Master Internship / PhD thesis project:

Quantum transport in voltage-biased topological Josephson junctions

Summary: Topological phases of matter have attracted much interest in recent years. Topological superconductors are of particular interest because they may host Majorana bound states [1]. Josephson junctions have been proposed as probes of topological superconductivity, and possible signatures of such Majorana bound states in topological Josephson junctions have indeed been observed [2,3,4]. However, important aspects related to the effect of the environment on the properties of the junction are still not fully understood. The aim of the project is to make progress in the understanding of quantum transport in voltage-biased topological Josephson junctions in the presence of an electromagnetic environment.

Detailed description: Topological phases of matter have attracted much interest in recent years. Topological superconductors are of particular interest because they may host Majorana bound states [1]. As two Majorana bound states are needed to form one ordinary fermion, they would allow one to create nonlocal qubits that are therefore insensitive to local perturbations. Furthermore, the Majorana bound states are an example of non-Abelian anyons such that topologically protected quantum operations may be realized by braiding them.

Josephson junctions have been proposed as probes of topological superconductivity. Transport measurements of voltage-biased junctions have revealed possible signatures of Majorana bound states, such as the disappearance of odd Shapiro steps in the presence of microwaves [2,4], or the Josephson radiation at half the Josephson frequency [3]. Nevertheless, the most striking signatures obtained in HgTe quantum wells in (vicinity of) the quantum spin-Hall regime [3,4] have not been fully understood so far. Indeed, theory predicts that such signatures should arise only in the presence of some backscattering mechanism of – most likely – magnetic origin, which could not be identified so far.

A missing ingredient of the theory is the lack of a full description of the dynamics of the internal “Majorana” degrees of freedom of the junction in the presence of an environmental electromagnetic circuit. The aim of the project will be to make progress along this line.

In equilibrium, Josephson junctions host Andreev bound states, whose energy depends on the superconducting phase difference, at energies below the superconducting gap. In a voltage-biased junction, the time-varying superconducting phase difference, which increases linearly with the bias voltage, induces non-adiabatic transitions between lower and higher energy states. In conventional junctions, these are Landau-Zener processes between two discrete Andreev states [5], while in topological junctions, these are Demkov-Osherov processes between an Andreev state and the quasiparticle continuum in the leads [6]. Using analytic methods, we will first study how such processes are affected by an environment described as a bath of electromagnetic oscillators, as in the Caldeira-Leggett model.

In the longer term, the results will be compared with a full numerical real-time simulation, in which the current fluctuations generated by the quasiparticle transfer will be re-injected as fluctuations in the bias-voltage through a self-consistent scheme. Once this approach will be validated, we will be in the position of making accurate simulations of the above-mentioned effects for more complicated hybrid structures.

[1] A.Y. Kitaev, Phys. Usp. **44**, 131 (2001)
[2] L.P. Rokhinson *et al.*, Nature Physics **8**, 795 (2012)
[3] J. Wiedenmann *et al.*, Nature Communications **7**, 10303 (2016)
[4] E. Bocquillon *et al.*, Nature Nanotechnology **12**, 137 (2017)
[5] D. Averin and A. Bardas, Phys. Rev. Lett. **75**, 1831 (1995)
[6] M. Houzet *et al*., Phys. Rev. Lett. **111**, 046401 (2013)

Required competences: Interested candidates should have a good basis in quantum mechanics, statistical physics, and condensed matter physics.

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