On electronic signatures of topological superconductivity

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Summary

Topological superconductors are a novel type of superconductors that carry Majorana particles at their boundary. These surface states are equal superpositions of electrons and holes, and hence are their own antiparticles. There has been a recent surge of theoretical and experimental effort to realize these special particles in the lab. While first observations support the theoretical predictions, fail-safe experimental evidence for Majoranas is still needed.

Part of the challenge is that due to their vanishing charge they are not easily detected electrically. According to theory their existence (which can be proved on topological grounds) only relies on the systems dimensionality and the presence of a few fundamental symmetries. This makes these particular surface states immune to microscopic imperfections like disorder. As a result of this protection one expects equally robust transport signatures. Majorana states can carry heat, but this is very difficult to measure accurately at low temperatures. For this reason electrical probes are much favored. In this thesis we propose and study electrical signatures of Majoranas that are present in spite of their charge neutrality. By applying scattering and random matrix theory we first examine their generic properties. With the tool of numerical simulations we then put our predictions to test on realistic systems.

If the topological superconductor has the form of a wire, a Majorana particle can be found at each end. Its presence causes a peak of the electrical conductance around zero voltage. At low temperatures this peak has a universal height of $2e^2/h$. One may expect a higher conductance peak if there are multiple Majoranas at the wire end. Generically, however, this cannot happen because multiple Majoranas repel each other and only single Majorana end states are stable. The symmetry that suppresses this repulsion is called chiral symmetry. In chapter two we investigate the effect of chiral symmetry on the wire's conductance. We derive a lower bound for the electrical conductance that allows one to determine the number of Majorana end states. In reality the chiral symmetry is only approximate, which is why we perform a numerical test on a realistic model. We find that the symmetry still holds in current experiments.

Wires are one dimensional. The thesis continues with a study of two dimensional topological superconductors. Here, the Majorana particles move along the edge of the system, either only in one or (protected by time-reversal symmetry) in both directions. In chapter three we propose an experiment with the geometry of a Corbino-disk, for which it is possible to detect and distinguish the two modes of movement. For this purpose we use oscillations of the electrical conductance that can be observed at the inner and outer edge of the disk.

In the following two chapters we extend our analysis to, so called, *statistical* topological superconductors. This extension is concerned with cases where some symmetries are broken locally but still exist in an average sense over long length scales. An example is a stack of superconducting wires that naturally experiences a strong anisotropy along vs across the direction of the wires. Majorana particles can move in both directions along the coupled wire ends. Disorder hinders their movement but it cannot completely suppress it. (The edge states avoid what is called localization.) In analogy to an earlier idea by Alexey Kitaev we refer to such edge states as *Kitaev edge states*. Although the edge states are again charge neutral we show that a measurement of time-dependent charge fluctuations can detect them in the electrical shot noise. As we show in the fifth chapter, Kitaev edge states also appear along domain walls in the middle of a topological superconductor.

The last two chapters of this thesis step out of the context of topological superconductivity. Instead these chapters are motivated by recent experimental advances in two fields. In chapter six we study the effect of large magnetic fields on electrons in graphene (a single atomic layer of graphite) when the material is also subject to a periodic electrical field. One finds an electronic band structure reminiscent of a butterfly that after its discoverer is named Hofstadter's butterfly. In the seventh chapter we present results of a collaboration with an experimental group in Delft, where we investigate electrons at the interface between two oxides ($LaAlO_3$ and $SrTiO_3$). The electrical resistance of this system strongly decreases when a magnetic field is applied parallel to the interface. Using semiclassical transport theory we are able to explain this behavior.