Nano-scale electronic structure of strongly correlated electron systems

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Summary

A common strategy to explain the electronic properties of most everyday materials is the reductionist approach. This strategy involves identifying and thoroughly studying the smallest building block of the system, electrons in this case, and scaling the properties of the building blocks to the size of the full system. Crucially, how the building blocks fit together, or how the electrons interact with each other, is ignored. The application of this approach works remarkably well to explain the properties of most materials, despite the strong Coulomb repulsion that electrons should experience between each other.

Modern research is increasingly focused on a class of materials called strongly correlated electron systems whose properties the reductionist approach struggles to explain. In these systems the Coulomb interaction between electrons is a crucial factor in determining the properties of the material. One of the consequences is that the number of electrons present in the system can play a major role in ways that go beyond the reductionist approach. One of the most notorious examples of such a system are the copper-oxide high-temperature superconductors. These superconductors emerge from an insulating system where the Coulomb interaction freezes the electrons in place. A slight change in the number of electrons in this system leads to a number of unconventional electronic states, among which a superconducting state with the highest known critical temperature at ambient pressure. How this superconducting state forms and disappears again, and its relation to the strongly insulating parent state, has eluded physicists ever since its discovery, and remains a highly active field of research.

The nanometer length scale offers a unique window into strongly correlated systems. The electronic properties can vary on these relevant length scales, and the flow of electrons on such length scales can feature hydrodynamic phenomena not possible on larger scales. In this thesis we present our contribution to the field of strongly correlated electrons system by exploring exactly this nano-scale. We employ the technique of scanning tunneling microscopy (STM) which allows us to measure the local distribution of electrons, or local density of states, with subatomic precision. We also explore how electrons flow through a mesoscopic structure of a strongly correlated material.

In Chapter 2 we take a closer look at how we study correlated systems, by comparing three spectroscopic techniques. The three techniques in question, ARPES, STM, and quantum oscillations, all measure (aspects) of the bandstructure of a material. To see how these techniques compare we apply them to Sr_2RhO_4, which acts as a model system, a metaphorical drosophila, of Fermi liquids. We measure the Fermi surface using ARPES and the quasi-particle interference (QPI) observed by STM, and compare this with the Fermi surface pocket sizes determined by quantum oscillations. The Fermi velocities determined by each of these techniques is given the same treatment, as are the quasi-particle lifetimes measured by ARPES and STM. In all of these cases we find that the three techniques are in agreement. This leads us to conclude that the disagreement between these measurement techniques that occurs in other strongly correlated systems is a reflection of their physics.

Next, we turn our attention to copper-oxide high-temperature superconductors, in particular the overdoped superconductors where the critical temperature decreases with increases doping. In Chapter 3 we measure the local density of states using STM of multiple samples covering a broad range of critical temperature, including a sample which is no longer superconducting due to the high doping level. This allows us to carefully study the disappearance of superconductivity in this material. We find that an increasingly large number of nanometer sized metallic regions emerge in the superconducting state as the critical temperature goes down. In particular we find superconducting regions in the sample that no longer superconducts on a macroscopic scale. We also find that the spectroscopic gap associated with superconductivity does not disappear through a reduction of the gap magnitude, but rather by acquiring an increasingly large density of states at the Fermi level, a filling of the gap. The breaking of Cooper pairs responsible for the gap filling is found to have a highly unusual relation with the gap magnitude. These observations combined lead to a picture of emergent granular superconductivity in the strongly overdoped copper-oxide superconductors governed by a pair breaking process which the most common theoretical approach fails to accurately describe.

In Chapter 4 we study the electronic structure in momentum space of the same copper-oxide superconductor samples by measuring the quasi-particle interference with STM. To increase the signal-to-noise ratio of our STM images we implement a machine learning algorithm for noise suppression. The use of self-supervised learning allows for effective noise reduction without the

large amounts of data necessary for more traditional supervised learning. Our QPI images of the overdoped copper-oxide superconductors reveal a full Fermi surface and rigid shift of the anti-nodal band as a function of doping. We note that different determinations of the exact doping level by various measurement techniques do not agree. We also observe the bending of the band due to superconducting gap and find an unusual feature near the gap edge associated with the presence of an additional ordered state. The presence of this feature of a broad doping range appears to be a poor fit with previous claims of charge density waves of ferromagnetic fluctuations in overdoped copper-oxide superconductors.

In Chapter 5 we move away from measurements of the electronic structure in either real or momentum space, and instead examine electrical transport in mesoscopic structures. On such a length scale the interactions between electrons can lead to transport phenomena typically associated with hydrodynamics, provided the disorder is not too strong. We argue that the strongly correlated unconventional superconductor Sr_2RuO_4 provides the right combination of strong interaction and low disorder to observe hydrodynamic behavior. Using modified Navier-Stokes equations to include a disorder term we simulate the flow of electrons in Sr_2RuO_4 through a structure previously used to successfully demonstrate hydrodynamic behavior, and calculate the expected voltage drop over the device. We then do the same for the strange metal phase of copper-oxide superconductors using results from the holographic description of this phase. Using our framework for hydrodynamic transport in the presence of disorder, we find that the higher amounts of disorder compared to Sr_2RuO_4 and the extremely low viscosity this state is proposed to have make hydrodynamic behavior highly unlikely. Despite this result we argue that it is still worthwhile carrying out this experiment in copper-oxide superconductors, given the limited amount of available data on mesoscopic transport in these systems.