competition between the ferromagnetic and antiferromagnetic exchange interactions give rise to destruct the dynamically first order phase transition as well as to disappear the DTCP at various $p$ values and for fixed reduced temperature and field frequency such as $k_B T/J = 0.5$ and 0.5, respectively.

![Figure 6: Variations of DTCP coordinates (a) $h^{\text{DTCP}}/J$ and (b) $k_B T^{\text{DTCP}}/J$ as a function of bond randomness ($p$) for considered values of oscillating field frequencies such as $\omega = 0.5$ and 1.0.](image)

As a final investigation, in Figs. 6 (a) and 6 (b), variations of DTCP coordinates $h^{\text{DTCP}}/J$ and $k_B T^{\text{DTCP}}/J$ with respect to the bond randomness are plotted for selected oscillating field frequencies such as $\omega = 0.5$ and 1.0, respectively. As seen in these figures, both the $h^{\text{DTCP}}/J$ and $k_B T^{\text{DTCP}}/J$ diminish with decreasing active ferromagnetic bond concentration, and the DTCP disappears after a certain value. It is also possible to notice that the coexistence region in the phase diagrams gets narrower and disappear with decreasing $p$ values. Besides, the coordinates of DTCPs explicitly depend on the applied field frequency, and one can easily deduce from the figures that the ordered phase regions and also positions...
of the DTCPs in related planes tend to expand because increasing field frequency gives rise to a growing phase delay between the magnetization and magnetic field and this makes the occurrence of the DPT difficult.

4. Concluding Remarks

In conclusion, we have looked for an answer how the time dependent oscillating magnetic field affects the DPT properties of $\pm J$ Ising model within the framework of effective field theory on a two dimensional square lattice. In our studied model the spin-spin exchange interaction has a probability $p$ and $1-p$ of taking on values $+J$ and $-J$, respectively. For this purpose, the Glauber type stochastic process has been used with great success to determine the time evolution of competing the magnetic system. After a detailed analytical and numerical operations, the DPBs separating the dynamically ordered and disordered phases has been obtained in different planes by benefiting from thermal variations of DOPs at various Hamiltonian parameters. It is found that the competition between $\pm J$ interactions causes the reentrant phenomena for some certain values of amplitude and frequency of the external applied field, and the ferromagnetic phase regions get expanded with decreasing amplitude which is more evident at low frequencies. One of the most important findings is that the bond randomness leads to destruct the dynamically first order phase transition as well as to disappear the coexistence regions. Namely, after a certain value of ferromagnetic or antiferromagnetic concentration, the first order phase transitions turn into the second order phase transitions and consequently, DTCPs disappear for all frequency values. Furthermore, it is observed according to Néel nomenclature that, the magnetization curves of kinetic $\pm J$ Ising model have been found to obey Q-type, L-type and P-type classification schemes under certain conditions (see Fig. 3(b)). We should also emphasize that the DPBs in related planes have been constructed by making use of the temperature variations of DOP, and our calculated phase boundaries do not include spin glass phase because there is no infinite cluster causing glass behavior. Recently, this type of calculation has been done and spin glass phase properties of the $d=3\ \pm J$ Ising model have been elucidated in detail within the framework of hard spin mean field theory.

On the other hand, it is a well known fact that effective field theory takes the standard mean field predictions one step forward by taking into account the single-site correlations which means that the thermal fluctuations are partially considered within the framework of effective field theory. It is possible to mention that the effective field theory can be successfully applied to such non-equilibrium systems in the presence of bond randomness, however, the true nature of the physical facts underlying the origin of the coexistence phase and also dynamic first order transitions may be further understood by benefiting from a well defined powerful method such as Monte Carlo simulation technique.

Acknowledgements

The numerical calculations reported in this paper were performed at TÜBİTAK ULAKBIM (Turkish agency), High Performance and Grid Computing Center (TRUBA Resources).

References

[1] R.J. Birgeneau, R.A. Cowley, G. Shirane, H.J. Guggenheim, Phys. Rev. Lett. 37 (1976) 940.
[2] J.M. Baker, J.A. Lourens, R.W.H. Stevenson, Proc. Phys. Soc. 77 (1961) 1038.
[3] T.E. Wood, P. Day, J. Phys. C 10 (1977) L333.
[4] S. Oseroff, R. Calvo, W. Giriat, J. Appl. Phys. 50 (1979) 7738.
[5] R.A. Cowley, G. Shirane, R.J. Birgeneau, E.C. Svensson, Phys. Rev. Lett. 39 (1977) 894.
[6] K. Adachi, K. Sató, M. Matsura, M. Ohashi, J. Phys. Soc. Jpn. 29 (1970) 323.
[7] H.A. Algra, L.J. de Jongh, J. Reeedijk, Phys. Rev. Lett. 42 (1979) 606.
[8] R.J. Eliot, B.R. Heap, D.J. Morgan, G.S. Rushbrooke, Phys. Rev. Lett. 5 (1960) 366.
[9] C. Domb, M.F. Sykes, Phys. Rev. 122 (1961) 77.
[10] M.F. Sykes, J.W. Essam, Phys. Rev. Lett. 10 (1963) 3.
[11] J. Jakubczak, Z. Mrozinska, A. Pekalski, J. Phys. C: Sol. Stat. Phys. 12 (1979) 2341.
[12] H.L. Frisch, E. Sonnenblick, V.A. Vyssotsky, J.M. Hammersley, Phys. Rev. 124 (1961) 1021.
[13] V.A. Vyssotsky, S.B. Gordon, H.L. Frisch, J.M. Hammersley, Phys. Rev. 123 (1961) 1566.
[14] S. Kirkpatrick, Phys. Rev. B 16 (1977) 4630.
[15] D. Stauffer, K. Binder, Z. Physik B 30 (1978) 313.
[16] H.O. Heuer, Phys. Rev. B 45 (1992) 5691.
[17] P.J. Reynolds, W. Klein, H.E. Stanley, J. Phys. C: Sol. Stat. Phys. 10 (1977) L167.
[18] M. Pischke, D. Zobin, J. Phys. C: Sol. Stat. Phys. 12 (1979) 4571.
[19] J.M. Yeomans, R.B. Stinchcombe, J. Phys. C: Sol. Stat. Phys. 11 (1978) L525.
[20] J.M. Yeomans, R.B. Stinchcombe, J. Phys. C: Sol. Stat. Phys. 12 (1979) 347.
[21] W. Klein, H.E. Stanley, P.J. Reynolds, A. Coniglio, Phys. Rev. Lett. 41 (1978) 1145.
