TIFR Annual Report 2006-07
THEORETICAL PHYSICS

Condensed Matter and Statistical Physics

HIGHLIGHTS

It was shown that the model of straight hard rod with only hard core interactions, the prototypical model of nematic liquids, shows a second phase transition from the nematic to disordered phase, as the density of rods is increased. The generic behaviour of sandpile models with sticky grains was studied using much longer simulations than before, showing that these are in the universality class of directed percolation.

Shock-tracking probe particles were shown to have strong effects on the steady state of a one-dimensional driven diffusive system, both in the presence and absence of a drive.

Electronic phase separation on the nanoscale was shown to arise in disordered delta-doped semiconductor heterostructures as a result of competition of disorder and nonlinear screening. The analysis successfully explained a recently observed intriguing dependence of the magnetoresistance on the electron density in the heterostructure.

Numerical evidence for a novel U(1) deconfined phase of matter in a system of interacting bosons on a pyrochlore lattice was obtained using Stochastic Series Expansion Quantum Monte Carlo methods.

TEXT

Probe Particle Dynamics

The properties of a large system are often studied by injecting probe particles, and monitoring their dynamics after steady state is reached. It is generally assumed that if the concentration of the probe particles is sufficiently low then the properties of the original system are not affected greatly by their presence. In this work, the validity of this assumption is examined by considering probe particles injected into a one-dimensional lattice gas of diffusing particles, with and without drive.

Probes are considered to exchange with particles and holes in the original system with the same rate but in opposite directions. Such probe particles tend to track the shocks (strong density variations) which may be present in the medium. A finite density of these shock-trackers in the asymmetric exclusion process was studied by Monte Carlo simulation. It was found that several dynamical properties of the probe particles show a crossover in

time from single particle to collective behaviour on a timescale which diverges as the probe density goes to zero, and have quite a strong effect on the medium.

Such probes produce an even stronger effect if a medium is initially in equilibrium. Even with a single probe particle, the system goes into a non-equilibrium steady state with a small current which arises from a system-wide density gradient due to the presence of the probe particle. When several such probe particles are present, they form a compact cluster which diffuses slowly through the medium with a diffusion constant that falls inversely with the system size. [S. Chatterjee and M. Barma]

Tagged Particle Correlations in Driven Systems

The Asymmetric Simple Exclusion Process is a paradigm to study nonequilibrium dynamics. It involves hard core particles evolving through stochastic dynamics on a lattice in the presence of an external drive. In the stationary state, the mean-squared displacement of a tagged particle shows interesting properties on a finite lattice. On a ring, the mean-squared displacement grows linearly with time at both small and very large times. It was found that at intermediate times, it shows oscillations with a size-dependent period. These oscillations arise from sliding density fluctuations in the stationary state with respect to the drift of the tagged particle, the density fluctuations being transported through the system by kinematic waves. It was shown that an exactly solvable linearized model captures the essential qualitative features seen in the finite size effects of the tagged particle correlations, besides providing an exact coarse-grained description of two other microscopic models [S. Gupta and M. Barma with S. N. Majumdar (LPTMS, Orsay, France) and C. Godreche (CEA Saclay, France)].

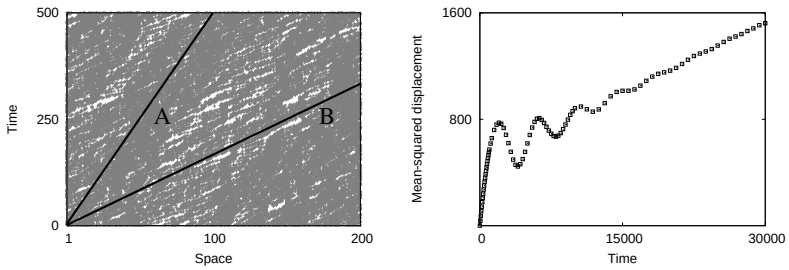

Figure 1: The figure on the left shows the time evolution of a stationary state configuration of the Asymmetric Simple Exclusion Process on a lattice of 200 sites in one dimension at quarter-filling. The trajectories of a density fluctuation and a tagged particle are marked by the solid lines A and B, respectively. In the figure on the right, the behaviour of the mean-squared displacement of a tagged particle is shown as a function of time on a one-dimensional lattice of 1024 sites at quarter-filling. The pronounced oscillations are due to kinematic waves which transport density fluctuations through the system.

Directed Diffusion of Reconstituting Dimers

Certain dynamical processes involving composite objects exhibit strongly broken ergodicity, with the number of dynamically disjoint sectors growing exponentially with system size. An example involves diffusion of pairs of particles, or dimers ($110 \longleftrightarrow 011$), wherein the dimers in question can reconstitute in time and do not keep their identity. In one dimension, the partitioning of phase space into many sectors, and the consequent dynamical behaviour was earlier understood in terms of a non-local construct known as the Irreducible String (IS), which is a constant of the motion.

When dimers are driven, so that they move only forward, the IS moves forward as well, but at a speed which differs from that of density fluctuations which are carried by a kinematic wave. A sector-dependent correspondence is used to map the dimer problem to the asymmetric exclusion process. This allows results to be obtained for the decay of correlation functions in space and time. In particular, it allows the determination of a critical density, which varies from sector to sector, at which the autocorrelation function decays as a power law, rather than exponentially. [M. Barma with M.D. Grynberg (Universidad Nacional de La Plata, Argentina) and R.B. Stinchcombe (University of Oxford, United Kingdom)]

Orientational ordering of long rods on a lattice

Onsager, in the fifties had noted that a model of solution of long hard rod-like molecules in a solvent would be expected to show an orientational ordering transition as a function of the concentration of the solvent molecules. However, whether or not the corresponding lattice model also shows an ordered phase has remained uncertain. The main problem has been the fact that in the maximum density limit the lattice model does not show any orientational order.

Monte Carlo studies in this work have provided very convincing numerical evidence that as the density of rods is increased, there is a transition from a disordered isotropic phase to a phase with orientational order. Then, it was pointed out that to be consistent with the fact that at maximum packing, there is no orientational order, there must be a second phase transition from nematic-like to disordered phase as density of rods is increased further. The possibility of this second transition has not been appreciated earlier. The critical densities for these transitions were estimated for long rods. [Anandamohan Ghosh and D. Dhar]

Generic behaviour of sandpiles with sticky grains

An important question in the study of driven systems is the understanding of different universality classes of behaviours. In the context of sandpile models of self-organized criticality, it was earlier argued that generic behaviour of sandpile models is in the universality class of directed percolation. The critical behaviour of sticky sandpiles is different from the case of zero stickiness. The latter belongs to the so-called Manna model class, which is

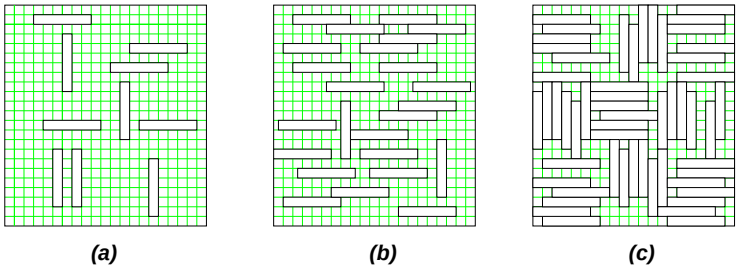

Figure 2: Schematic representation of different phases of the hard rod system on a square lattice. (a) The low-density disordered phase (b) Intermediate density ordered phase (c) the high density disordered phase.

characterized by different critical exponents. These conclusions were supported by detailed Monte Carlo simulations of different models.

There has been some controversy in the literature about the validity of these conclusions in the case where there is no preferred direction. Some Monte Carlo studies of fixed energy sandpile models gave results not in agreement with ours. The earlier simulations were extended to ten times larger sizes, and much better statistics, and it was shown that the new simulations agree with the earlier conclusions, and the large avalanche clusters of sticky sandpiles are like the direction-percolation clusters, and not like the Manna model clusters. [D. Dhar and P. K. Mohanty (SINP, Kolkata)]

Unconventional Transition from Superfluid to Mott Insulator Phase of Hard-Core Bosons on the Checkerboard Lattice

Conventional Landau theory of phase transitions rules out a generic second order phase transition between two different ordered states that break different symmetries. This conventional wisdom has been recently questioned by Senthil and co-authors who have argued that Berry phase effects in quantum phase transitions can invalidate Landau's original conclusion, and allow a direct second order phase transition in such situations.

In this context, a model of hard-core bosons on the checkerboard lattice with nearest neighbour unfrustrated hopping t and 'tetrahedral' plaquette charging energy U was studied. Analytical arguments and Quantum Monte Carlo simulations lead to the conclusion that the system undergoes a zero temperature (T) quantum phase transition from a superfluid phase at small U/t to a large U/t Mott insulator phase with $\rho = 1/4$ for a range of values of the chemical potential μ. Further, the quarter-filled insulator breaks lattice translation symmetry in a characteristic four-fold ordering pattern, and occupies a lobe of finite extent in the μ-U/t phase diagram. A Quantum Monte-Carlo study slightly away from the tip of the lobe provided evidence for a direct weakly first-order superfluid-insulator transition. A combination of indirect numerical evidence and analytical arguments lead to the conclusion that the transition *at* the tip of the lobe belongs to a different Landau-forbidden second-order

universality class. [A. Sen and K. Damle with T.Senthil (MIT)]

Unusual liquid state of hard-core bosons on the pyrochlore lattice

In most conventional phases of matter, the elementary quasi-particle excitations carry the same quantum numbers as the microscopic constituents of the many-particle system. For example, Landau Fermi-liquid quasiparticles carry spin 1/2 and charge $-e$ just like the interacting electrons that make up this Fermi liquid. However, in recent years there has been a great deal of interest in exceptional situations where this is not true. In these exceptional 'deconfined' phases, the propagating quasi-particle excitations can be thought of as being the result of the break-up (fractionalization) of the elementary constituents that make up the many-body system.

In this context a study of the physics of hard-core bosons with unfrustrated hopping (t) and nearest neighbour repulsion (V) on the three dimensional pyrochlore lattice was performed. At half-filling, it was shown that the small V/t superfluid state eventually becomes unstable at large enough V/t to an unusual insulating state which displays no broken lattice translation symmetry. Equal time and static density correlators in this insulator are well-described by a mapping to electric field correlators in the Coulomb phase of a U(1) lattice gauge theory, allowing for an identification of this insulator with a previously conjectured U(1) fractionalized Mott insulating state with gapped charge 1/2 (in units of boson charge) excitations. The possibility of observing this phase in suitably designed atom-trap experiments with ultra-cold atoms was also discussed, as were specific experimental signatures. [A. Banerjee and K. Damle, with Y.B. Kim (Toronto) and S.Isakov (Toronto)]

Magnetotransport in disordered delta-doped heterostructures

At low densities, electrons confined to two dimensions in a delta-doped heterostructure can arrange themselves into self-consistent droplets due to disorder and screening effects. This droplet picture was used to study magnetotransport in the heterostructure, and the expected dependence on electron density of several quantities relevant to this transport, in the regimes of weak and moderate magnetic fields, was derived. Recent experiments in such devices had reported an intriguing dependence of the magnetoresistance on the electron density as well magnetic field induced resistance oscillations. These observations had been cited as strong evidence for an ordered state such as a Wigner crystal or charge density wave. The droplet picture proposed in this work was able to qualitatively and quantitatively explain these experiments without having to invoke any scenario with electronic ordering. [V. Tripathi with M. P. Kennett (Simon Fraser University, Canada)]