Final Report: Quantum Phases of Nanosystems

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INTRODUCTION

This project addressed phenomena at the intersection of four of the major themes of contemporary condensed matter physics: states of matter with strong correlations among the electrons, open quantum systems, quantum systems far from equilibrium, and interfaces between distinct types of quantum matter.

Electronic correlations are a central issue in many areas of condensed matter physics, from emergent many-body phenomena in complex materials to optical or transport properties of molecules. "Quantum impurities" are paradigmatic many-body systems that consist of a local interacting region connected to non-interacting bulk. They are important theoretically as more tractable models of strongly interacting systems that still contain much of the interesting many-body physics. Moreover, quantum impurities occur in real materials and nanoelectronic structures. For instance, the electronic correlations underling the Coulomb blockade in nanostructures are of the quantum impurity type. In this project, we showed how to produce several exotic states of matter using quantum impurity effects in nanostructures. These can be regarded as quantum simulation electronic correlations in other systems.

"Open quantum systems" refers to quantum systems that are connected to an environment and so not isolated. They are receiving increasing attention because of both fundamental interest in the decoherence induced when a quantum system interacts with its environment and the relevance to processes of societal relevance such as photosynthesis and energy capture. In the systems we studied, openness introduces dissipation. While typically dissipation is harmful to quantum many-body effects, we showed how it can be harnessed to produce novel states of correlated electrons.

Interest in non-equilibrium phenomena is widespread within condensed matter physics, e.g. in quantum materials, nanoscale structures, or quantum thermodynamics. When quantum effects are important for a collection of interacting particles (electrons in the nanostructure in our case), the nature of the non-equilibrium state is largely unknown. Driving a system into a non-equilibrium state affects and probes the quantum many-body correlations in novel ways, raising issues of fundamental interest. On the other hand, driving a system in some fashion is essential for any practical application. With the recent surge in interest in quantum technologies, driven quantum many-body systems have been proposed for a variety of technologies in, e.g., quantum nanoelectronics and solar energy conversion. Understanding the nature of non-equilibrium quantum many-body states will lay a foundation on which future such technologies can be built. We obtained results for two types of non-equilibrium nanoscale scenarios: the electrical current flowing in a nanoscale structure subject to a large bias voltage (that is, the $I(V)$ curve), and the response of a qubit to incident microwave photons.

There has been an explosion of interest in interfaces between qualitatively different quantum states. One drive has been interfaces between different correlated materials, but the main drive has been topological effects that occur at the interface between topologically trivial and non-trivial materials. In this work, we focused on the interface of a singlet s-wave superconductor with either massless Dirac fermions or a quantum Hall state. Both of these are realized in the graphene/MoRe studied here at Duke in the group of Prof. Gleb Finkelstein, with whom we have close connections. We found the conditions under which one has interference of chiral edge states of correlated electrons along this interface.

Two main physical systems are considered. One is quantum dots (or other nanostructures) made in carbon nanotubes or graphene. These may be connected to dissipative electrical contacts (leads) or to a superconductor. The other system is qubits, for instance of the superconducting type, connected to microwave waveguides. Such nanosystems provide excellent platforms for studying non-equilibrium many-body phenomena in the form of quantum impurity models. First, the interactions are in a local region, making these systems more tractable, but can be made increasing complex by adding elements. Second, the exquisite experimental tuning that has been demonstrated allows control over the parameters in the system. Finally, bias voltages can be easily applied to drive the system into a highly non-equilibrium regime. These nanoscale systems are realizations of quantum impurity models; the knowledge gained in their study transfers to other quantum impurity models such as those that arise in studies of quantum materials.

The results of this theoretical project are focused in five areas as listed in the table of contents (Sections I to V). These results are briefly summarized in the following sections, along with references to our published papers which provide details as well as more context and interpretation. For references to work by other groups, see citations in the publications.

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I. USING DISSIPATION TO PRODUCE MANY-BODY STATES: QUANTUM SIMULATION OF STRONGLY CORRELATED MATERIALS

Quantum fluctuations and coherence are key distinguishing ingredients in quantum matter. Two phenomena to which they give rise, for instance, are *quantum phase transitions*, changes in the ground state of a system driven by its quantum fluctuations, and *quantum noise*, the effect on the system of quantum fluctuations in its environment, for no system is truly isolated (open quantum systems). Understanding the intersection of these two topics—the effects of quantum noise on quantum phase transitions—is important for understanding quantum matter. It is natural to suppose that decoherence produced by the noise will suppress quantum effects, and in particular inhibit or destroy a quantum critical state. Indeed, a variety of calculations demonstrate this in both equilibrium and non-equilibrium contexts. In this project, we presented striking counterexamples to the notion that environmental noise necessarily harms quantum many-body effects: in the systems we studied, quantum noise stabilizes novel quantum many-body states.

A. Transport through Dissipative Quantum Dots: Quantum Critical State

In an extensive study that spanned the length of the project period, we investigated how interesting correlated states of electrons can be produced by coupling a quantum dot to dissipation [1–8]. We analyzed both equilibrium and non-equilibrium situations. The most significant result is that the quantum phase diagram of the system has a quantum critical point—a point in the system's parameter space that separates two competing quantum ground states. Near this point, the state of the system is delicately balanced with strong quantum fluctuations. In both the equilibrium and non-equilibrium regimes (applied voltage bias), we were able to find the properties of the system analytically.

B. Qubit + Waveguide: The Spin-Boson Model

When a quantum object (a qubit) interacts with an environment, quantum information in the qubit subsystem is lost, but it is in principle preserved in the entangled many-body state of the global system. The nature of this complete wavefunction has received little attention, especially regarding the entanglement generated among the reservoir states. In this work, we discovered a simple emerging structure of wavefunctions in open quantum systems, using a combination of numerical many-body quantum tomography and a new variational theory [9–12]. We focused on the spin-boson model, namely a single two-level system (e.g., a qubit or spin of an electron) coupled to an environment of bosons (e.g., microwave photons in a waveguide or phonons, respectively). After showing that the method works well for the ground state, we extended it to dynamical, non-equilibrium situations.

II. PROBING AND CREATING MAJORANA ZERO MODES WITH QUANTUM DOTS

Majorana fermions, an exotic type of quasiparticle, are attracting a great deal of attention in a variety of condensed matter contexts. We studied the properties of Majorana zero modes (MZM) in a classic topological system [13, 14] as well as in a novel quantum dot setting [2, 4, 6].

A. Probing a Topological Majorana by Transport through a Quantum Dot

Majorana bound states may be realized at the ends of a one-dimensional *p*-wave superconductor for which the proposed physical system is a semiconductor nanowire with Rashba spin-orbit interaction to which both a magnetic field and proximity-induced *s*-wave pairing are added. In view of these proposals, how to detect and verify the existence of MZM becomes a key issue.

We proposed a setup for detecting a Majorana zero mode consisting of a quantum dot coupled to the end of the (effectively *p*-wave) superconducting nanowire. The Majorana bound state at the end of the wire strongly influences the conductance through the quantum dot: driving the wire through the topological phase transition causes a sharp jump in the conductance by a factor of $1/2$ [13]. We continued working on Majorana fermion modes in quantum wires, investigating whether an applied periodic field can help stabilize them by creating so-called Floquet Majorana fermions [14].

B. Majorana Zero Mode in the Dissipative Resonant Level Model

In the context of the dissipative quantum dot discussed in Sec. I A, we showed that the quantum critical point can be understood in terms of (non-topological) Majorana zero modes (MZM) [2, 4, 6]. The main result is that this is a good system in which to study the properties of MZM. In addition, the non-topological MZM in this system can hybridize with the topological MZM in a nanowire (see Secs. II A and V A) and so can be used to probe topological effects.

III. NON-EQUILIBRIUM QUANTUM MANY-BODY PHYSICS AT THE NANOSCALE

This work addressed nonequilibrium properties of correlated electrons and photons in two types of nanofabricated systems. Correlated systems exhibit a wide variety of novel and poorly understood phenomena and remain a major challenge in contemporary physics.

A. Non-Equilibrium Quantum Critical Steady State in Quantum Dots

The first system involved electronic correlations in a quantum dot, one in which dissipation causes the correlations (Sec. I A), making it an open quantum system with a non-Markovian environment. This system has a quantum phase transition—a sudden qualitative change in the ground state as a function of tuning parameters. At the transition, known as a quantum critical point (QCP), novel correlated states are observed: these are typically referred to as “non-Fermi liquids” in that they do not follow the Fermi-liquid paradigm for normal metallic states. A common feature of most of these systems is that the correlations are produced by operators (interactions) that cause frustration and act locally. A thorough understanding of systems in which correlating operators act in a single local region is, then, an essential foundation. Such a system is known as a "quantum impurity problem". In nanoscale systems, such correlated electron physics in a local region, as well as nonequilibrium phenomena and dissipation, arise naturally and under conditions that can be controlled.

The main results obtained [7, 8] are the analytical calculation of the nonequilibrium nonlinear I-V curve of a dissipative resonant level (DRL) model (modeling the quantum dot connected to its environment) when the system is tuned either very near or exactly to the QCP. In the latter case, we studied the approach of the system to the QCP with large conductance [7], while in the former the system approaches the QCP but then veers away to a low conductance state ("crossover" behavior) [8]. We emphasize that the strength of the dissipation is *arbitrary*, as is necessary to compare to experiment (for which the dissipative resistance is $R \approx 0.75h/e^2$). Indeed, in both cases we compared the theory, which has no free parameters to fit, to experimental data from the group of Gleb Finkelstein here at Duke. Throughout the temperature and bias voltage range studied, the agreement was excellent.

B. Driven Qubits and Entanglement

The driving of qubits and their subsequent entanglement is a key question for future quantum technologies. We obtained results in two contexts. First, periodic driving can enhance topological effects in quantum wire systems and so the presence of Majorana zero modes. We analyzed such a situation using Floquet spectral techniques [14]. Second, the dynamics of a system after a sudden change in a parameter—a phenomenon known as a quantum quench—offers considerable insight into the system. We extended the wavefunction techniques that we developed for the ground state (Sec. I B) to a quench scenario and obtained new results for the dynamics of a qubit strongly coupled to a photonic or phononic environment [11].

C. Waveguide Quantum Electrodynamics (QED)

Waveguide Quantum ElectroDynamics (wQED) is a rapidly growing area focused on the coherent interaction between quantum emitters and the one-dimensional (1D) field of a waveguide. Condensed matter and materials realizations include a quantum dot coupled to a quantum wire and a superconducting qubit coupled to a microwave waveguide. In such systems, a growing number of unique nonlinear and interference phenomena are being unveiled. The interest is both fundamental and applied. Fundamentally, correlations and interference of the photons are enhanced by the 1D geometry: the interaction with the emitters generates an effective interaction that leads to strong correlation of the photons (non-classical light). Applied interest stems from the need to move and manipulate quantum information, converting the information from stationary qubits into "flying qubits" in the waveguide.

We obtained results on four topics [12, 15–17], as follows.

First, we studied wQED in the ultra-strong coupling regime using the polaron methods mentioned above [12]. Here, a ubiquitous assumption made in quantum optics—the rotating-wave-approximation (RWA)—cannot be made, as exemplified by the importance of photon production (i.e. 1 input photon generates 3 out). We showed that, because of the production of many low energy photons, off-resonant inelastic scattering is *never* given correctly by the RWA and is, in fact, much larger.

Second, we studied the formation of a class of bound states in the continuum (BIC)—bound stationary states that arise within a continuum of unbound states [15]. A key question is how to form and prepare such states so as to enable potential applications, such as quantum memory which requires light trapping at the few-photon level. We showed that (i) delayed quantum dynamics in the presence of nonlinearity is essential, and (ii) BICs in waveguide-QED can be excited via multi-photon scattering. This provides a solvable example of non-Markovian quantum dynamics in a nonlinear system, a scenario of interest in many areas of contemporary physics.

Third, we introduced a novel way to generate entanglement among two qubits—a key resource for quantum communication as well as computing. The novelty in this approach is that one starts from a high power classical input. Then, by detecting individual reflected photons, because of special interference properties of two qubits coupled to a waveguide, the qubits become entangled. Thus, each reflected photon heralds the creation of a maximally entangled state of the two qubits [16].

Finally, we showed that there is a second-order phase transition as a function of driving strength in a simple system consisting of a weakly nonlinear resonator subjected to a two-photon drive. The simplicity of the system allows it to be analyzed from several viewpoints, yet the presence of a true phase transition, including hysteresis in the time dependence, makes the physics involved rich. The simplicity also implies that the model is relevant to several different types of experimental systems [17].

IV. MESOSCOPIC MANY-BODY PHYSICS IN NANOSYSTEMS

In the early stages of this project we studied the ground state of two prototypical nanoscale many-body systems—a quantum dot and a quantum wire.

A. Mesoscopic Fluctuations in a Fermi Liquid from Weak to Strong Coupling

The Fermi liquid is a ubiquitous state of electronic matter. Indeed, it is so common that systems can have several different Fermi liquid phases, leading to crossovers between Fermi liquids with different characteristics. In the bulk, clean case, the evolution of the quasiparticles in such a crossover is straight forward: the quasiparticles are labeled by $\sim\vec{k}$ because of translational invariance and so are in one-to-one correspondence. However, in a disordered or mesoscopic setting, interference affects the two sets of quasiparticles differently. We studied how the quasiparticles in one Fermi liquid are related to those in the other. We focused on an Anderson impurity coupled to a finite mesoscopic reservoir described by random matrix theory, a structure which can be realized using quantum dots and wires. We found strong but not complete correlation between the mesoscopic properties in the two limits, as well as several universal features [18–21].

B. ZigZag Phase Transition in Quantum Wires

The low-density electron gas, where the Coulomb interaction is large compared to the kinetic energy, is a paradigmatic strongly correlated system. We used quantum Monte Carlo techniques to study the nature of the ground state wavefunctions throughout a quantum phase transition that occurs when the electrons are localized. At the lowest densities, the electrons form a linear chain in the wire, but as the density increases, symmetry about the axis is spontaneously broken and a zigzag configuration occurs. We demonstrated that (i) the linear to zigzag transition occurs at parameters relevant to experiments in quantum wires and (ii) a transition to a phase with long-range zigzag correlations occurs even in narrow wires where large quantum fluctuations smear out density correlations. We showed that the quantum phase transition in these wires differs substantially from the classical case [22].

V. INTERFACES BETWEEN DISTINCT QUANTUM STATES OF MATTER

There has been an explosion of interest in *interfaces between qualitatively different quantum states* during the last ten years. One drive has been interfaces between different correlated materials, but the main drive has been topological effects that occur at the interface between topologically trivial and non-trivial materials. In such a system, a variety of exotic edge phenomena arise such as Majorana zero modes in 1D, chiral or helical edge states in 2D, and Dirac or Weyl semimetals at the surfaces of materials in 3D. In addition to the fundamental interest in topological effects in condensed matter, topological excitations are being very actively pursued because they may lead to robust approaches to quantum computation. In the later part of this project, we obtained results for two such systems.

A. States in Quantum Dots

We analyzed a system in which a topological Majorana zero mode (tMZM) combines with a Majorana produced by quantum frustration (fMZM) to produce a novel ground state [6]. The system that we studied combines two parts, a grounded topological superconducting wire that hosts two tMZMs at its ends, and an on-resonant quantum dot connected to two dissipative leads. The quantum dot with dissipative leads creates an effective two-channel Kondo state in which quantum frustration yields an isolated fMZM at the dot. We showed that coupling the dot to one end of the topological wire stabilizes the tMZM at the other end. This provides a route to achieving an unpaired Majorana zero mode.

B. Graphene Quantum Hall State and Superconductor

In collaboration with our experimental colleagues at Duke, we explored the interface between two prototypical phases of electrons with conceptually different ground states: the integer quantum Hall insulator and the s-wave superconductor [23]. We conducted detailed tight-binding calculations for a quantum Hall–superconductor interface and found clear signatures of hybridized electron and hole states, which we refer to as chiral Andreev edge states (CAES). Their interference can turn an incoming electron into an outgoing electron or a hole, depending on the phase accumulated by the CAES along their path. Our results demonstrate that these excitations can propagate and interfere over a significant length, opening future possibilities for their coherent manipulation.

In the citations below, the journal reference is hyperlinked to the publishers page, while the arXiv reference is linked to the publicly available “accepted manuscript” version. For a list of publications in chronological order, see below.

Project Publications Cited

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