Chapter 6

Summary and Conclusions:

6.1 Summary of my work:

6.1.1 Main studies:

In my thesis, I have tried to bring out some of the nonequilibrium aspects of driven ferromagnetic systems. I have described in details the dynamical behaviors of different kinds of ferromagnets under temporally and spatially varying magnetic field and their subsequent phase transitions.

Starting from a detailed review of previous studies on ferromagnetic systems in the first chapter with appropriate references, I have discussed in subsequent chapters, the manner by which the dynamical phase transitions in nonequilibrium conditions, specially under temporal as well as spatially varying magnetic field can be characterized. Different kind of ferromagnetic systems (Ising, Blume-Capel, general spin-S etc.) have their own characteristic responses that are influenced by the nature of perturbing magnetic field. I have mainly presented my studies regarding nonequilibrium phase transition under the influence of propagating magnetic field wave and standing magnetic field wave. It is seen that though the nature of nonequilibrium phase transitions are more or less similar under various kinds of perturbing fields, the dynamical patterns of spins have particular differences. The nonequilibrium phase transition of a $2D$ Ising ferromagnet driven by propagating magnetic field wave belongs to the same Universality class as that of $2D$ equilibrium Ising ferro-para phase transition.

In subsequent subsections I have summarized the main observations discussed in subsequent chapters.

In **Chapter-1**, I have mainly discussed about the previous studies [[1]-[10]] done on magnetic systems in different nonequilibrium conditions. I have pointed out the main motivation behind my aim of research. Studies on various aspects of different types of magnetic systems, specially of ferromagnetic systems, reveal their characteristic behaviors. These studies have profound technological as well as academic implications and have research interests also. In modern era of advanced technologies, studies of different equilibrium [11] and nonequilibrium [12, 15, 16, 17] phases of magnetic system play a vital role. We have seen some experimental findings [12, 13, 14] that support many theoretical and simulated results.

In **Chapter-2**, I have discussed the nonequilibrium phase transition in an Ising ferromagnet driven by propagating [19] and standing magnetic wave [20]. Using Monte-Carlo technique a square Ising lattice is simulated for such study. Under both type of magnetic perturbation, the nature of response of Ising ferromagnet is found to be nearly same. It is seen that the system undergoes dynamical phase transition from symmetric to symmetry-broken phase as the system is cooled down below the transition temperature. The symmetric phase is determined by the symmetric distribution of both the up and down spin states throughout the Ising lattice. As a result the instantaneous value of magnetization per site becomes nearly zero. In contrast, at low temperature the mutual spin-spin interaction holds the spins together towards a particular direction and the symmetric distribution of spin states is lost. The value of the order parameter, which is defined [18] as the time-averaged magnetization per site over a full period of magnetic oscillation, is nearly zero in the symmetric phase and it takes nonzero values in the symmetry-broken or pinned phase. The nature of transition is continuous. It is observed that the transition temperature depends on the values of magnetic field amplitude and wavelength of the magnetic wave. The transition temperature is lower for higher field amplitude when wavelength is constant. For constant field amplitude it is lower for shorter wavelength. The phase boundary, drawn in the plane of magnetic field amplitude and dynamical transition temperature, shrinks towards lower field and lower temperature for shorter wavelength. Though in both the kind of magnetic field wave perturbation, we see similar nature of dynamic phase transition, the actual spin configurations on the lattice are distinctly different, specially in the symmetric phase, for different nature of magnetic perturbation. We observe a coherent propagation of alternate spin bands in the high temperature symmetric phase for propagating wave like magnetic perturbation; but in case of standing magnetic wave, in symmetric phase, alternate spin bands do not propagate, rather they oscillate out of phase with the oscillation of the magnetic field. Also, it is observed that at the nodes of the standing magnetic field wave the probability of spin flip is higher. Thus, the nature of magnetic perturbation determines the dynamics and the lattice morphologies in the different phases.

In **Chapter-3**, the study of nonequilibrium phase transition in ($S = 1$) Blume-Capel (BC) ferromagnet [21], under the influence of propagating and standing magnetic field waves, has been discussed in two dimensions using MC simulation method. The spins are updated at Metropolis rate using parallel spin updating rule. The corresponding three spin states for a $S = 1$ spin BC ferromagnet are $(+1, 0$ and $-1)$. In BC ferromagnet the spins have intrinsic anisotropy. With the increase in the strength of anisotropy spins prefer the state $s^z = 0$ to the states $s^z = \pm 1$. The influence of both the kind of magnetic waves on the nature of phase transition is found to be the same. In both the kind of magnetic perturbations two distinct phases have been identified; namely: the pinned or symmetry-broken phase and the symmetric phase. At temperatures above the transition temperature all the spin states have equal probabilities and are thus symmetrically distributed over the whole lattice dimensions. While below the transition temperature the symmetric distribution of spin states no longer persists, the spins switched to either $+1$ or -1 states. As a result the order parameter, which is the time-averaged magnetization per site over a full period of magnetic oscillation, takes non-zero values. In symmetric phase the value of order parameter is zero. In case of propagating magnetic wave, in symmetric phase, there is a coherent propagation of spin bands (having most of the spin values of any band either $+1$ or -1). This phase is called the propagating spin wave phase. At the boundaries of spin bands, the value of magnetic field is zero. As a result we see some greater population of spin state $s^z = 0$ there. In case of standing magnetic field wave, the symmetric phase is quite different from that of the propagating magnetic field wave. Here, spin bands do not actually propagate, while these bands oscillate with the same frequency as that of the magnetic field oscillation. The transition temperature is determined from the peak positions in the temperature variations of the steady state values of the variance of order parameter and the dynamical specific heat. It is observed that the transition temperature depends on the value of the magnetic field amplitude and the strength of anisotropy for a fixed frequency and wavelength of the magnetic field waves. Actually, the dynamical transition temperature decreases with the increase in those values. Phase boundaries are drawn in the field amplitude and transition temperature plane with anisotropy strength as parameter and in the plane of anisotropy strength and temperature with magnetic field amplitude as parameter. In both the cases the phase boundaries shrink inwards for higher values of the respective parameters.

Chapter-4 deals with discussions on the general behavior of nonequilibrium phase transition of a spin-S Ising ferromagnet [22], driven by externally applied magnetic field in the form of propagating wave, standing wave and uniformly oscillating field. Two dimensional spin-S Ising ferromagnets having ($S = 1,\ \frac{3}{2},\ 2$ & 3) are simulated using MC method to study the dynamical behavior of the nonequilibrium phases. Spins of unit magnitude are updated at Metropolis rate using parallel updating rule. For a spin-S ferromagnet there are $(2S+1)$ number of spin states. The distribution of these different spin states, for a particular S, over the lattice sites depends on the temperature and the local spatio-temporal variation of the magnetic field. At lattice sites where the value of magnetic field is high, the relative probability of spin states ($s^z = \pm 1$) is higher than the other spin states, whereas at sites, where the value of magnetic field is nearly zero, the relative probability of other spin states increase. Depending on the values of magnetic field amplitude h_0 and S two phases; namely: pinned or symmetry-broken phase and symmetric phase are observed. High temperature phase is the symmetric phase. In this phase spins actually follow the magnetic field oscillation and eventually form the propagating phase in case of propagating magnetic wave, oscillating spin clusters phase in case of standing magnetic wave or the uniformly oscillating phase in case of uniformly oscillating magnetic field wave. Below the transition temperature spins are locked in a particular state ($s^z = +1\ or\ -1$), because the thermal energy together with the energy from the magnetic field wave become insufficient to overcome the cooperative spin-spin interaction between the spins. Thus the symmetric spin arrangement is lost in the lattice. The value of order parameter is large in this symmetry-broken or pinned phase as compared to that in the symmetric phase, where it is nearly zero. In this respect it is found that the nature of phase transition is similar for all the different kinds of magnetic perturbation but the morphological structures of spins in the lattice have distinct differences, specially in the symmetric phase, for different kind of magnetic field variations. We see a coherent propagation of spin bands in case of propagating wave, whereas alternate spin bands oscillate out of phase in case of standing wave. But in case of uniformly oscillating magnetic field, spins oscillate as a whole in the lattice with the same frequency of oscillation of the magnetic field. The dynamic phase diagram drawn in the $(T_d - h_0)$ plane shrinks towards the lower values of T_d and h_0 for higher values of S. This manifests the fact that the dynamic transition temperature decreases when there are more number of spin states corresponding to the value of S. The transition temperature seems to approach a minimum value in the limit of very large number of S.

In **Chapter-5** I have mainly concentrated on the nature of nonequilibrium phase transition [28] in an Ising spin-$\frac{1}{2}$ ferromagnet driven by propagating magnetic field wave and discussed on the scaling behavior of such nonequilibrium phase transition. Using Monte-Carlo method with parallel updating rule the dynamics of spin, under such driven condition, is simulated and the steady state dynamical quantities such as the dynamic order parameter Q and the dynamic susceptibility χ_L^Q are calculated for different lattice dimensions L. The temperature variation of the fourth order Binder Cumulant [27] (for $L = 16,\ 32,\ 64,\ and\ 128$) precisely determines the dynamic transition temperature for such nonequilibrium ferro-para transition. Adopting the finite size analyses [[12]-[15]] method the estimated values of critical exponents are found to be close to that obtained in the equilibrium ferro-para transition [11]. The values of the critical exponents found from the Monte-Carlo studies are $\beta/\nu = 0.146\pm0.025$ and $\gamma/\nu = 1.869\pm0.135$ (measured from the data read out at the critical temperature obtained from Binder cumulant), and $\gamma/\nu = 1.746 \pm 0.017$ (measured from the peak positions of dynamic susceptibility) respectively for Q and χ_L^Q. Whereas, the values, reported from Onsager exact solution [11], are respectively $\beta/\nu = 1/8$ and $\gamma/\nu = 7/4$. Thus, we may conclude that such a kind of nonequilibrium phase transition in a $2D$ Ising ferromagnet driven by linearly polarized propagating magnetic field wave belongs to the same universality class of the two-dimensional equilibrium Ising ferro-para phase transition.

6.2 Outline of future studies.

The study of dynamical behavior and nonequilibrium phase transition in driven ferromagnetic systems, described here has shown promises and prospects of studies in various other magnetic models as well. We may study nonequilibrium in various ferromagnetic systems as well as in any other systems. Let me briefly mention the scope of such studies:
(i) We may extend similar kind of studies in three dimensions as well and see the bulk behavior of a ferromagnetic system driven by propagating and standing magnetic field wave.
(ii) *Continuous spin systems*; such as: Heisenberg ferromagnet, XY model etc. driven

by propagating and standing magnetic wave can be studied by Monte-Carlo simulation. It is worthy to mention here that very recently the dynamic phase transition is studied [29] in 3D XY ferromagnet driven by propagating magnetic wave and standing magnetic wave.

(iii) The response and the nonequilibrium phase transition can be studied in *Layered spin systems*; such as: bi-layered or tri-layered model magnets, antiferromagnet etc. driven by propagating magnetic wave and standing magnetic wave using Monte-Carlo method.

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