Annual PhD report - 1st year

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XXXVI cycle

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1 Research activity

My research activity in condensed matter physics fits into the context of the characterization of topological phases of quantum systems in and out of equilibrium. This is a highly promising research area from both the fundamental research point of view and the technological one. Indeed, topological boundary states have huge potential in spintronics, superconducting spintronics, and topological quantum computation.
In the following I describe in further detail the topics I addressed and the original results I achieved during the last year.

- Concerning quantum computation, a main role is played by zero-dimensional topological bound states. Among these, in the last ten years an intense research activity has been devoted to the so-called Majorana zero-modes (MZMs) since they seem the best candidate as qubits to implement a topologically protected quantum computation.
  In this framework, a tricky and yet intriguing difficulty is represented by the existence of bound states that share some features with MZMs being however topologically trivial and therefore much less interesting for the mentioned purpose.
  The first aspect I dealt with is the study of a context where MZMs and other boundary states coexist.

  In low-energy models studied in the context of MZMs, the paradigmatic scenario is that of two topological gapped phases separated by the occurrence of a topological phase transition, when the system becomes gapless. Usually, one of the phases hosts MZMs, while in the other topological bound states are absent. In [1], a unidimensional system violating this paradigm has been analyzed: different boundary states may coexist in an unexpected scenario.
  Indeed, one of the gapless phases of our model could exhibit one bound state at most (technically, similar to a so-called Tamm-Shockley state); more conventionally, in the other phase two MZMs at the two edges of the system were recovered.
  We showed both numerically and analytically that, surprisingly, the Tamm state remains partially localized even when the spectrum becomes gapless. Despite this fact, we demonstrated that the Majorana polarization shows a clear transition between the two regimes, and that the topological properties of the MZMs are not spoiled by the persistence of the Tamm state at the transition.

- My second work aimed in the direction of spintronics applications. In this area, the most innovating playground emerged in the last fifteen years is probably represented by two-dimensional topological insulators, due to the helical nature of their one-dimensional edge channels. This means that along the edge states the electron spin and the direction of propagation are locked, such that they are eigenstates of the helicity operator. Such a property makes it possible to manipulate spins as an outcome of the manupulation of the edge states by means of metallic contacts, gates, external magnetic fields, superconductors, and quantum point contacts (that are basically constrictions) between the helical edges. To this regard, an interesting and yet not much studied system is that of a helical constriction between superconducting leads, which represents a particular case of Josephson junction and has been the subject of my work.

  In the mentioned system, a magnetic flux and an external bias were included, as well as tunneling events between the two edges of the topological insulator occurring along the entire region. The objects of my analysis have been the AC and DC Josephson currents through the structure.
  I showed that our model admits an unusual 4π-periodic component in the AC Josephson current, persisting in a wide range of parameters. This robustness makes it a convenient tool to test our theoretical model for a superconducting quantum point contact in experiments.
  I then moved to the zero-bias limit and studied the DC Josephson current, where the 4π-periodicity is again present. However, more interestingly, I found an occurrence of the so-called "φ_0-Josephson effect". This anomalous Josephson effect is defined by a non-zero current flow even in the absence of a phase difference between the superconductors and it is in general related to a time-reversal symmetry breaking. In our model, such symmetry breaking is due to a peculiar characteristic of the quantum point contact, namely the edge reconstruction. Through this work I hence suggested a way to experimentally detect the edge reconstruction of the superconducting quantum point contact.
  Before submitting these results, there are still other aspects of the system that we think deserve to be deepened.

2 Publications

[1] Vigliotti, L.; Cavaliere, F.; Carrega, M. and Traverso Ziani, N., *Assessing Bound States in a One-Dimensional Topological Superconductor: Majorana versus Tamm*, Symmetry, **13**, 1100 (2021).

3 Courses and exams

I have attended the following courses:

- Quantum Optics, Dr. Dario Ferraro (PhD course)
  Exam to be given soon

- Fasi topologiche della materia condensata, Dr. Niccolò Traverso Ziani (Master Degree course)
  Exam given on September 15th

4 Schools and conferences

- **GGI School: Lectures on Statistical Field Theories**
  February 8-19 2021, 36 hours, held online

https://www.ggi.infn.it/sft/SFTschool/
A report is in preparation to be submitted as a replacement of a course.

- **SIF 107th Congress**
  September 13-17 2021, held online
  https://www.sif.it/attivita/congresso/107
  I was accepted to contribute with the talk *"4π-periodic AC current through helical Josephson junctions"*.

- **Admitted to Cargèse MesoSchool 2021**
  October 4-16 2021, to be held in presence at the Institute of Scientific Studies of Cargèse (IESC, Corsica, France)
  https://mesoschool2021.sciencesconf.org/
  I will present a poster in the poster session.