Hybrid Josephson junctions and their qubit applications

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Summary

A Josephson junction is a device where a thin insulating barrier or a nanostructure is placed between two superconducting leads. A superconductor is characterized by an order parameter that is a complex number. The phase difference $\Delta\phi$ between the order parameters of the two superconducting leads is a coordinate typically used to describe the state of the junction. Such a junction is essential to superconducting qubits that store quantum information due to its anharmonic spectrum. Therefore, understanding the physics of these junctions is crucial for predictions of the qubit's main qualities, such as the dephasing and relaxation time. Most modern superconducting qubits use Josephson junctions with an insulating barrier (tunneling junction). One of this thesis aims is to explore other possibilities that may allow for better properties of the qubit.

Chapter 2 considers a qubit with a Josephson junction containing a single resonant level connected in parallel with a capacitor (capacitive shunt). For the control of the qubit, it is necessary to have a gate controlling the charge on the capacitor. However, fluctuations of the energy of the qubit with the gate voltage (charge dispersion) decrease the dephasing time. The charge dispersion is typically reduced by making the capacitor very large. However, this also increases the size of the qubit and the dielectric losses. In this Chapter, we study how the charge dispersion changes if a resonant level junction is used instead of the tunneling one. We show that, for the same transition frequency and capacitance of the qubit, the charge dispersion can be significantly reduced in some fine-tuned regimes.

In Chapter 3 we add an additional inductive shunt to the circuit considered in Chapter 2. The spectrum of the qubit doesn't depend on the gate voltage, but such a circuit can be used to implement a so-called bifluxon qubit, where a conservation law forbids its decay. We also show that for a sufficiently large inductance, the Hamiltonian of the circuit is dual to a topological superconducting island.

Chapter 4 concerns a planar Josephson junction with an altermagnetic material in between two superconductors. Altermagnetism is a new kind of magnetic order with a spin-polarized Fermi surface and broken time-reversal symmetry, but with zero net magnetization. We take a microscopic approach to the problem and look at how the states localized at the junction – Andreev bound states – are affected by altermagnetism. We derive that these states are spin-split and observe that for certain ranges of the junction's length, the minimum of the energy of the junction is achieved at $\Delta\phi = \pi$ rather than at $\Delta\phi = 0$ (as in most Josephson junctions, such as the tunneling one). This type of junction can be a useful element for the creation of qubits protected against relaxation. It can provide a stable π phase bias in circuits implementing elements with conserved parity of Cooper pairs. The parity can act as a conserved quantity limiting the relaxation of the qubit. This type of qubit is dual to the bifluxon qubit mentioned in the previous paragraph.

In Chapter 5, we investigate magnetotransport in minimally twisted bilayer graphene. Minimally twisted bilayer graphene is a 2D material made of two graphene layers twisted at a very small angle $\sim 0.1^\circ$ with respect to each other. The material typically relaxes to a superlattice of domains with two relative upper and bottom layer alignments. If a perpendicular electric field is applied, the transport in such a material is dominated by a network of ballistic channels propagating along the domains. We study the dependence of the conductance of such a sample as a function of the perpendicularly applied weak magnetic field. The conductance shows oscillations that can be mapped to the Bloch oscillations of electrons in a 1D crystal.

In Chapter 6, we study magnetotransport in 2D materials, where the Fermi surface is open in one direction. This is a generalization of the situation studied in Chapter 5. We show that such materials feature a magnetic focusing effect with the focusing length $\Delta x = (eaB/h)^{-1}$ (where B is the applied magnetic field and a is the lattice constant). This effect is distinct from the usual magnetic focusing effect due to the Lorentz force and has no classical analogue. We also generalize our results to the case of multiple open orbits weakly coupled with each other.