Exploring Instabilities of Bad Metals with Optical Spectroscopy.
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What happens when a near infinity of electrons is confined to a periodic potential, interacting with each other under the influence of the Coulomb interaction? This question has captivated generations of condensed matter physicists, from both the experimental and theoretical persuasion, and the answer appears to be ‘unpredictable’. In the past century, the condensed matter community has discovered that many different ‘ordered’ states can emerge out of the quantum soup made from interacting electrons.

Famous examples of such ordered quantum states are magnets and superconductors. Magnets are probably most easily imagined by the human mind and are microscopically often represented as a pattern of small magnets, all lined up periodically in space. Quantum mechanically, this description is already not completely correct as the ‘ordering’ often really takes place in momentum space. In non-magnetic metals there is an equal fraction of electrons with spin-up and spin-down. In magnets such as iron, a small fraction of the electrons preferentially occupy momentum states with one particular spin direction under the influence of the Coulomb repulsion. This results in a net magnetic moment for the crystal as a whole, but the key point is that the electrons are in fact completely delocalized over the entire crystal. The order of a superconductor is even more difficult to describe. In this case the electrons form so-called Cooper pairs (bound states of two electrons) and the ordering takes place in the quantum mechanical phase of the macroscopic wavefunction describing the whole ensemble of Cooper pairs.

In the first decade of the twenty-first century we have witnessed a remarkable turn in our understanding of ‘order’ and have possibly found a new method to classify electronic states of matter in general. Borrowing concepts from the mathematical theory of topology (a framework to describe knots and twists using the abstract language of mathematics), we have learned that macroscopic wavefunctions can be distinguished using so-called topological invariants. In this language, variations of ordered states are distinguished by different values of such invariants. The most famous example of this is the quantum Hall state, where abrupt changes in the topological invariant with magnetic field result in sudden jumps in the conductivity.

The importance of topological order and the role it plays in the formation of new ground states of interacting electron systems is not exactly known, but is an active topic of research and underlies the research presented in this thesis. In the past four years, I have used optical spectroscopy to investigate two classes of materials that display phase changes as function of temperature. Chapter 4 describes the optical properties of Co-doped $BaFe_2As_2$, a member of a family of high temperature superconductors, known as the iron-pnictide high T_c's, while chapter 5 concerns the correlated, and possibly topological, Kondo insulator: SmB_6.

The (low temperature) groundstate of these two materials is completely different, but at high temperature they are in some sense similar: both materials feature a strongly temperature and frequency dependent optical response that has become known as a 'bad metal'. In 'clean' metals one would expect a so-called Drude response for the optical conductivity at low energy. The Drude response can be characterized by a frequency and temperature independent scattering rate; an average time between collisions that does not depend on temperature, indicating that the electrons behave as a gas of freely moving particles. Instead, bad metals feature a strong temperature and frequency dependent scattering rate indicative of residual interactions between the electrons. In such materials, a careful analysis of the optical response not only provides fingerprints of the interactions responsible for the bad metal behavior, but also of the key driving forces behind the instabilities that lead to the ordered electronic states at low temperature.

In this thesis I discuss how optical spectroscopy (Chapter 2) can be effectively used (Chapter 3) in the study of instabilities of interacting electron systems. For the study of the iron-pnictides (Chapter 4), I developed a new method to visualize the complex optical response of the normal state. This allows me to demonstrate that the metallic state is in fact very close to being a Fermi liquid. In the final chapter (Chapter 5), I discuss a careful reexamination of the changes that take place in the optical response of SmB_6 as it changes from a bad metal to a Kondo insulator. This analysis provides new evidence that the Kondo insulating state is formed under the influence of the Coulomb interaction and that the Kondo state is therefore adiabatically connected to a simple hybridized band insulator.