Quantum computation with Majorana zero modes in superconducting circuits

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Summary

Majorana modes are special zero-energy quasiparticles that can appear at the ends of superconducting wires or bound to vortices in superconducting films. They are interesting because they are predicted to have non-Abelian quantum statistics. This means that the presence of several Majorana modes in a superconductor leads to a degenerate quantum ground state, and that exchanging the position of two modes may result in a rotation of the ground state wave function within this degenerate manifold. Different rotations may not commute with each other, hence a sequence of these exchanges can be seen as a quantum algorithm executed on the initial wave function. Superconductors with Majorana modes are prominent candidates to realize a quantum computer naturally endowed with resilience to errors and decoherence, so that, ideally, its operation would not require quantum error correction.

It is a challenge to manipulate and measure the quantum state of a collection of Majorana modes. The first six chapters of this thesis contain a concrete design proposal to realize both tasks using the powerful techniques of superconducting circuits. The main idea behind the proposal is that different ground states of a collection of Majorana modes are degenerate if the superconductor is grounded, but can be split in energy if the superconductor is floating. The reason behind this behavior is that the quantum states differ by fermion parity, which is equal to the electric charge contained in the superconductor modulo $2e$. In the presence of a small but finite electrostatic energy, this difference in fermion parity becomes measurable.

The electrostatic energy of a superconducting island can be controlled with exponential sensitivity by varying the magnetic flux through a split Josephson junction connecting the island to the ground, as is routinely done in experiments with superconducting circuits. This gives us a realistic and flexible tool to control the interaction between Majorana modes. The response of Majorana modes to a magnetic flux is studied in chapter 2 in a simple DC SQUID geometry, and in chapters 3 and 4 in larger circuits which allow for braiding of two Majorana modes, the readout of the result, and even the execution of more complex algorithms. The braiding operation, in particular, is implemented not by adiabatic motion of the Majorana modes, but by performing an adiabatic trajectory in the parameter space of their pairwise Coulomb couplings.

Chapter 7 contains the results of a collaboration with the experimental group of

Dr. Leo DiCarlo in Delft. We analyze the behavior of simple NbTiN superconducting circuits with Josephson junction formed by InSb nanowires, rather than the more conventional oxide tunnel junctions. Because the density of carriers can be modulated by a side gate, these devices have a gate-tunable plasma frequency. Moreover, the theoretical analysis of the microwave spectroscopy of current oscillations across a split junction reveals that the spectrum is very sensitive to the non-sinusoidal current-phase relation of the nanowire junction. These hybrid superconducting circuits constitute a first step towards the realization of the Majorana circuits described in the previous chapters.

In chapters 8 we apply the ideas of the first six chapters in different contexts. For instance, in chapter 8 we demonstrate that charging interactions are useful not only for manipulating Majorana modes appearing in superconductors, but also for their ancestors appearing in the fractional quantum Hall effect at filling $\nu = 5/2$. Chapter 9 shows instead that the idea to braid Majorana modes by controlling their mutual coupling - rather then directly moving them in space - can be generalized to all types of non-Abelian anyons, provided some simple assumptions on their mutual interactions hold. Chapter 10 explores the properties of parafermionic zero modes, which are the “fractional” analogue of Majorana modes occurring in systems where superconductivity is induced on the edge of a fractional quantum Hall edge at filling 1/3. Finally, chapter 11 focuses on the transport properties of a linear array of superconducting islands situated on the quantum spin Hall edge, a system which effectively realizes a chain of coupled Majorana modes. We show that weak Coulomb interactions, appearing as quantum phase slips between different islands, remove the quantization of Andreev conductance in the topological phase, while thermal conductance at the Majorana phase transition remains quantized.