Università di Genova | DIFI DIPARTIMENTO DI FISICA

Annual PhD report - 2nd year

Lucia Vigliotti
XXXVI cycle

Advisors: Dr. Niccolò Traverso Ziani, Prof. Maura Sassetti

1 Research activity

During this second year of PhD, my research activity has focused on the study of topological Josephson junctions (JJs) with different geometries, following several theoretical approaches. In a topological JJ, two superconducting electrodes are connected through the edge state channels of a quantum spin-Hall (QSH) insulator, which are helical (the direction of motion is bound to the spin polarization). Such an interplay of the Josephson effect and the QSH effect arouses great interest in view of spintronics applications, even more if the junction is pierced by a magnetic field.

In the presence of a magnetic field, a Cooper pair travelling across a JJ acquires a gauge-invariant phase consisting of two inputs: the difference between the phases of the two superconducting condensates and an Aharonov-Bohm phase associated with the magnetic flux enclosed by the pair's path. The supercurrent is a function of such gauge-invariant phase; if maximized with respect to the first contribution, it returns the interference pattern associated to the junction. This signature is of high relevance for the characterization of JJs. Although there are plenty of works in the literature concerning interference patterns, they are still unexplored for many conceivable JJs. Even more interestingly, there are several experimental occurrences of anomalous interference patterns, and it is hence required a theoretical effort to assess their origin providing more refined and reliable models for their background junctions.

More precisely, it has been repeatedly observed, in different setups, the presence of interference oscillations with a fundamental period of $2\phi_0$ – where $\phi_0 = h/2e$ is the (superconducting) magnetic flux quantum –, twice the usual one. The reason for this doubling is to be sought in the transmission of single electrons (charge quantum of e) through the junction in addition to that of Cooper pairs (charge quantum of $2e$). The coexistence and competition among the pair picture and the single-electron picture pave the road to a new, and very rich, way of thinking the current transport in superconducting systems. During the last year I aimed at analyzing the frameworks and the consequences of such a major role acquired by the single-electron physics in the superconducting context. I now summarize my main works and results.

1. I have concluded a work started last year, in which I studied a long QSH constriction, halfway in a topological JJ, including forward scattering events, meaning single-electrons jumping from one edge to the other preserving the direction of motion and flipping the spin. This leads to a 4π-periodic interference SQUID pattern, whereas in the absence of the mentioned inter-edge tunneling it is expected

to be 2π-periodic. The physical explanation I have given resides in the fact that, as mentioned in the introduction, the dominant effect induced by the tunneling involves a single electron within the pair. I have argued that, more generally, whenever in a constriction there is the possibility to switch from a Cooper pair living on one side and a Cooper pair living on both sides, anomalous periodicities can emerge. This work has been published in [1].

2. In a second published work [2] I have generalized this system to the (more realistic) case of reconstructed edges, which implies that the aforementioned inter-edge tunneling occurs with a different probability for electrons moving in opposite directions. I have shown that the anomalous periodicity in the piercing flux, predicted in the absence of reconstruction, is still present. I have then assessed its visibility by giving analytical expressions that are remarkably simpler than the ones of the previous work, which also facilitated the physical interpretation in terms of interference effects.

3. I have completed the study of the DC (zero-bias) Josephson current of the system in 2., which I started last year. I had already found that such current is reminiscent of the time-reversal symmetry and inversion symmetry breaking due to the edge reconstruction, resulting in the so-called φ_0- (or "anomalous-") Josephson effect. This year I have finalized this work better inspecting the temperature dependence of the effect; it is currently in preparation [3].

4. I have finally inspected what happens if the inter-edge tunneling is uniformly present in the junction and not confined to a small subregion. In this case, the computation of the gauge-invariant phases requires closer attention. I have given a tabulation of the possible transport processes and a handy procedure to compute the corresponding phases up to the second order in the inter-edge tunneling amplitude. I have shown that the resultant interference pattern deviates towards a Fraunhofer pattern – as one can expect, since it is the typical pattern associated to homogeneous transport – though not conventional: it decays as a second power of the flux and its minima periodicity approaches $2\phi_0$. This work is yet to be submitted.

5. At present, I am working on a ring-shaped JJ, treated with the scattering matrix approach. The supercurrent is computed by means of the Andreev bound states in the junction. It is shown that the two geometrical configurations of long/short superconducting regions (compared to the coherence length) display differently periodic interference patterns (ϕ_0 or $2\phi_0$). This is again due to the allowed or forbidden transmission of single electrons besides Cooper pairs. This work is yet to be submitted.

These works have been carried out in collaboration with some colleagues abroad: A. Calzona (1., 3., 4., 5.) and B. Trauzettel (1., 4., 5.) from the University of Würzburg, and F. S. Bergeret (5.) from the Materials Physics Center in San Sebastián.

2 Publications

[1] Vigliotti, L.; Calzona, A.; Trauzettel, B.; Sassetti, M. and Traverso Ziani, N., *Anomalous flux periodicity in proximitised quantum spin Hall constrictions*, New Journal of Physics, **24**, 053017 (2022).

[2] Vigliotti, L., *4π-periodic AC Josephson current through a reconstructed quantum spin Hall constriction*, Il Nuovo Cimento, **71**, 45 C (2022).

[3] Vigliotti, L.; Calzona, A.; Sassetti, M. and Traverso Ziani, N., *φ_0-Josephson effect in a reconstructed topological junction* (tentative title), in preparation.

3 Courses and exams

I have attended the following course:

- Theory of crystalline solids, Dr. Sergey Artyukhin (PhD course)
  Exam given on June 13th

I still have to be examined on the school I followed in place of a PhD course and on the Quantum Optics course. This will be done within the end of this PhD year.

4 Schools and conferences

- **Cargèse MesoSchool 2021**
  October 4 - 16 2021, held in presence at the Institute of Scientific Studies of Cargèse IESC (France)
  `https://mesoschool2021.sciencesconf.org/`
  I have presented a poster in the poster session (*"AC and DC currents through a Josephson junction based on a helical constriction: 4π-periodicity and φ_0-Josephson effect"*).
- **Topological Quantum Matter: theory and applications**
  March 28 - April 1 2022, held in presence in Santa Margherita Ligure (Italy)
  `https://www.difi.unige.it/it/eventi/2022/03/28/topological-quantum-matter-theory-and-applications`
- **SIF 108th Congress**
  September 12 - 16 2022, held in presence at the Università degli Studi di Milano (Italy)
  `https://www.sif.it/attivita/congresso/108`
  I contributed with the accepted talk *"Unconventional transport of Cooper pairs in topological Josephson junctions"*.
- **Soon: Northern Lights Conference 2022**
  October 12 - 15 2022, to be held in presence at the National Museum of Iceland in Reykjavík (Iceland)
  `https://www.northernlightsconference22.eu/`
  I will present a poster in the poster session (*"Unconventional transport of Cooper pairs in topological Josephson junctions"*).

5 Others

- Didactic tutor, project A_FARM_02:
  tutor for the course Matematica of the degree in Chimica e Tecnologie Farmaceutiche, 40 hours.
- Support teaching activity:
  exercise classes for the course Analisi Matematica 1 of the bachelor's degree in Ingegneria Meccanica, 30 hours.
- I have been a referee for the journal Physica E.
- My contribution to the 107^{th} Sif (Italian Physical Society) Congress has been awarded the first prize for the best of the Condensed Matter section.
- I have been invited by Prof. Trauzettel at the Physics Department of the University of Würzburg on May 9 - 13, to deepen our project published in [1]. During my stay I have also had the opportunity to take part in interesting discussions with the experimental group.