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Dynamic-symmetry-breaking *breathing* and *spreading* transitions in ferromagnetic film irradiated by spherical electromagnetic wave

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ABSTRACT

The dynamical responses of a ferromagnetic film to a propagating spherical electromagnetic wave passing through it are studied by Monte Carlo simulation of two dimensional Ising ferromagnet. For a fixed set of values of the frequency and wavelength of the spherical EM wave, and depending on the values of amplitude of the EM wave and temperature of the system, three different modes are identified. The static *pinned* mode, the localised dynamical *breathing* mode and extended dynamical *spreading* mode are observed. The nonequilibrium dynamical-symmetry-breaking *breathing* and *spreading* phase transitions are also observed and the transition temperatures are obtained as functions of the amplitude of the magnetic field of EM wave. A comprehensive phase diagram is drawn. The boundaries of breathing and spreading transitions merge eventually at the equilibrium transition temperature for two dimensional Ising ferromagnet as the value of the amplitude of the magnetic field becomes vanishingly small.

1. Introduction

Ising model is a widely used prototype to study the phase transition phenomena. Because of its simplicity, even in the case of nonequilibrium behaviour, this model is being extensively and successfully used [1]. The hysteresis and dynamical phase transitions are two important responses of kinetic Ising ferromagnet to an oscillating magnetic field and play an important role in modern research of nonequilibrium phenomena [1].

Particularly, in this field, the journey was started to study the responses of kinetic Ising model to an oscillating magnetic field. The dynamical meanfield equation was solved and dynamic phase transition was observed [2]. Much effort was devoted to study the responses by Monte Carlo simulations. The hysteretic responses and dynamic symmetry breaking nonequilibrium phase transition were studied extensively. A considerable amount of research was performed to establish this phase transition as a nonequilibrium phase transition [3–11]. Recently, the surface and bulk dynamic transitions were studied in kinetic Ising model and the different classes of universality were observed [12].

Not only in Ising ferromagnet, the dynamic phase transition was observed in Ising metamagnet both from meanfield study [13] and Monte Carlo simulations [14]. The various kinds of nonequilibrium phase transitions were observed in classical vector spin models. Recently, the nonequilibrium phase transition was observed [15] in magnetic nanocomposites by MC simulations.

Apart from the simulational studies of kinetic Ising model, researchers are also paying attention to observe the dynamical phase transitions in Blume–Capel model [16], Blume–Emery–Griffith model [17] and classical vector spin models [18–21].

Experimentally, the dynamic symmetry breaking was also observed in ultrathin Co film on Cu(001) by surface magneto-optic Kerr effect [22]. However, it may be mentioned here that all the studies referred above have a common feature. In those cases, the magnetic field was sinusoidally oscillating but was uniform over the space at any particular instant.

Very recently, the nonequilibrium dynamic phase transition was also observed in Ising ferromagnet swept by linearly polarised electromagnetic *plane* wave [23–25]. In these cases, the spatio-temporal variations of the magnetic field were considered. Here, the coherent motion of spin clusters was found and phase boundaries were drawn.

In this present paper, the dynamical responses of two dimensional Ising ferromagnet to a electromagnetic *spherical* wave are studied by Monte Carlo simulation. The layout of the paper is as follows: Section 2 describes the model and the Monte Carlo simulation scheme, the numerical results are reported in Section 3, the paper ends with concluding remarks in Section 4.

2. Model and simulation

The two dimensional Ising ferromagnet (having uniform nearest neighbour interaction) in the presence of a propagating spherical

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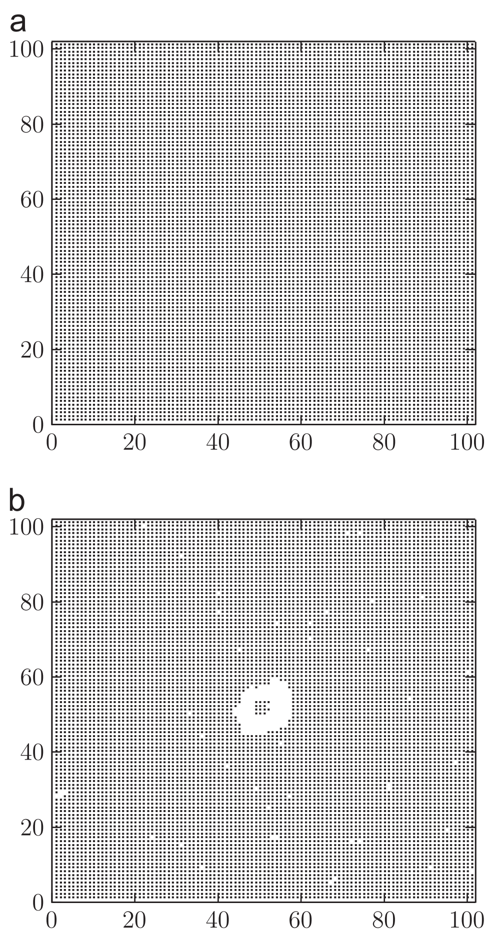

Fig. 1. The pinned (a) and breathing (b) modes on the lattice. Dots represents up spins only. (a) h_0=2.5, T=0.30 and (b) h_0=2.5 and T=1.45. Here, $\lambda=15.0$, $f_0=\omega_0/2\pi=0.01$ and t=4000 MCSS.

electromagnetic field wave (having spatio-temporal variation) can be represented by the following time dependent Hamiltonian:

$$H(t) = -J\Sigma s(x,y,t)s(x',y',t) - \Sigma h(x,y,t)s(x,y,t) \tag{1}$$

The Ising spin variable, $s(x,y,t)$ assumes value ± 1 at lattice site (x,y) at time t on a square lattice of linear size L. The uniform ferromagnetic nearest neighbour interaction strength is $J(>0)$. The first sum represents the Ising spin–spin interaction. The spin–field interaction resides in the second summation. The $h(x,y,t)$ is the value of the magnetic field (at point (x,y) and at any time t) of the propagating (radially outward) spherical electromagnetic wave (originating from the centre (x_0,y_0) of the lattice). The form of spherically propagating wave is

$$h(x,y,t) = h_0 \frac{e^{i(2\pi f_0 t - 2\pi r/\lambda)}}{r} \tag{2}$$

where $r = \sqrt{(x-x_0)^2 + (y-y_0)^2}$. The $h_0, f_0 = \omega_0/2\pi$ and λ represent the amplitude, frequency and the wavelength respectively of the propagating spherical electromagnetic field wave which originates from r=0 and propagates radially outwards. This form of the propagating field was obtained from the solution of spherically symmetric Maxwell's equation representing the electromagnetic wave. In the present simulation, a $L \times L$ square lattice is considered. The boundary condition, used here, is periodic in both (x and y) directions. The initial (t=0) configuration, as the all spins are up ($s(x,y,t=0) = +1$ for all x and y), is taken here. The spins are updated randomly (a site (x,y) is chosen at random) and spin flip occurs (at temperature T) according to the Metropolis probability

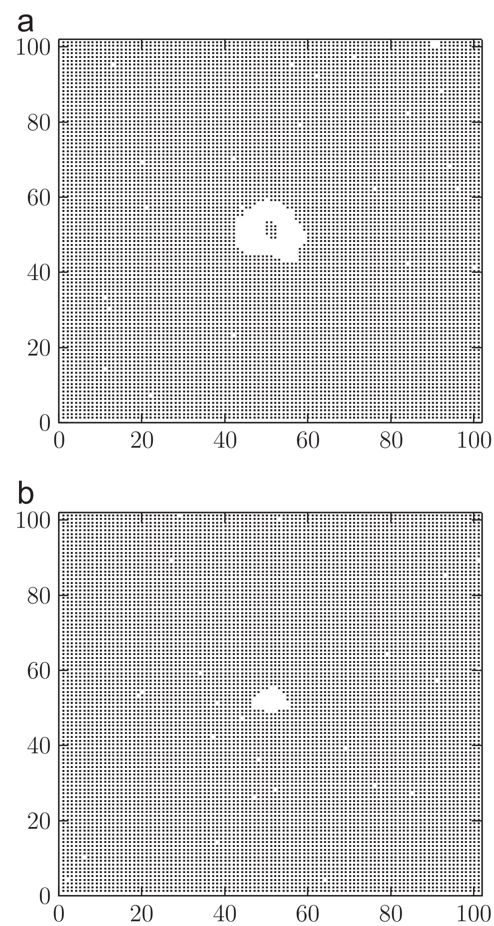

Fig. 2. The breathing mode on the lattice. (a) h_0=2.5, f_0=0.01, λ=15.0, T=1.25 at t=3970 MCSS. (b) h_0=2.5, f_0=0.01, λ=15.0, T=1.25 at t=4000 MCSS.

[26] of single spin flip (W)

$$W(s \to -s) = \text{Min}[\exp(-\Delta E/kT), 1], \tag{3}$$

where ΔE is the change in energy due to spin flip and k is the Boltzmann constant. L^2 such random updates of spins defines the unit time step here and is called Monte Carlo Step per spin (MCSS). Here, the magnetic field and the temperature are measured in the units of J and J/k respectively. The dynamical steady state is reached by heating the system slowly (in the presence of the propagating field) in small step ($\delta T = 0.05$ here) of temperature. It may be mentioned here that the same dynamical steady state was observed to be achieved by cooling the system from a high temperature random configuration. The frequency and wavelength of the propagating magnetic field were kept fixed (f=0.01 and λ=15.0) throughout the study. The total length of simulation is 2×10^5 MCS and first 10^5 MCS transient data were discarded to achieve the stable dynamical steady state. Since the frequency of the propagating field is f=0.01, the complete cycle of the field requires 100 MCS. So, in 10^5 MCS, 10^3 numbers of cycles of the propagating field are present. The time averaged data over the full cycle (100 MCSS) of the propagating field are further averaged over 1000 cycles. Here, the number of cycles is denoted by n_c.

The quantities measured are instantaneous local magnetisation density in the circle of radius $\lambda/2$: $m_b(t) = \sum s(x,y,t)/(N_b)$, where the sum is carried over the number of sites (N_b) lying within the circle of radius $\lambda/2$ centered at the centre (x_0,y_0) of lattice. In the present study, the lattice size L is taken equal to 101. So, the coordinates of the centre are (x_0=51, y_0=51) and N_b is the total number of lattice sites within this circle. The dynamic order parameter of breathing transition is defined as $Q_b = (\omega/2\pi)\oint m_b(t)\,dt$. The fluctuations in