Signatures of Majorana zero-modes in nanowires, quantum spin Hall edges, and quantum dots

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Citation

Mi, S. (2015, April 22). *Signatures of Majorana zero-modes in nanowires, quantum spin Hall edges, and quantum dots*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/32780

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Issue Date: 2015-04-22

Summary

Majorana zero-modes are states that appear in the middle of the excitation gap (the zero-point of energy), in materials known as topological superconductors. They have the potential to become a building block for a quantum computer and are also of interest in their own right, because of their unusual effect on transport properties. The topic of this thesis is the theoretical study of the Majorana zero-modes in systems of different dimensionality: the two-dimensional quantum spin Hall insulator, the one-dimensional nanowire, and the zero-dimensional quantum dot.

Following a brief Introduction in Chapter 1 on the concept of a Majorana zero-mode, Chapter 2 begins to examine them in the InSb nanowire that has been studied experimentally by the Kouwenhoven group in Delft. The softness of the induced superconducting gap is a puzzling aspect of the experiment that we would like to understand. We find that the relatively large mean free path, in combination with a partial coverage of the nanowire by the superconductor, is the likely origin of the soft gap. One important conclusion of our study is that the presence of a soft gap does not prevent the formation and observation of a Majorana zero-mode at the end-point of the wire.

We then move on to the edge of a quantum spin-Hall insulator, formed by a quantum well in a heterostructure of HgTe/CdTe or InAs/GaSb. The lack of a tunnel barrier in such a system was an obstacle in the search for Majorana zero-modes. In Chapter 3 we propose that in the presence of weak disorder and weak magnetic field, a gate tunable metallic puddle can play the role of a barrier for the edge states, confining the Majorana zero-mode at the interface with a superconductor. This is a practical alternative to barriers formed out of magnetic insulators. We show that a constriction in the quantum well allows for braiding of Majorana zero-modes on opposite edges, which is the key step needed for applications

in quantum computing.

We continue with this two-dimensional system in Chapter 4, where we investigate the remarkable observation by the group from Rice University that the helical edge states in InAs/GaSb quantum wells persist in perpendicular magnetic fields as large as 8T. Although we cannot quite explain the experimental data, we do find an unusual phase diagram in our model calculation: The critical breakdown field for helical edge conduction splits into two fields with increasing disorder, an upper critical field for the transition into a quantum Hall insulator (supporting chiral edge conduction) and a lower critical field for the transition to bulk conduction in a quasi-metallic regime. The spatial separation of the inverted bands, typical for broken-gap InAs/GaSb quantum wells, is essential for the magnetic-field induced bulk conduction — there is no such regime in the HgTe quantum wells studied by the Würzburg group.

The last two chapters deal with quantum dots, coupled to superconductors by point contacts. In Chapter 5 we study the appearance of zero-bias resonances in the differential conductance, which are a hallmark of Majorana zero-modes. We find that the characteristic Y-shaped resonance profile in the B, V plane (B is magnetic field, V is applied voltage) is not necessarily a Majorana signature. The poles of the scattering matrix have a tendency to stick to the imaginary energy axis even in the topologically trivial regime, simply as a consequence of particle-hole symmetry. What is needed is broken time-reversal and broken spin-rotation symmetry (known as symmetry class D). When spin is conserved (class C) the effect does not appear. We suggest ways in which these “fake” Majorana resonances can be distinguished from the real thing.

Finally, in Chapter 6 we investigate whether it is possible to effectively break time-reversal symmetry by applying a phase difference between superconductors in a multi-terminal superconducting quantum dot. The need to apply a magnetic field is a severe experimental complication, and it would be very welcome if this could be avoided. Three terminals suffice to realize a “discrete vortex”, which mimics most of the effects of a true magnetic vortex. We demonstrate that it is possible to switch the fermion parity of the superconducting ground state by varying the phase differences, all at zero magnetic field in the quantum dot. A modification of this design (combining it with a topological insulator) might be used to trap and manipulate Majorana zero-modes in zero magnetic field.