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THEORETICAL PHYSICS

Condensed Matter and Statistical Physics

HIGHLIGHTS

An effective time-independent potential is derived for a confined Brownian particle subjected to a rapidly oscillating space-dependent force. Significant quantum effects are found in the intermediate regime of damping.

The effect of heat bath coupling and confineent on dissipative diamagnetism in determining low temperature thermodynamics is demonstrated in this work.

Separate expressions for different quantum thermodynamic functions in the two limits of very low and very high temperature for a charged magneto-oscillator are presented for different kind of heat bath models.

Essential role of magnetocrystalline anisotropic energy in interpreting equilibrium magnetization and static susceptibility of noninteracting single domain nanoparticles is studied in this work.

It was shown that nuclear relaxation measurements may be used to unambiguously detect long-range magnetic and crystalline order in electron gases in disordered semiconductor heterostructures. Transport measurements (the standard probe) will not be useful in this case.

TEXT

Patterns made in growing sandpiles

Patterns produced by adding grains at a single site on a flat substrate in sandpile models provide nice examples of complex patterns produced from simple deterministic local non-linear evolution rules. The authors have earlier studied some of the patterns in abelian sandpile models on the two-dimensional Manhattan lattice and the F-lattice. These results were extended to the case with multiple sources, and when there is a single source, with a point sink, or a line sink. For the pattern with one point sink, it was shown that the diameter of the pattern with N particles added grows as $(N/\log N)^{1/2}$. For a wedge of angle θ, with particles added near the vertex of the wedge, the diameter grows as $N^{\frac{\theta}{\pi+2\theta}}$ [D. Dhar and T.Sadhu]

The Kitaev model in the large spin S limit in two dimensions

The zero temperature state of a classical Heisenberg model on the hexagonal lattice with Kitaev model couplings was studied. The exact ground state manifold was determined, and it was shown that the partition function is equivalent to that of a height model at a non-zero temperature with nearest neighbor couplings. It was shown that the energy -energy correlation function has an algebraic decay at zero temperature, but the decay is exponential at all non-zero temperatures. [S. Chandra, K. Ramola and D. Dhar]

Asymptotic shape of the cluster of visited sites of an Eulerian walker

An Eulerian walker on a square lattice was studied, where each site has an arrow which can point in up, down, left or right directions. The initial configuration of the arrows is a random. The Eulerian walker is defined by the rule that on arriving at a site, the arrow is rotated by 90° clockwise, and then walker takes a step in the direction of the arrow. Monte Carlo simulations performed here suggest that the asypmtotic shape of the region visited by the walker, for large number of steps N, is a perfect circle. It was also found that, at large distance from the origin, the variance of the number of visits becomes zero. In the presence of noise, the mean square displacement of the walker, $\langle R_N^2 \rangle \sim N^{2\nu}$, is found to have a crossover from the Eulerian ($\nu = 1/3$) to a simple random walk ($\nu = 1/2$) behaviour. [R. Kapri and D. Dhar]

Equation of state of a model glass

In current physics literature, the glassy state is usually described as a non-equilibrium state of matter that is relaxing to equilibrium very slowly. For a non-equilibrium state, observables like pressure or density would be time dependent, and the conventional wisdom is that it makes no sense to talk of equation of state of a glassy material, as the system is not in thermal equilibrium, and thermodynamical quantities like temperature and entropy are not well-defined. In fact, the calculation of the exact partition function of the system, even if it were possible, would fail to give the give correct result, as it would describe the properties of the corresponding equilibrium state (e.g. of quartz, and not of window glass).

However, the authors have argued that materials like window glass, for a given history of preparation, and at temperature near the room temperature, have a well-defined macroscopic density, and velocity of sound. Over a time scale of seconds and days these materials are in some restricted thermodynamical equilibrium. While the notion of restricted ensembles is not so new, and one often talks of free-energy landscapes, the explicit calculation has not been possible so far.

A simple toy model is discussed where the equation of state of a glassy material can be exactly calculated. This approach has been studied earlier by the authors, under the name *pico-canonical ensembles*. A one dimensional lattice gas is considered, with nearest neighbor

couplings, and Markovian evolution. The transition rates satisfy detailed balance condition, but the system is non-ergodic in the glass phase, and the phase space breaks up into many disjoint sectors in the glass phase. The partition functions have been calculated for each sector. Then one has to further average the thermodynamical quantities like the free energy in the sector, using the probability weight that the system will fall into that sector. [D. Dhar and J. L. Lebowitz(Rutgers Univ)]

Semiclassical spin liquid state of Nd-Langasite

Motivated by recent experiments on Nd-langasite, a study of the effect of strong easy axis single-ion anisotropy D on $S > 3/2$ spins interacting with antiferromagnetic exchange J on the Kagome lattice was undertaken. When $T \ll DS^2$, the collinear low energy states selected by the anisotropy map on to configurations of the classical Kagome lattice Ising antiferromagnet. However, the low temperature limit is quite different from the cooperative Ising paramagnet that obtains classically for $T \ll JS^2$. It was found that sub-leading $\mathcal{O}(J^3S/D^2)$ multi-spin interactions arising from the transverse quantum dynamics result in a crossover from an intermediate temperature classical cooperative Ising paramagnet to a semiclassical spin liquid with distinct short-ranged correlations for $T \ll J^3S/D^2$ [A. Sen and Kedar Damle, with R. Moessner (Dresden)].

Collinear ordering of frustrated triangular lattice antiferromagnets

Antiferromagnetically coupled moments on the frustrated triangular lattice typically order in a coplanar state at low temperature. However it was demonstrated that the presence of not-very-large easy axis single ion anisotropy leads to an interesting orientationally ordered collinear state in triangular lattice antiferromagnets with moments $S \geq 3/2$. This ordered state breaks the symmetry of $\pi/3$ rotations about a lattice site, while leaving intact the translational symmetry of the lattice [A. Sen and Kedar Damle, with F. Wang (Berkeley)].

Quantum Brownian motion under rapid periodic forcing

The steady state behaviour of a confined quantum Brownian particle subjected to a space-dependent, rapidly oscillating time-periodic force is studied. To leading order in the period of driving, the result of the oscillating force is an effective static potential which has a quantum dissipative contribution, V_{QD}, which adds on to the classical result. This is shown using a coherent state representation of bath oscillators. V_{QD} is evaluated exactly in the case of an Ohmic dissipation bath. It is strongest for intermediate values of the damping, where it can have pronounced effects. [M. Bandyopadhyay and M. Barma]

Dissipative diamagnetism — role of heat bath coupling and confinement in determining low-T thermodynamics

The purpose of this work is to show how the low-temperature thermodynamics of Diamagnetism is sensitive to the nature of coupling to the environment. In all cases of couplings considered here however the free energy, the entropy and the specific heat fall off to zero as power law in conformity with the third law of thermodynamics. The influence of confinement is also separately discussed. [M. Bandyopadhyay and S. Dattagupta (IISER, Kol)]

Quantum thermodynamics of a charged magneto-oscillator coupled to a heat bath

Explicit results for various quantum thermodynamic function (QTF) of a charged magneto-oscillator coupled to a heat bath at arbitrary temperature are demonstrated in this paper. Discernible expressions for different QTF in the two limits of very low and very high temperatures are presented for three popular heat bath models : the Ohmic, single relaxation time and blackbody radiation ones. The central result is that the effect of magnetic field turns out to be important at low temperatures as well as at high temperatures. It is observed that the dissipation parameter, γ, and the cyclotron frequency, ω_c, affect the decaying or rising behaviour of various QTF in just the opposite way to each other at low temperatures. In the high temperature regime, the effect of γ is much pronounced than that of ω_c. [M. Bandyopadhyay]

Thermodynamic properties of magneto-anisotropic nanoparticles

The purpose of this paper is to study the thermodynamic equilibrium properties of a collection of non-interacting three-dimensional (3D) magnetically anisotropic nanoparticles in the light of classical statistical physics. The present analysis is related with the interpretation of equilibrium magnetization and static susceptibility of nanomagnetic system as a function of external magnetic field, B, and temperature, T. This study reveals the essential role of magneto anisotropic energy in the interpretation of the magnetic behaviour of a collection of noninteracting single domain nanoparticles. [M. Bandyopadhyay]

Kondo lattice scenario in disordered semiconductor heterostructures

Semiconductor mesoscopic structures have been associated with a wide range of strongly correlated electron phenomena such as the fractional quantum Hall effect, Kondo effect, the 0.7 conductance anomaly in ballistic quantum wires, Coulomb blockade, and Wigner crystallisation and charge density waves. In a recent work [C. Siegert et al., Nature Phys. 3, 315 (2007)], the possible Wigner crystallization of ionised dopants in a delta-doped

semiconductor heterostructure has been argued, on the basis of transport measurements, as inducing a spin-1/2 Kondo lattice in the 2D electron gas in the heterostructure. This holds the exciting prospect of exploring the phase diagram and transport properties of 2D Kondo lattices over a wide range of material parameters such as electron density and disorder. In our paper it is argued that an alternate scenario based on the competition of the Kondo effect and exchange interaction in a small number of disorder induced quantum dots can also account for the main observations. A different probe is thus needed as transport measurements cannot be relied in this case to detect long range magnetic and crystalline order. In the present work, it is shown that nuclear relaxation rates would be qualitatively different for these different physical scenarios and may be used to unambiguously distinguish them. [K. Dhochak and V. Tripathi]

Superconductivity and Hall effect in disordered epitaxial NbN films

The experiments in this work were conducted by P. Raychaudhuri's group in DCMPMS in TIFR. Niobium Nitride (NbN) is a conventional superconductor with a moderately large transition temperature which has been found to be useful for studying disorder and other effects that degrade superconductivity. Disorder (parametrized by the product of the Fermi wavevector and the mean free path) which in this experiment is introduced by Nitrogen sputtering causes a systematic degradation of the transition temperature, and naturally, also makes the samples more resistive in the normal state. The transition temperature degradation was however found to be too large compared to the expectation from theoretical analyses (Anderson, Muttalib and Ramakrishnan (1983); Maekawa, Ebisawa and Fukuyama (1985)) based on localisation models. Hall and resistivity measurements in the normal state, reported in this work, then revealed that increasing disorder was accompanied by decreasing carrier density, while the mean free path was largely unaffected. The effect of decreasing carrier density was large enough to account for the observed degradation of the transition temperature. [S. P. Chockalingam, M. Chand, J. Jesudasan, V. Tripathi and P. Raychaudhuri]

Tunneling studies in a homogeneously-disordered s-wave superconductor

Continuing our studies of homogeneously disordered superconductors, tunnelling measurements were made in order to understand the relation between the superconducting gap and transition temperature. In the BCS theory of homogeneous superconductors, the transition temperature is proportional to the superconducting gap, and a small amount of disorder does not affect this proportionality. In contrast, strongly disordered superconductors (e.g. granular superconductors) may show local superconductivity (Cooper pairing) while global phase coherence may be absent. Tunnelling measurements in this case will reveal a superconducting gap even though globally one does not have superconductivity. In this work, the disorder was homogeneous and not strong enough to cause evident granularity of the superconductor. It was observed that for all but the least disordered films where

the mean free path was of the order of ten times the the inverse Femi wavevector, the superconducting gap as measured by tunnelling spectroscopy did not show a tendency to vanish at the transition temperature. There are two implications of this work: (1) the issue of global phase coherence may be important even in disordered epitaxial superconducting films that are not granular, and (2) tunnelling spectroscopy does not always measure the superconducting gap. Instead, it measures the parity gap, which is the energy difference between an odd and even number electron state in a region in the sample of size of the order of the localization length. These two quantities coincide when global phase coherence is established. The latter possibility is suggested in a recent work (M. V. Feigelman, L. B. Ioffe, V. E. Kravtsov and E. A. Yuzbashyan (2007)). [S. P. Chockalingam, M. Chand, S. Kamlapure, J. Jesudasan, A. Mishra, V. Tripathi and P. Raychaudhuri]