Università di Genova | DIFI DIPARTIMENTO DI FISICA

# Annual PhD report - 3rd year

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XXXVI cycle

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## 1 Research activity

The main research subject I addressed during my PhD have been topological Josephson junctions, hybrid structures made of two superconducting leads linked by a Quantum Spin Hall Insulator (QSHI). The latter hosts two helical and topologically protected counter-propagating channels on its boundaries, which attract intense research interest in view of their several potential application in quantum technologies. The regions of QSHI in close contact to the superconductors inherit superconducting correlations due to the proximity effect, making such a Josephson junction an optimal platform to inspect the interplay of topology and superconductivity. In particular, transport through the structure is mediated by Cooper pairs travelling from one lead to the other through the edge states.

In this framework, my work during the last year aimed at characterizing this system in cases where the edges interact somehow with each other. In this respect, the reference length scale is the coherence length $\xi$ of the induced superconducting pairing, which represents effectively the Cooper pair's size and, in turn, the distance over which the two bounded electrons can split. An example is their injection and propagation over opposite edges, permitted if the junction's width is $\sim \xi$. This process is called Crossed Andreev Reflection (CAR), and competes with the propagation of both electrons along a same edge, the Local Andreev Reflection (LAR). Besides enhancing the technological relevance of the setup, the phenomenon of Cooper pair splitting is notable from a fundamental point of view, allowing to include and inspect the role of single-electron physics in the superconducting context. In particular, I investigated this topic declined into two scenarios: 1. if the edges are brought close to one another in a so-called constriction, each electron can undergo inter-edge tunneling on its own; 2. if the edge channels have spatial extent comparable to $\xi$, the accessible trajectories for the two electrons across the junction are remarkably increased. The consequences of this fact, especially in combination with magnetic interference effects, were still largely unexplored.

In the following, I provide more details on both cases and the corresponding obtained results.

1. Concerning the proximitized QSH constriction, we analyzed the consequences of the edge reconstruction, which is a spatial separation arising between the two channels on each edge. This might happen as a result of electron-electron interactions, which make such rearrangement electrostatically convenient. The edge reconstruction has been implemented in our theoretical model through an unbalance

between the different inter-edge tunneling amplitudes at play. Interestingly, this breaks both time-reversal symmetry and inversion symmetry, allowing for two connected and promising behaviors: the $\varphi_0$ Josephson effect and the superconducting diode effect. The first consists in the presence of a finite Josephson current – called anomalous Josephson current – in the absence of a phase difference between the two superconductors, and has recently been experimentally observed. It is remarkable because it can be used to design phase batteries, and to drive superconducting circuits and superconducting memories. The second, experimentally observed as well, inspires great perspectives, given the analogy to its semiconducting counterpart that basically paved the way to modern electronics. While the breaking of inversion symmetry can be provided by the geometry of the nanostructure or by the microscopic lattice, the breaking of time-reversal symmetry is often driven externally by means of applied magnetic fields. Notably, for the reconstructed edge system, no external magnetic field is needed. We analytically showed that, unexpectedly, the anomalous effect is reinforced by a temperature increase in a range of parameters. The peculiar temperature dependence has been substantiated by a simple argument based on Fermi's golden rule approach, and represents a clear cut signature of the constriction. Our results open the way to the design of phase batteries in the system, remarkably in the absence of external magnetic fields, and make it possible to envision the direct integration of the $\varphi_0$ junction we considered with other functional nanostructures built on a same QSHI sample. Lastly, by performing our perturbative calculations at higher orders, we expect the setup to show the superconducting diode effect. These results have been published in [1].

2. The second work was inspired by discussions with the experimental group in Würzburg. Although the edge states are usually modeled in theory as strongly localized, they can rather be broadened through the junction and possibly overlap. Since the two electrons of a Cooper pair can propagate and explore the junction independently over length scales comparable to $\xi$, the number of paths they can follow remarkably increases, both via LAR and via CAR. If the junction is pierced by a magnetic flux, this gives rise to wider possibilities for the Aharonov-Bohm phases they acquire. The maximal current as a function of the magnetic flux, which results from the interference of all paths, becomes rapidly decaying and can exhibit different periods in terms of the superconducting flux quantum $\phi_0 = h/2e$. Both features are absent in the case of localized states. We suggested a way of describing this system, generalizing the long-lasting Dynes and Fulton approach, and addressed the question whether CAR processes can bring along interference oscillations with a periodicity $2\phi_0$ as in the case of CAR for localized edge states. We found that the answer is affirmative and identified the best regime to observe such periodicity, finding conditions that, surprisingly, appear to be experimentally relevant. These results have been published in [2].

With these works and my research over the past three years, I aimed at demonstrating that experimentally realizable nanostructures combining superconductivity and constrictions between helical edges are entitled to a huge variety of functionalities and host intriguing anomalous effects. Having set up the conceptual and formal framework, it is now possible to model experimentally interesting scenarios in this direction.

# 2 Publications


[1] Vigliotti, L.; Cavaliere, F.; Passetti, G.; Sassetti, M. and Traverso Ziani, N., *Reconstruction-Induced $\varphi_0$ Josephson Effect in Quantum Spin Hall Constrictions*, Nanomaterials, **13(9)**, 1497 (2023).

[2] Vigliotti, L.; Calzona, A.; Traverso Ziani, N.; Bergeret, F. S.; Sassetti, M. and Trauzettel, B., *Effects of the Spatial Extension of the Edge Channels on the Interference Pattern of a Helical Josephson Junction*, Nanomaterials, **13(3)**, 569 (2023).

# 3 Courses and exams

I have attended the following course:

- Crash Course on Theoretical Condensed Matter Physics, Dr. Niccolò Traverso Ziani (PhD course)
  Exam given on September 13th

I have passed the remaining exams of:

- Quantum Optics, Dr. Dario Ferraro (PhD course)
  Exam given on September 1st
- Topological Quantum Matter: theory and applications (doctoral school)
  Exam given on July 11th

# 4 Schools and conferences

- **Modern Aspects in Quantum Materials and Quantum Technology 2022**
  November 17 - 20 2022, held in presence in Greifswald (Germany)
  `https://physik.uni-greifswald.de/ag-eschrig/maqmqt22/`
  I have presented a poster in the poster session ( *"Unconventional transport of Cooper pairs in topological Josephson junctions"*).
- **Session plénière 2022 du GDR 2426 Physique Quantique Mésoscopique**
  November 28 - December 1 2022, held in presence at the Centre Paul-Langevin in Aussois (France)
  `https://gdr-meso-ple-22.sciencesconf.org/`
  I have presented a poster in the poster session ( *"Unconventional transport of Cooper pairs in topological Josephson junctions"*).
- **Quantum Transport: Disorder, Interactions and Integrability**
  January 26 - 27 2023, held in presence in Rome (Italy), but attended online
  `https://www.lincei.it/en/node/9966`.
- **Rencontres de Moriond 2023 - Quantum Mesoscopic Physics**
  March 25 - April 1 2023, held in presence in La Thuile (Italy)
  `https://moriond.in2p3.fr/2023/Meso/`
  I have presented a poster in the poster session ( *"Unconventional transport of Cooper pairs in topological Josephson junctions"*).
- **Condensed Matter & Low Temperature Physics 2023**
  June 5 - 11 2023, held in presence in Kharkiv (Ukraine), but attended online
  `https://www.ilt.kharkov.ua/cmltp2023/index.html`.
- **Bound states in superconducting nanodevices**
  June 11 - 14 2023, held in presence in Budapest (Hungary)
  `https://www.boundstates2023.eu/`
  I have presented a poster in the poster session ( *"Assessing Bound States in a One-Dimensional Topological Superconductor: Majorana versus Tamm"*).

- **Non-equilibrium Quantum Materials Design**
  June 27 - 29 2023, held in presence in Ingelheim (Germany), but attended online
  `https://www.spice.uni-mainz.de/neqmd-2022-home/`.

- **CMD30 FisMat2023**
  September 4 - 8 2023, held in presence at the Università degli Studi di Milano (Italy)
  `https://eventi.cnism.it/cmd30-fismat`
  I gave a contributed talk *"New insights into Quantum Spin Hall-based Josephson junctions"*.

- **Italian Physical Society 109th Congress**
  September 11 - 15 2023, held in presence at the Università di Salerno (Italy)
  `https://www.sif.it/attivita/congresso/109`
  I gave a contributed talk *"Reconstruction-Induced $\varphi_0$ Josephson Effect in Quantum Spin Hall Constrictions"*.

- **Soon: SFB Q-M&S's Summer School 2023**
  October 2 - 6 2023, to be held in presence at the Institute of Science and Technology Austria in Klosterneuburg (Austria)
  `https://owncloud.tuwien.ac.at/index.php/s/lePOarpbYm8DbU7`
  I will present a poster in the poster session (*"New insights into Quantum Spin Hall-based Josephson junctions"*).

# 5 Others

- Referee activity for New Journal of Physics and for Physical Review & Physical Review Letters.
- I have been invited by Prof. Serbyn at the Institute of Science and Technology Austria on June 14 - 17, where I gave the seminar *"New insights into Quantum Spin Hall-based Josephson junctions"*.
- The last months have been partially spent in writing down my doctoral Thesis.