Off equilibrium dynamics in the 3d-XY system

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Abstract. We investigate through Monte Carlo simulations the non-equilibrium behaviour of the three-dimensional XY-model quenched from a high temperature state to its ferromagnetic and critical phases. The two-times autocorrelation and response functions are determined in the asymptotic (scaling) regime, from which the nonequilibrium exponents $\lambda$ and critical $\lambda'$ are extracted. The form of the scaling function is in agreement with the prediction of local scale-invariance. The so-called limit fluctuation-dissipation ratio $X_\infty$ is shown to vanish in the ordered phase and to reach a constant value around 0.43 for the critical quench.

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1 Introduction

After the investigations on aging in glass models, efforts have been concentrated on the study of non-disordered model systems since it was soon realized that some of the basic aspects of aging are present in simple systems too with some characteristic features. In most studies, special attention is put on pure ferromagnetic models undergoing a second order phase transition. Typically, one cools down a sample initially prepared in its high temperature phase to its ordered phase. As time is running, domains start to grow with a linear size $l \sim t^{1/z}$. In the thermodynamic limit, equilibrium is never reached which implies an infinite relaxation time. In order to probe aging, which implies a full dependence on the past evolution, it is useful to compute two-times correlations:

$$ C(t, t_w) = \langle \sigma(t) \sigma(t_w) \rangle $$

and linear responses

$$ R(t, t_w) = \left. \frac{\delta \langle \sigma(t) \rangle}{\delta h(t_w)} \right|_{h=0} $$

where $\sigma$ is the order parameter, $t$ the observation time and $t_w$ the waiting time ($\leq t$). Usually, at a coarse-grained level, the dynamics of such systems is described by a Langevin equation:

$$ \frac{\partial \phi_i(t)}{\partial t} = -\frac{\delta H[\phi]}{\delta \phi_i} + \eta_i(t) $$

where $H$ is the free-energy functional, $\eta_i(t)$ is a thermal gaussian noise at site $i$ with:

$$ \langle \eta_i(t) \rangle = 0, \quad \langle \eta_i(t) \eta_j(t') \rangle = 2T \delta(t - t') \delta_{i,j} $$

As mentioned above, the breakdown of time translation invariance implies that the two-time functions do not merely depend on $t - t_w$ but explicitly on $t$ and $t_w$. On the bases of general scaling arguments, one postulates the following scaling laws for the autocorrelation and autoresponse functions:

$$ C(t, t_w) \approx t_w^{-\lambda} f_C(t/t_w) $$

and

$$ R(t, t_w) \approx t_w^{-1-a} f_R(t/t_w) $$

In the asymptotic limit, where $t \gg t_w \gg 1$, $f_C$ and $f_R$ decay algebraically:

$$ f_C(x) \sim x^{-\lambda_C/z}, \quad f_R(x) \sim x^{-\lambda_R/z} $$

where $z$ is the dynamic exponent and $\lambda_C, \lambda_R$ are respectively the correlation and response exponents.

A consequence of the breakdown of time-translation invariance is the violation of the fluctuation-dissipation theorem (FDT) which relates for equilibrium systems the response to the correlation function via:

$$ R(t - t_w) = \frac{1}{T} \frac{\partial C(t - t_w)}{\partial t_w}. $$

When the system is not at equilibrium $R(t, t_w)$ and $C(t, t_w)$ both depend on $t$ and $t_w$, and the FDT does not hold anymore. One introduces a new function $X(t, t_w)$ defined by:

$$ R(t, t_w) = \frac{X(t, t_w)}{T} \frac{\partial C(t, t_w)}{\partial t_w}, $$
which measures the deviation from equilibrium. In some mean-field theory of glassy systems, where it was first formulated, the fluctuation-dissipation ratio (FDR) $X(t, t_w)$ depends on time only through a functional dependence on $C(t, t_w)$.\cite{2} That is $X = X(C(t, t_w))$. In this case, inserting \ref{4} with respect to $t_w$, one gets $T \chi = \int_{C(t, t_w)} X(C') dC'$, so that the slope of the parametric plot susceptibility $\chi$ versus the correlation function $C$ will give the FDR. In the asymptotic regime, for such pure ferromagnetic models, the FDR reaches a constant value $X_\infty$ after an initial quasi-equilibrium regime where $X = 1$ (FDT valid). It was argued that this asymptotic constant is universal and characterises the non-equilibrium process.\cite{11} When a ferromagnetic system is quenched toward its ferromagnetic phase, the long-time dynamics is governed by the diffusion of domain walls and the coarsening of domains. This coarsening leads to a vanishing FDR $X_\infty = 0$.\cite{8,9,10} The scaling functions defined previously are fulfilling this requirement. In the case of a critical quench, that is exactly at the critical temperature, several studies on various systems have given some insights. In that case, the reason for aging is related to the development of the spatial correlations over a length scale $\xi$ that grows as $t^{1/\nu_2}$ where $\nu_2$ is the critical dynamic exponent. So the system is still disordered over a length scale larger than $\xi(t)$, while it looks critical in regions smaller than $\xi(t)$. In the thermodynamic limit, the equilibration is unaccessible since the system is of infinite size so $\xi(t)$ indefinitely increases. For a fully disordered initial state, one has in the kinetic spherical model $X_\infty = 1 - 2/d$ for $2 < d < 4$ and $X_\infty = 1/2$ for $d \geq 4$.\cite{11} For algebraic initial correlations, it was shown on the kinetic spherical model that there exists a rich kinetic phase diagram, depending on the space-dimension $d$ and the algebraic decay exponent $\omega$.\cite{34} Where the limit value $X_\infty$ is either vanishing or depending on $d$ and $\omega$. In the 1d Glauber-Ising model, it was shown that $X_\infty$ is independent on $\omega$.\cite{13} A systematic field-theoretical approach was developed to calculate the limit FDR\cite{14} and applied to several models, ferromagnetic systems at criticality, dilute Ising model, model C dynamics.\cite{15,16,17} Simulations in 2d systems gave $X_\infty = 0.34$ for the Ising model,\cite{31,18} $X_\infty = 0.41$ for the three states Potts model, $X_\infty = 0.47$ for the 4-states Potts model.\cite{32} In 3d, $X_\infty = 0.40$ was obtained for the Ising model.\cite{11} Recently, performing a Monte Carlo simulations with Glauber dynamics, we found from the susceptibility versus correlation function slope a continuously varying FDR in the 2-d XY model quenched below the Kosterlitz-Thouless point.\cite{13} But in this case, one has to use with great care this slope, since the actual definition of the FDR $X_\infty$ leads to a logarithmically vanishing result. In this paper, we present the results obtained on the 3-d XY model quenched onto criticality and below.

2 The 3d XY-model

The XY-model is one of the most popular theoretical models. As it is well-known, in the two-dimensional case there is no finite magnetization at non-zero temperature, but nevertheless there is indeed a topological phase transition occurring at finite temperature due to vortex pairing.\cite{22,21} In three dimensions, the scenario is more conventional since the additional dimension permits the existence of an ordered phase at finite temperature. Thus, the 3d-system presents a second-order phase transition which is probably related to the density of vortex-strings.\cite{22,23}. The Hamiltonian reads:

$$\mathcal{H} = \sum_{\langle i, j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

where $i, j$ are nearest neighbour sites on a cubic lattice and the $\mathbf{S}_i$ are two-dimensional classical spins whose length is set to unity. From high-temperature series analyses, the predicted critical inverse temperature is \cite{21}: $\beta_c = 1/T_c = 0.4539 \pm 0.0013$. In our simulations, we use the value $\beta_c = 1/T_c = 0.4542$ obtained from a Monte Carlo study.\cite{24}. The critical exponents have been estimated by renormalisation group techniques and $\epsilon$-expansions.\cite{24,27} In our study we take the values of the critical exponents obtained in ref.\cite{25} from a numerical approach:

$$\beta \approx 0.349 \quad \nu \approx 0.672.$$ \hspace{1cm} (11)

Simulations on the three-dimensional XY model with periodic boundary conditions have revealed that the critical exponents' density of vortex-strings $\omega = 1.75$ and $\nu = 0.67$. For a quench below the critical temperature, that is in the ordered phase, one has $z = 2.0$.\cite{14}

3 Numerics

We simulate the dynamics through a single spin-flip algorithm of Glauber like form where the transition rates $p$ related to the single flip $\{\theta_i\} \rightarrow \{\theta'_i\}$, where the $\theta$s are the angular variables of the XY model, reads:

$$p(\{\theta_i\} \rightarrow \{\theta'_i\} = \frac{\exp(-\beta \mathcal{H}[\theta'_i])}{\exp(-\beta \mathcal{H}[\theta_i]) + \exp(-\beta \mathcal{H}[\theta'_i])}$$

with $\beta$ the inverse temperature. One may notice here that the Metropolis algorithm, with transition rate $p = \min[1, \exp(-\beta \Delta E)]$, leads to the same time evolution of the autocorrelation and susceptibilities, as we have checked it.

The two-times autocorrelation function is calculated via

$$C(t, t_w) = \frac{1}{L^2} \sum_{i} \langle \cos[\theta_i(t) - \theta_i(t_w)] \rangle$$

where the brackets $\langle \cdot \rangle$ stand for an average over initial configurations and realisations of the thermal noise.

The two-times linear magnetic susceptibility $\chi(t, t_w)$ can be computed by the application of a random magnetic field. The amplitude of the field has to be small in order to avoid nonlinear effects. The ZFC-susceptibility is usually computed utilising a random distributed field via:

$$\chi(t, t_w) = \frac{1}{h^2 L^3} \sum_{i} \langle h_x \cos \theta_i(t) + h_y \sin \theta_i(t) \rangle$$

\hspace{1cm} (14)

where $h_x$ and $h_y$ are the components of the random magnetic field.
where the line stands for an average over the field realisations. Indeed, here we concentrate on a different approach which is based on the lines of ref. [31]. By definition, the linear autoresponse function \( R(t, t_w) \) is

\[
R(t, t_w) = \frac{1}{L^2} \sum_i \left( \frac{\delta(\cos \theta_i(t))}{\delta h_x(t_w)} + \frac{\delta(\sin \theta_i(t))}{\delta h_y(t_w)} \right) \bigg|_{h=0} \ .
\]

(15)

Following ref. [31], we can reexpress the linear response function in the form [19]

\[
R(t, t_w) = \beta(\cos \theta_i(t)[\cos \theta_i(t) + 1] - \cos \theta_i^w(t + 1)) \\
+ \beta(\sin \theta_i(t)[\sin \theta_i(t) - 1] - \sin \theta_i^w(t + 1)) \ ,
\]

(16)

where \( \cos \theta_i^w \) and \( \sin \theta_i^w \) are the components of the local Weiss magnetisation:

\[
S_i^{x,y} = \frac{1}{\beta} \frac{\partial}{\partial h_{x,y}} \ln Z \bigg|_{h=0} \ ,
\]

(17)

where \( Z_i = \exp(-\beta H(\theta_i, h)) + \exp(-\beta H(\theta_i', h)) \) is the local partition function in the field. Finally the fluctuation dissipation ratio is calculated via

\[
X(t, t_w) = \frac{TR(t, t_w)}{C(t, t_w + 1) - C(t, t_w)} \ .
\]

(18)

4 Results

4.1 Quenches below \( T_c \)

We present the results obtained on systems of linear size \( L = 50 \), with periodic boundary conditions, quenched in the low-temperature phase from an infinite-temperature initial state. The averages are performed with the use of more than 5000 samples. The expected behaviour of the two-times autocorrelation function for coarsening processes is at sufficiently long times [4]:

\[
C(t, t_w) = M_{eq}^2(T) f_C \left( \frac{t}{t_w} \right)
\]

(19)

where \( M_{eq}(T) \) is the equilibrium magnetisation at the temperature \( T \). In order to check this behaviour, we have simulated quenches at two different temperatures, \( T = 0.9 \) and \( T = 1.5 \), using the Glauber like dynamics. The results are shown respectively on figure 1 and 2.

For small time separations, we clearly see that the correlations rapidly decay to the expected plateau values \( M_{eq}^2(T) \), here estimated numerically by the use of an independent Wolff algorithm simulation [34,35]. For large time separations, the system enters in a scaling region where the correlation functions are described by a scaling function \( f_C \) of the variable \( x = t/t_w \). As expected, the aging scaling function finally decays algebraically in the asymptotic limit with an exponent \( \lambda_C \) roughly about 1.7 ± 0.1. However, we clearly see that as the temperature is increased the finite-size effects become stronger.

![Fig. 1. Asymptotic behaviour of the autocorrelation function at \( T = 0.9 \). The dashed line corresponds to the value \( M_{eq}^2(T) \) and the solid line represents the algebraic decay of \( f(t/t_w) \).](image1)

![Fig. 2. Asymptotic behaviour of the autocorrelation function at \( T = 1.5 \). The dashed line corresponds to the value \( M_{eq}^2(T) \) and the solid line describes the algebraic decay of \( f(t/t_w) \).](image2)
Moreover, as it can be seen from figure 3 and figure 4, the scaling function \( f_R(x) \approx x^{-\lambda_R/z} \) at \( x \gg 1 \). Furthermore, if one assumes that the response function transforms covariantly under local scale-transformations, one expects for the scaling function \( f_R \) \[ f_R(x) = r_0 x^{1+a-\lambda_R/z} (x-1)^{-1-a} \] \( (22) \) where \( r_0 \) is a normalization constant. For a disordered initial state we expect \( \lambda_R = \lambda_C = \lambda \), with the nonequilibrium exponent \( \lambda \) bounded by \( d/2 \leq \lambda \leq d \), where \( d \) is the euclidian dimension of the system.

We have computed the autoresponse function at temperatures \( T = 0.9 \) and \( T = 1.5 \). On figure 3 and figure 4(left), assuming that \( a = 1/z = 1/2 \), the rescaled response function is plotted as a function of \( t/t_w \). The collapse of the different waiting time curves is quite good. The value \( a = 1/2 \) had been already found numerically and analytically in the 3D Glauber-Ising model \[ [38] \] and the 3D kinetic spherical model \[ [39, 40] \]. We have performed an analysis at fixed ratio \( t/t_w \) that corroborates the power law prefactor in \[ (21) \] with \( a \) close to 1/2 at large \( t/t_w \) as seen on figure 4. In fact, numerically we obtain a value which is slightly larger than 1/2, around 0.6 but the tendency when increasing \( t/t_w \) is toward the decrease of the effective \( a \) value.

Due to important thermal fluctuations the algebraic regime \( x^{-\lambda_R/z} \) is hardly accessible. However, our datas seem to validate the relation \( \lambda_C = \lambda_R \) as it can be seen on figure 3 and figure 4 for \( T = 0.9 \) and \( T = 1.5 \) respectively. Moreover, as it can be seen from figure 3 and 4, the scaling function \( f_R(x) \) is hardly accessible. However, our datas with \( r_0 = 0.18 \). The dashed line is a guide to the eyes for the power law behaviour. Right: Power-law decay of the response function at fixed \( x = t/t_w \) ratios and \( T = 1.5 \). The results are corroborating the value \( a = 1/2 \).

\[ R(t, t_w) \approx t_w^{1-a} f_R \left( \frac{t}{t_w} \right) \] \( \quad (21) \)

where \( \lambda_R = \lambda_C = \lambda \), with the nonequilibrium exponent \( \lambda \) bounded by \( d/2 \leq \lambda \leq d \), where \( d \) is the euclidian dimension of the system.

As discussed in the previous section, the asymptotic value of the fluctuation-dissipation ratio \( X_{\infty} \) is expected to vanish in the low temperature phase. Assuming that \( \lambda_C = \lambda_R \), the fluctuation-dissipation ratio evaluated from the asymptotic behaviour of \[ (19) \] and \[ (21) \] vanishes as:

\[ X(t, t_w) \approx t_w^{-a} f_X(t/t_w) \] \( \quad (23) \)

where \( f_X(x) \) is a scaling function related to \( f_C(x) \) and \( f_R(x) \) with \( \lim_{x \to \infty} f_X(x) = \text{const.} \), a time-independent feature of the critical fluctuations.
constant. On figure 5 we have plotted the rescaled FDR obtained numerically at $T = 0.9$, assuming $a = 1/2$, for different waiting times as a function of $t/t_w$. We see a very good collapse of the different waiting time datas. The solid line is the expected scaling form obtained from the definition of the FDR together with the scaling functions $f_C$ and $f_R$ assuming the local scale prediction with $r_0 = 0.18$. Asymptotically, the scaling function $f_X$ reaches a constant value:

$$
\lim_{x \to \infty} f_X(x) = \frac{\text{Tr}_0}{M^2_{eq}(T) \lambda - 2} \quad (24)
$$

which is close to 0.08 at $T = 0.9$. In the inset graph of figure 5, we have represented the FDR $X(t, t_w)$ as a function of the autocorrelation function $C(t, t_w)$ for different waiting times, where we see the vanishing of the $X$ ratio as the correlation decay.

### 4.2 Critical quench

We focus now on the critical quench starting from a high-temperature initial state. In the vicinity of the critical point, the magnetisation at equilibrium behaves as $|T - T_c|^\beta \sim \xi^\beta_{eq}$ and with $\xi_{eq} \sim L^{1/z_c}$ one expects for the two-times autocorrelation function the form:

$$
C(t, t_w) = A^c_{C} \frac{t}{t_w}^{2\beta/z_c} f_{C}^{c} \left( \frac{t}{t_w} \right) . \quad (25)
$$

The expected scaling for the autosponse function is given by

$$
R(t, t_w) = A^c_{R} \frac{t}{t_w}^{1-2\beta/z_c} f_{R}^{c} \left( \frac{t}{t_w} \right) . \quad (26)
$$

The scaling functions $f^{c}_{C,R}$ are expected to decay algebraically at large time separation with the same exponent $\lambda^c_R = \lambda^c_C$, however different from the low-temperature one.

The numerical calculations have been performed on periodic cubic lattices of linear size up to $L = 50$ and the physical quantities have been averaged over 5000 noise realisations. On figure 6 we have plotted the rescaled two-times autocorrelation functions for different waiting times. The collapse of the rescaled functions is very good, in agreement with the form $\mathbb{28}$. Moreover, at large $t/t_w$ we clearly see a power-law behaviour from which by an algebraic fit we extracted the exponent $\lambda^c_C/z_c \simeq 1.34$ that fulfills the scaling bounds $d/2 \leq \lambda^c_C \leq d$ (remember that $z_c$ is close to 2). Analysing more carefully the datas, we obtain a serie of estimates for the exponent $\lambda^c_C/z_c$ that are represented on figure 7. Our final estimate is

$$
\lambda^c_C/z_c = 1.34 \pm 0.05 \quad (27)
$$

We have also explored the finite-size effects in more details. For that purpose we have studied the time evolution of cubic systems of linear sizes $L = 10, 20, 30$ and 40. Assuming that

$$
C(t, t_w, L) = b^{-2\beta/\nu} C(b^{-z_c} t, b^{-z_c} t_w, b^{-1} L) \quad (28)
$$

with $b = L$ we obtain the scaling form

$$
C(t, t_w) = L^{-2\beta/\nu} \mathcal{F} \left( \frac{t}{L^{z_c}} , \frac{t_w}{L^{z_c}} \right) . \quad (29)
$$

On figure 8, we have plotted $\mathcal{F}$ for different sizes at fixed ratio $x \equiv t_w/L^{z_c} = 0.1$ as a function of $t/L^{z_c}$. Taking into account $\mathbb{28}$ and $\mathbb{29}$, we expect that the scaling function $\mathcal{F}$ has an algebraic decay with the exponent $-\lambda^c_C/z_c$ for $t$ not too large. The collapse of the curves is quite good. For earliest times the system is still in quasi-equilibrium and for biggest times the growth of correlated domains is limited by the size of the system. The numerical datas seem to validate the scaling assumption $\mathbb{29}$.

We focus now on the autosresponse functions computed with formula $\mathbb{10}$. The quantities are quite noisy since thermal fluctuations are of the same order as the amplitude of the response at long times. From $\mathbb{30}$, one should have $a = b$ and $\lambda^c_R = \lambda^c_C = \lambda^c$ since the initial state is
fully disordered. On figure 9, the rescaled autoresponse is represented as a function of \( t/t_w \) for several waiting times \( t_w \). We see that the decay of the autoresponse function is compatible with the algebraic assumption with \( \lambda R/z_c = \lambda c/z_c \simeq 1.34 \).

As stated previously, the out-of-equilibrium behaviour is somehow characterised by the FDR \( X(t, t_w) \), calculated numerically via (18). Assuming the scaling forms of the two-times autocorrelation and response functions, the FDR is supposed to be a function of the ratio \( t/t_w \) only. This behaviour is well reproduced on figure 10, where we have plotted the FDR \( X(t, t_w) \) as a function of \( t_w/t \) calculated on a system of linear size \( L = 30 \), and for different waiting times. In the long time limit \( t_w/t \to 0 \), the FDR approaches a constant value, around 0.4, but due to the numerical noise, basically related to the numerical derivative of \( C(t, t_w) \), it is difficult to give a more precise value. However, if one supposes an asymptotic linear form

\[
X(t, t_w) \simeq X_\infty + \delta t_w/t ,
\]

it is possible to extract the value:

\[
X_\infty = 0.43 \pm 0.04 .
\]

In ref. [15], the limit FDR was calculated in an \( \epsilon \) expansion. The two-loop expansion leads to a value \( X_\infty = 0.416(8) \) that perfectly fits, within the error bars, our estimate.

5 Conclusion and outlooks

We have studied the relaxation behaviour of the 3D XY-model quenched from its high temperature state to its ferromagnetic phase and at criticality. Through Monte Carlo simulations, we have computed the autocorrelation function and its conjugate response function on cubic lattices of maximal linear size \( L = 50 \). From our data, we have confirmed the general scaling scenario at and below criticality. The autocorrelation non-equilibrium exponent \( \lambda c \) below \( T_c \) was found to be around 1.7. The scaling analysis of the linear autoresponse function confirmed...
the equality $\lambda_R = \lambda_C = \lambda$, expected for quenches from a fully disordered initial state. At criticality, we have confirmed that the correlation and response function behave as:

$$C(t, t_w) = t_w^{\alpha} f_C(t/t_w) \quad \text{and} \quad R(t, t_w) \approx t_w^{-a} f_R(t/t_w),$$

with $a = b = 2\beta/\nu z_c$. This conclusion has been supported by a finite-size analysis on systems of linear sizes $L = 10, 20, 30, 40$ and 50. From the data on the correlation function we extracted the value $\lambda_c/z_c \simeq 1.34$ for the nonequilibrium critical exponent and checked its compatibility with the response function data. One may notice that this value is very close to that obtained in the 3d-Ising model, that is $\lambda_c/z_c \simeq 2.8$. It is remarkable to notice that the local scale-invariance prediction for the response function is very nicely fulfilled either at criticality and below. Although at criticality field-theoretical approach showed a deviation from the local scale-invariance prediction, it is very difficult to see numerically this very small discrepancy. In the ordered phase, since the nonequilibrium exponent is very close to the order parameter.

Moreover, we have given a new verification of the correlation function has a scaling form which is very close to the theory. This very small discrepancy. In the ordered phase, since the nonequilibrium exponent is very close to the order parameter.

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References

1. J.-P. Bouchaud, L. F. Cugliandolo, J. Kurchan, M. Mézard, in Spin Glasses and Random Fields, edited by A. P. Young (World Scientific, Singapore, 1998); L. F. Cugliandolo, Lecture notes, Les Houches, July 2002.
2. L. F. Cugliandolo and J. Kurchan J. Phys. A 27, 5749 (1994).
3. L. F. Cugliandolo, J. Kurchan and L. Peliti Phys. Rev. E 55, 3898 (1997).
4. C. Godreche and J. M. Luck, J. Phys. Cond. Matter 14, 1589 (2002); M. Henkel, Adv. Solid State Phys. 44 (2004) in press.
5. L. F. Cugliandolo, J. Kurchan and G. Parisi J. Phys. I (France) 4, 1641 (1994).
6. A. J. Bray, Adv. Phys. 43, 357 (1994).
7. D. S. Fisher and D. A. Huse, Phys. Rev. B 38, 373 (1988); D. A. Huse, Phys. Rev. B 40, 304 (1989).
8. A. Barrat, Phys. Rev. E 57, 3629 (1998).
9. L. Berthier, J. L. Barrat and J. Kurchan, Eur. Phys. J. B11, 635 (1999).
10. S. A. Cannas, D. A. Stariolo and F. A. Tamarit, Physica A 294, 362 (2001).
11. C. Godreche and J. M. Luck, J. Phys. A 33, 9141 (2000).
12. E. Lippiello and M. Zannetti, cond-mat/0001103.
13. M. Henkel and G. M. Schütz, J. Phys. A 37, 591 (2004).
14. P. Calabrese and A. Gambassi, Phys. Rev. E 65, 066120 (2002).
15. P. Calabrese and A. Gambassi, Phys. Rev. E 66, 066101 (2002).
16. P. Calabrese and A. Gambassi, Phys. Rev. B 66, 212407 (2003).
17. P. Calabrese and A. Gambassi, Phys. Rev. E 67, 036111 (2003).
18. P. Mayer, L. Berthier, J. Garrahan et P. Sollich, Phys. Rev. E 68, 016116 (2003).
19. S. Abriet and D. Karevski, Eur. Phys. J. B 37, 47 (2004).
20. V. L. Berezinskii, Sov. Phys. JETP 32, 493 (1971).
21. J. M. Kosterlitz and D. J. Thouless, J. Phys. C 6, 1181 (1973); J. M. Kosterlitz, J. Phys. C 7, 1046 (1974); J. Villain, J. Physique 36, 581 (1975).
22. G. Kohring, R. E. Shrock and P. Williams, Phys. Rev. Lett. 57, 1358 (1986).
23. G. A. Williams, Phys. Rev. Lett. 59, 1926 (1987).
24. M. F. Ferre, M. A. Moore and M. Wortis, Phys. Rev. B 8, 5205 (1973).
25. A. P. Gottlob and M. Hasenbusch, Physica A 201, 593 (1993).
26. J. C. Le Guillou and J. Zinn-Justin, Phys. Rev. B 21, 3976 (1980); R. Guida and J. Zinn-Justin, J. Phys. A 31, 8103 (1998).
27. K. G. Wilson and M. E. Fisher, Phys. Rev. Lett. 28, 240 (1972).
28. M. Hasenbusch and T. Török, J. Phys. A 32, 6361 (1999).
29. L. M. Jensen, B. J. Kim and P. Minnhagen, Europhys. Lett. 49, 644 (2000); P. Minnhagen, B. J. Kim and H. Weber, Phys. Rev. Lett. 87, 037002 (2001).
30. M. Mondello and N. Goldenfeld, Phys. Rev. A 42, 5865 (1990); M. Mondello and N. Goldenfeld, Phys. Rev. A 45, 657 (1992).
31. C. Chatelain, J. Phys. A 36, 10739 (2003); F. Ricci-Tersenghi, Phys. Rev. E 68, 065104 (2003).
32. C. Chatelain, cond-mat/0404017.
33. A. Picone and M. Henkel, J. Phys. A 35, 5575 (2002).
34. U. Wolff, Phys. Rev. Lett. 62, 361 (1989).
35. W. Janke, Phys. Lett. A 148, 306 (1990).
36. A. Picone and M. Henkel, Nucl. Phys. B688, 217 (2004).
37. M. Henkel, Nucl. Phys. B641, 405 (2002).
38. M. Henkel, M. Pleimling, C. Godrèche and J.-M. Luck, Phys. Rev. Lett. 87, 265701 (2001).
39. T. J. Newman and A. J. Bray, J. Phys. A 23, 4491 (1990).
40. J. G. Kissner and A. J. Bray, J. Phys. A 26, 1571 (1993).
41. C. Yeung, M. Ruo and R. C. Desai, Phys. Rev. E 53, 3073 (1996).
42. M. Henkel, M. Paessens and M. Pleimling, Europhys. Lett. 62, 664 (2003).