Annual PhD Report – First Year

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XL cycle

Supervisors:

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1 Research Activity

During my first year of PhD in theoretical condensed matter physics, I have focused on exotic aspects of superconductivity. In particular, I have investigated Quantum Spin Hall systems coupled to superconductors, where the low-energy physics of helical edge states displays unconventional properties that are of great interest both from a fundamental perspective and for potential applications in low-dimensional superconducting quantum electronics. In parallel, I have been interested in the numerical modeling of two-dimensional systems with strong spin–orbit coupling, an activity that has allowed me to theoretically describe experiments carried out in collaboration with the NEST laboratory of Scuola Normale Superiore in Pisa.

Within this framework, I have pursued two main directions.

First, I carried out a fully theoretical project in which I developed new computational and analytical techniques to investigate the superconducting diode effect in topological systems hosting topological helical edge states in proximity to superconductors. In this work, I proposed routes to control the superconducting diode effect via externally applied magnetic and electric fields, and explored the interacting regime where tunneling between edge channels can drive spontaneous time-reversal symmetry breaking via edge reconstruction. This analysis allowed me to identify the superconducting diode effect as a clear signature of edge reconstruction and to demonstrate a mechanism for an intrinsic diode effect without magnetic fields [1].

In parallel, I contributed to the theoretical modeling of experiments on InSb nanoflag devices. In particular, I developed numerical formalisms to describe SQUIDs based on planar Josephson junctions, reproducing their gate-tunable quantum interference patterns and skewed current–phase relations, and evaluating their performance as nanoscale magnetometers [2]. I also analyzed scanning gate microscopy measurements on InSb nanoflag Josephson junctions, providing a theoretical framework for the observed conductance modulation in the normal state and for the local manipulation of supercurrent flow in the superconducting regime [3].

Together, these works illustrate the development of novel theoretical tools and their application to advanced superconducting hybrid devices, bridging fundamental studies of symmetry breaking with the interpretation of experimental observations.

2 Publications

[1] S. Fracassi, N. Traverso Ziani, M. Sassetti, M. Carrega, S. Heun, *Superconducting diode effect in Quantum Spin Hall nanostructures*, in phase of submission.

[2] A. Chieppa, G. Shukla, S. Traverso, G. Bucci, V. Zannier, S. Fracassi, N. Traverso Ziani, M. Sassetti, M. Carrega, F. Beltram, F. Giazotto, L. Sorba, S. Heun, *Unveiling the Current-Phase-Relationship of InSb Nanoflag Josephson Junctions using a NanoSQUID Magnetometer*, Nano Letters, DOI: 10.1021/acs.nanolett.5c03765 (2025)

[3] A. Lombardi, G. Shukla, G. Bucci, S. Salimian, V. Zannier, S. Traverso, S. Fracassi, N. Traverso Ziani, M. Sassetti, M. Carrega, F. Beltram, L. Sorba, S. Heun, *Supercurrent modulation in InSb Nanoflag-based Josephson Junctions by Scanning Gate Microscopy*, arXiv:2506.15342 (2025)

3 Courses and Exams

- Non abelian gauge theories, Prof. Nicola Maggiore (PhD course) – Exam not given yet.
- Energetics in the quantum regime, Prof. Dario Ferraro (PhD course) – Exam not given yet.
- Quantum phases of matter, Prof. Subir Sachdev (online course from Harvard) - Attendance only.

4 Conferences and Contributions

- Scientific meeting, Pisa, NEST labs (Scuola Normale Superiore), 20/01/2025-21/01/2025 – I gave an oral presentation about theoretical modelling of thier experiments.
- Capri Spring School 2025, Capri, 06/04/2025-13/04/2025 –I gave a Student Talk on my master thesis.
- Mallorca Topological Quantum Matter, Palma di Mallorca, 05/05/2025-09/05/2025 – I gave a Conference: *Superconducting diode effect and anomalous supercurrent in a locally perturbed topological Josephson Junction.*