Preface

The idea of this volume emerges from the "International Workshop on the Physics of Zero and One Dimensional Nanoscopic Systems," which was held on 1-9 February 2006 at Saha Institute of Nuclear Physics, India. The theme of the workshop was to understand physically the recent advances in nanoscale systems, like, quantum dots, quantum wires, 2D electron gases, etc. A limited number of distinguished physicists were invited to give pedagogical lectures and discuss core methods including the latest developments. This volume consists of self-contained review articles on recent theories of the evolution of Kondo effect in quantum dots, decoherence and relaxation in charged qubits, edge-state transport through nanographites and quantum Hall systems, transport through molecular bridges, coherence and interaction in diffusive mesoscopic systems, persistent current in mesoscopic rings, and, the thermoelectric phenomena of nanosystems. As these are rapidly growing subjects, we hope that this book with contributions from the leading experts will serve as a stimulus for new researchers and also become a landmark to the body of the knowledge in the field. We have presented the articles on quantum dots first, then on quantum wires and finally on 2D electron gases. A brief account of each chapter is given below:

The first chapter by Avraham Schiller starts with a brief historical note on the Kondo problem. The Anderson Hamiltonian for the ultra-small quantum dot is then mapped onto the Kondo Hamiltonian applying a suitable canonical transformation eliminating charge fluctuations. A detailed study of resistivity and conductance for tunneling through ultra-small quantum dots is given. The Toulouse limit, where the model can be solved exactly using standard techniques is studied here using Abelian bosonization. At $T = 0$ and $B = 0$, a Lorentzian zero-bias anomaly is observed in the differential conductance as a function of voltage bias. Nonzero temperature smears out the zero-bias anomaly and nonzero magnetic field splits the peak into two. In this article, a diagrammatic approach known as noncrossing approximation (NCA) to the Kondo problem is also introduced within slave boson representation. There is a sharp Abrikosov-Suhl resonance near the Fermi level in the equilibrium dot density of states. This resonance splits as the voltage bias sufficiently exceeds the Kondo temperature which is also supported by experiments.

The second chapter by Yuval Oreg and David Goldhaber-Gordon reviews a theoretical analysis of a system consisting of a large electron droplet coupled to a small electron droplet. This system displays two-channel Kondo behavior at experimentally accessible temperatures. Special emphasis is put on the estimate of the two-channel Kondo energy scale using a perturbative renormalization group approach. Their predictions for the differential conductance in a scaling form is convenient for experimental analysis. They have also pointed out some open questions.

In the third chapter K. Kikoin and Y. Avishai show that a new ingredient in the study of the Kondo effect in quantum dots (also called artificial molecules) is the internal symmetry of the nano-object, which proves to play a crucial role in the construction of the effective exchange Hamiltonian. This internal symmetry combines continuous spin symmetry ($SU(2)$) and discrete point symmetry (such as mirror reflections for double dots or discrete C_{3v} rotation for equilateral triangular dots). When these artificial molecules are attached to metallic leads, the effective exchange Hamiltonian contains operators which couple states belonging to different irreducible representations of the internal symmetry group. In many cases, the set of dot operators appearing in the effective exchange Hamiltonian generate a group which is referred to as the dynamical symmetry group of the system dot-leads. These dynamical symmetry groups are mostly $SO(n)$ or $SU(n)$. One of the remarkable outcomes of their study is that the pertinent group parameters (such as the value of n) can be controlled by experimentalists. The reason for that is that the Kondo temperature turns out to be higher around the points of accidental degeneracy where the dynamical symmetry is "more exact" and these points can be tuned by experimental parameters such as gate voltages and tunneling strength. In this review the authors have clarified and expanded these concepts, and discussed some specific examples. They go from "light to heavy" starting from a simple quantum dot, moving on to discuss double quantum dot (where only permutation (reflection) symmetry can be considered as internal one) and finally elaborate on a triple quantum dot. In particular they concentrate on the difference between the chain geometry (where the three dots composing the triple dot are arranged in series) and the ring (triangular) geometry. When a perpendicular magnetic field is applied, the triple quantum dot in the ring geometry displays a remarkable combination of symmetries: $U(1)$ of the electromagnetic field, $SU(2)$ of the dot spin and C_{3v} of the dot orbital dynamics. The magnetic field controls the crossover between $SU(2)$ and $SU(4)$ dynamical symmetries and this feature shows up clearly in the conductance versus magnetic field curve.

The fourth chapter with contribution from Alex Grishin, Igor V. Yurkevich and Igor V. Lerner describes some essential features of loss of coherence by a qubit (controllable two-level system) coupled to the environment. They first presented the well-known semiclassical arguments that relate both decoherence and relaxation to the environmental noise. Then they show that models with pure decoherence (but no relaxation in qubit states) are exactly solvable. As an example, they have treated in detail the model of fluctuating background charges which is believed to describe one of the most important channels of decoherence for the charge Josephson junction qubit. They show that the decoherence rate is linear in T at low temperatures and saturates to a T-independent classical limit at 'high' temperatures, while depending in all the regimes non-monotonically on the coupling of the qubit to the fluctuating background charges. They have also considered, albeit only perturbatively, the qubit relaxation by the background charges and demonstrated that a quasi-linear behavior of the spectral density of noise deduced from the measurements of the relaxation rate can be qualitatively explained.

The contribution by Katsunori Wakabayashi in the fifth chapter elucidates the role of the edge states on the low-energy physical properties of nanographite systems. He first discussed the basics of the electronic properties of the nanographte ribbons and pointed out the existence of edge-localized states near the zigzag edge. He then presented the electronic properties of the nanographite systems in the presence of magnetic field and provides a simple picture for the origin of half-integer quantum Hall effect in graphene. The study of the orbital and Pauli magnetization shows that a nanographite system with zigzag edges exhibits strong paramagnetic response at low-temperature due to the edge states, and there exist a crossover from a weak diamagnetic response at room temperature to a strong paramagnetic response at low temperature. It is also observed that electron-electron interaction can produce a ferrimagnetic spin polarization along the zigzag edge. In this article author also describes the electron transport properties of nanographite ribbon junctions. A single edge state cannot contribute to electron conduction due to the non-bonding character of the edge states. However, in the zigzag ribbons edge states can provide a single-channel for electron conduction in the low-energy region due to the bonding and anti-bonding interaction between the edge states. The remarkable feature is the appearance of zero-conductance dips in the single-channel region where current vortex with Kekulé pattern is observed. Its relation with the asymmetric Aharonov-Bohm ring is also discussed.

The sixth chapter by K. A. Chao and Magnus Larsson is a review of the thermoelectric phenomena in nanosystems. Starting from the discovery of thermoelectric phenomenon in 1822 by Seebeck, the authors have divided the development of thermoelectricity into three stages. They pointed out that the thermodynamic theory was the driving force in the first stage, during which the Seebeck effect, the Peltier effect, the Thomson coefficient, the dual roles of thermoelectric power generation and refrigeration, and the efficiency of thermoelectric processes were extensively investigated and understood fairly well qualitatively. For a long time the practical use of thermoelectricity was measuring temperature with thermocouples. The beginning of the second stage was marked by the correct calculation of the efficiency of thermoelectric generator and refrigerator by Altenkirch in 1909. It was demonstrated that the efficiency depends mainly on a quantity which was later called the figure of merit. A higher value of this figure of merit indicates a better thermoelectric material. Using the free electron gas as a model system, Ioffe calculated the figure of merit and predicted doped semiconductors as favorable thermoelectric materials. Using the figure of merit as an indicator, and guided by the semi-classical transport theory, the search for better thermoelectric materials had lasted for a long time until around 1980s when the modern material technology enabled the fabrication of layer materials with nanometer thickness. This is the end of the second stage. In the second stage the search for new thermoelectric materials was based on the semi-classical Boltzmann transport equation, in which the dominating scattering process results in slow diffusive transport and so low value of the figure of merit. In layer materials it is possible to reduce the scattering and a new thermoelectric mechanism is found in the so-called thermionic transport. Thermionic emission of electrons from a hot surface is a well-studied physical process, and the emitted current density depends on the temperature and the work function of the emitting materials. In principle, large thermionic current can be achieved if one can reduce the work function to sufficiently low. With the advancement of material fabrication technology to produce high quality layer materials, there has been much progress in thermionics. The reduction of layer thickness in order to achieve efficient transport process also inevitably creates new fundamental problems, many of which are of quantum mechanical nature. Therefore, in the present third stage of thermoelectricity, we face the challenge of an entirely new field to which the macro-scale thermoelectric theory does not apply. This new field is the nano-scale thermoelectricity. The main theme of this chapter is to provide a smooth transition of thermoelectric phenomena from macro-scale systems to nano-scale systems.

The review article by Gilles Montambaux in the seventh chapter gives a nice introduction to coherent effects in disordered electronic systems. Avoiding technicalities as most as possible, he presented some personal points of view to describe well-known signatures of phase coherence like weak localization correction or universal conductance fluctuations. He showed that these physical properties of phase coherent conductors can be simply related to the classical return probability for a diffusive particle. The diffusion equation is then solved in various appropriate geometries and in the presence of a magnetic field. The important notion of quantum crossing is developed, which is at the origin of the quantum effects. The analogy with optics is exploited and the relation between universal conductance fluctuations and speckle fluctuations in optics is explained. The last part concerns the effect of electron-electron interactions. Using the same simple description, the author derived qualitatively the expressions of the Altshuler-Aronov anomaly of the density of states, and of the correction to the conductivity. The last part, slightly more technical, addresses the question of the lifetime of a quasi-particle in a disordered metal.

The eighth chapter by Georges Bouzerar is on the phenomenon of persistent current in mesoscopic normal metal rings. With a brief introductory note he first showed that the single particle picture can neither explain the magnitude nor the sign of the persistent current measured in diffusive metallic mesoscopic rings. This naturally lead him to the main part of the article – the interplay between electron-electron interaction and disorder. One important result is that electron-electron interaction can either enhance or suppress persistent current depending on the strength of the interaction. The underlying physics has been discussed in details.

The ninth chapter by Santanu K. Maiti and S. N. Karmakar focuses on electron transport through nanostructures. The authors first briefly introduce the Green's function technique in this study. Electron transmission through various molecular bridges are investigated in detail within the tight-binding framework. They show that the transport properties through such bridges are highly sensitive to relative position of the atoms in the molecule, coupling between molecule and electrodes, and also to the external magnetic or electric fields. The theoretical results are in qualitative agreement with the experimental observations. These model calculations provide better physical understanding of the transport problems through nanostructures. The authors have suggested some molecular devices in which electron transport can be tuned efficiently.

Finally, the tenth chapter by S. Sil, S. N. Karmakar and Efrat Shimshoni is on quantum Hall effect. This article provides an account of the exotic statistical nature of the quasi-particles in quantum Hall system. For instance, an electron in the presence of electron-electron interaction and strong magnetic field may undergo Bose condensation by charge-flux composite, and fractional charge excitations emerge as quasi-particles. These quasi-particles manifest lot of surprises in the studies of quantum Hall systems. This review is on both the integer and fractional quantum Hall effects within the field theoretic framework. In this review, the authors have also discussed the role of the edge states on integer and fractional quantum Hall effects to understand the experimental results.

It is our great pleasure to thank Prof. Yuval Gefen and Prof. Bikas K. Chakrabarti for their invaluable cooperation and support in organizing the international workshop without which this book might have not seen the light of the day. In this context, we also thank Prof. Hans Weidenmueller, Prof. Yoseph Imry, Prof. Markus Buttiker, Prof. Amnon Aharony and Prof. Yigal Meir for their advices and encouragements. We wish to thank all the invited speakers who made the workshop successful and all the authors who have contributed to this volume. We are very much grateful to Prof. Peter Fulde and Dr. Claus Ascheron for recommending the publication of this book. Thanks are also due to Dr. Angela Lahee and Dr. Elke Sauer from Springer-Verlag for friendly collaboration. Fine help and constant encouragement from our colleagues in this endeavor is also highly appreciated. Finally, we thank the

"Centre for Applied Mathematics and Computational Science (CAMCS)" of Saha Institute of Nuclear Physics in India for providing financial support.

Kolkata,
January 2007

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http://www.springer.com/978-3-540-72631-9

Physics of Zero- and One-Dimensional Nanoscopic Systems

Karmakar, S.N.; Maiti, S.K.; Jayeeta, C. (Eds.)

2007, XVI, 336 p., Hardcover

ISBN: 978-3-540-72631-9