# Ph.D. Annual Report
# XXXVII ciclo
# September 2024

**Ph.D. student:** Simone Traverso
**Supervisors:** Niccolò Traverso Ziani, Maura Sassetti

## Summary of research activity

During the third year of my Ph.D., after completing an open project on finite size effects in the Haldane model for a Chern insulator (see $2^{\text{nd}}$ year report)- resulted in publication [1] -I started working on (topological) superconductivity and quantum transport in mesoscopic systems.

In this context, I started a collaboration with Dr. Fernando Dominguez, from the Institut für Mathematische Physik at the Technische Universität Braunschweig (Germany), which I visited for two weeks in December 2023. This joint project aimed at studying the $p$-wave superconducting Haldane model, with a focus on assessing finite size effects on the topological superconducting phase. First, the bulk 2-dimensional (2D) phase diagram was characterized, leading to the discovery of a gapless, nodal topological superconducting phase, presenting chiral Majorana modes in open flakes. Surprisingly, the localization properties of these topological edge states were found to crucially differ for armchair and zigzag edge, being localized on the first and fully delocalized on the latter. Then, the effect of quantum confinement was investigated, by considering narrow zigzag nanoribbons. In this regime, the computed 1D topological phase diagram presented width-dependent, re-entrant features. When the model parameters lied in the topological region, quasi-0D Majorana bound states (MBSs) were found localized at the two ends of an open zigzag nanoribbon. Majorana modes are zero energy quasiparticles satisfying the usual fermionic statistics. However, their creation and annihilation operators are equal. This property leads to many interesting phenomena and makes MBSs suitable for various applications, *e.g.* in fault-tolerant quantum computation. The topological character of the bound states in our system was confirmed by computing the zero bias conductance in normal - superconductor (NS) junctions, with the latter consisting of the aforementioned superconducting Haldane model. A zero bias peak sharply quantized at $2e^2/h$ was found whenever the superconducting lead lied in the topological region, proving the presence of an MBS in the superconducting part. These results were reported in the preprint [3], currently undergoing peer-review.

In the second part of the year I actively joined the on-going collaboration between my group and Prof. Stefan Heun's group at NEST-CNR (Pisa) on the project PRIN2022 TopoFlags - "Non reciprocal supercurrent and topological transition in hybrid Nb-InSb nanoflags". I thus started working on Josephson junctions (JJs), *i.e.* SNS junctions, manifesting an equilibrium current in presence of a phase difference among the two superconductors. JJs represent one of the most crucial building blocks in the quest for quantum technologies, particularly for the field of quantum computation. Among many other applications, JJs have been shown to be suitable platforms for realizing the superconducting diode effect. Following this line of research, in [2] I collaborated to investigate the effects of a local capacitive or magnetic tip on a topological JJ, that is, a JJ in which the normal part consists of a topological insulator. Here it was shown that although a capacitive tip does not lead to non-reciprocal transport, a magnetic one, acting locally on one of the topological edges in the normal region, can induce anomalous Josephson response and superconducting diode effect, depending on the direction of the tip magnetic field.

Currently, I am assessing the transport properties of a system formed by a pair of InSb-based JJs, arranged in a SQUID geometry. The aim is to model the experimental devices realized in the NEST-CNR laboratories in Pisa, looking for a prediction of a parameter range or a geometrical configuration in which interesting phenomena like the supercurrent rectification may be observable.

## List of publications


[1] Traverso, S., Sassetti, M., Traverso Ziani, N. Emerging topological bound states in Haldane model zigzag nanoribbons. npj Quantum Mater. 9, 9 (2024).

[2] Fracassi, S., Traverso, S., Traverso Ziani, N., Carrega, M., Heun, S., Sassetti, M. Anomalous supercurrent and diode effect in locally perturbed topological Josephson junctions. Appl. Phys. Lett. 124, 242601 (2024).

[3] Traverso, S., Traverso Ziani, N., Sassetti, M., Dominguez, F. Emerging Majorana bound states in superconducting Haldane nanoribbons. arXiv preprint, arXiv:2407.06925 (2024).


## List of attended courses and exams given

- Energetics in the quantum regime - Exam passed
- Hands-on Crash Course on Theoretical Condensed Matter Physics - Exam to be sustained in October 2024
- Seminar on a topic from the attended Ph.D. school *International School of Physics "Enrico Fermi", course 215 "Topology and Materials"* - Exam to be sustained in October 2024

## List of schools/workshops/conferences attended

- Conference *CMD31*, Forum Braga, Braga, Portugal, 02/09/2024 - 06/09/2024. I presented an oral contribution titled "Emerging topological bound states in (superconducting) Haldane model zigzag nanoribbons" on the 03/09/2024.
- *International School of Physics "Enrico Fermi", course 215 "Topology and Materials"*, Varenna, Italy, 17/07/2024 - 22/07/2024. I presented a poster titled "Emerging Majorana bound states in superconducting Haldane nanoribbons".
- *Autumn School on Correlated Electrons: Orbital Physics in Correlated Matter*, Forschungszentrum Jülich, Germany, 18/09/2023 - 22/09/2023. I presented a poster titled "A local mapping from clock-spins to interacting fermions".

## Visits to foreign institutions

- Visit to the group of Prof. Patrik Recher at Technische Universität Braunschweig, Institut für Mathematische Physik, Germany, 10/12/2023 - 22/12/2023. I held a seminar titled "Emerging topological bound states in Haldane model zigzag nanoribbons" on the 21/12/2023.