On transport properties of Weyl semimetals

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Summary

Topological semimetals are a new class of materials, in which the conductance and the valence band touch accidentally at discrete points of the Brillouin zone. Near these touching points, the dispersion relation is linear and the massless excitations move with an energy-independent velocity (much like the speed of light for photons). This leads to fascinating transport properties, that have been observed in the two-dimensional semimetal graphene.

In three dimensions, the story becomes even more interesting. The accidental touching points are topologically protected by the third spatial dimension. Near the Fermi energy, the spectrum consists of an even number of cones, each of which is described by the Weyl equation of relativistic quantum mechanics. The Weyl cones come in two different chiralities, they are sources and sinks of Berry curvature. These unique features lead to remarkable electromagnetic properties such as a huge negative magnetoresistance, chiral Landau levels, and the chiral magnetic effect. At the surface of a Weyl semimetal, the Fermi surface consists of open contours, called Fermi arcs. Fermi arcs start and end at projections of the bulk Weyl cones onto the surface Brillouin zone. These topologically protected states and their transport properties are the main focus of this thesis.

We begin in chapter two by studying the related antiferromagnetic topological insulators. In these systems time-reversal symmetry is broken locally but restored in conjunction with a translation by half a unit cell. Unlike true time-reversal symmetry, this effective time-reversal symmetry is destroyed by disorder. In our studies however, we find a remarkable robustness of the topological phase against electrostatic disorder. The reason is that the symmetry still holds *on average*, placing the antiferromagnetic topological insulator in the class of statistical topological insulators. At the phase transition between a normal insulator and an antiferromagnetic topological insulator the bulk gap closes at discrete points in the Brillouin zone, forming a linear low energy spectrum: Weyl cones.

In a Weyl semimetal, the antiferromagnetic coupling is replaced by a ferromagnetic coupling. This breaks time-reversal symmetry and stabilizes the Weyl semimetal phase. In chapter three of this thesis, we study one of the key transport signatures of a Weyl semimetal, the chiral magnetic effect. It is one of the features that distinguishes a Weyl semimetal from graphene. For this effect, a magnetic field strong enough to form Landau levels is needed. We find that there also exists a variant of the chiral magnetic effect in a weak magnetic field without Landau levels. This variant is likely to be more easily accessible in an experimental setting.

In the fourth chapter, we continue to study the surface Fermi arcs. While they have been clearly observed in optical experiments, some of their unique properties can only be probed by transport experiments. A key difficulty in devising such a transport experiment is that, in contrast to a topological insulator, both the bulk and the surface of a Weyl semimetal are conducting. Therefore, it is difficult to distinguish the surface from the bulk response. We address this problem by bringing the Weyl semimetal with broken time-reversal symmetry in contact with a conventional superconductor. The superconductor does not affect the bulk of the Weyl semimetal, but splits the Fermi arcs into nearly charge neutral Majorana modes. We show how we can trap Majorana fermions using a tunnel barrier.

In the fifth chapter, we venture beyond the horizon of Weyl semimetals and study Fermi arcs in the pseudo-gap phase of high temperature cuprate superconductors. These have been interpreted as signatures of a novel pairing mechanism called "Amperian pairing", because the attraction resembles the Amperian force of parallel electrical currents. We examine how the Andreev scattering of electrons into holes is affected by the Amperian pairing. We conclude by showing how a transport experiment in a tri-junction can be used to detect the Amperian pairing.