1.3.11 Quantum transport and Majorana fermions in hybrid systems

Since the first prediction of real solutions to the Dirac equation, known as Majorana fermions, there have been many attempts to demonstrate their occurrence in nature~\cite{WilczekNatPhys2009}, but a clear evidence is still lacking. Besides the natural search for these elusive particles in high-energy physics, it has been recently suggested that Majorana fermions can exist as exotic excitations in certain condensed-matter systems [The field has be recently reviewed in J. Alicea, Rep. Progr. Phys. 75 , 076501 (2012)].

The importance of finding Majorana fermions in condensed-matter systems is not only related to their fundamental interests. It is also rooted in the non-Abelian braiding statistics of these particles which could be exploited as a basis for decoherence-free topological quantum computation [1].

We focused on a specific proposal [2] realized with spin-orbit-coupled semiconducting nanowires in proximity to an s-wave superconductor and subjected to an in-plane magnetic field This wire can support Majorana-fermion bound states at its ends when parameters such as chemical potential, magnetic field, and superconducting pairing are properly tuned }. The S-nanowire is said to be in the topological phase when Majorana bound states are present, while it is topologically trivial otherwise.

We have considered [3] a multi-band semiconducting nanowire subjected to spin-orbit coupling, superconducting pairing and a longitudinal Zeeman field.

Depending on the values of such parameters, the nanowire presents a non-trivial topological phase in which a pair of Majorana modes, at an energy equal to the chemical potential, are localized at its ends.

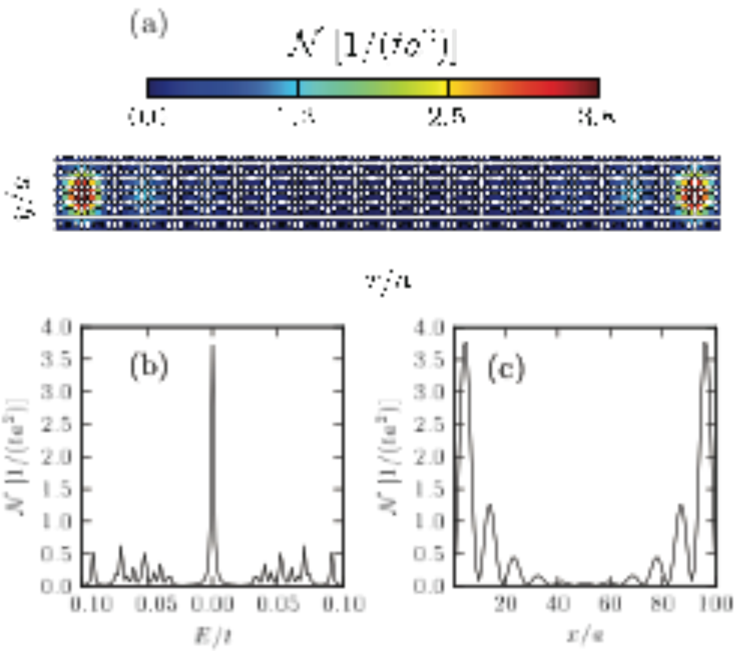


Figure 1 (a) LDOS of an isolated superconducting nanowire in the topologically non-trivial phase at an energy very lose to the chemical potential. Bound states at both ends of the wire are apparent. (b) LDOS at a given position as a function of energy. A sharp peak corresponding to a Majorana bound state is present at zero energy. (c) LDOS at very low energy along the wire.

We have carefully calculated and analyzed the local density of states (LDOS) of such nanowires in the case where they are coupled to normal regions (such as electrodes or links) and we have compared the topologically non-trivial and trivial phases in different situations. This is a situation of particular importance for the experimental detection of Majorana modes.

When the nanowire is coupled to a normal electrode we have found that the peak in the LDOS at zero energy (with respect to the chemical potential), corresponding to the Majorana mode, broadens with increasing coupling strength to the electrode, eventually disappearing for ideal coupling. Interestingly, for finite coupling the peak is also present on the normal electrode, though being of smaller amplitude and broadening more rapidly with the strength of the coupling.

Additional interesting features emerge in realistic wires where the proximity varies along the section of the wire. We have shown that topological adiabatic pumping occurs in a class-D superconducting nanowire connected to a metallic lead [4]. This is the case when the lead supports a single propagating mode or when the nanowire is coupled to the lead through a quantum point contact.

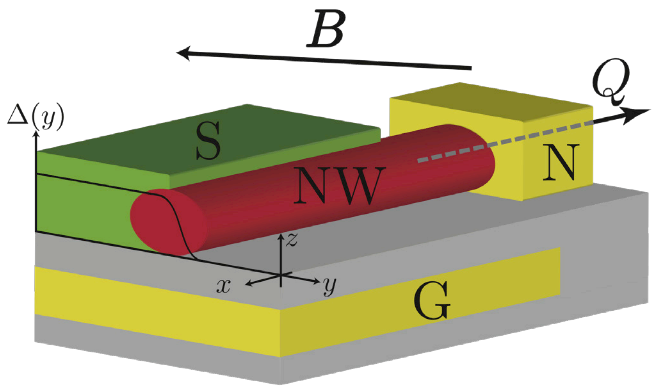
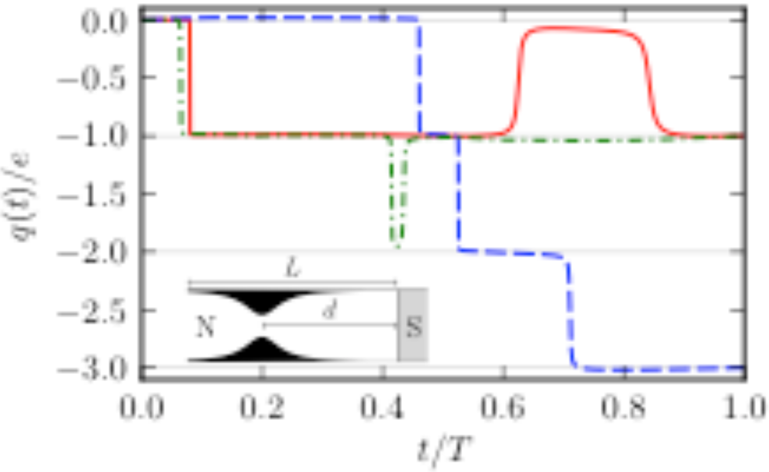


Figure 2. Sketch of the system. A spin-orbit coupled nanowire (NW) is subject to a tilted Zeeman field and in contact with a bulk superconductor (S) which induces a pairing gap. Due to the lateral contact the induced gap is space-dependent as illustrated in the figure. The wire is in contact with a normal lead (N). By changing in time the chemical potential (through the gate voltage) and the Zeeman field a charge Q is pumped through the NW-N interface

The necessary condition to achieve a topological pumped charge is that the phase diagram presents a non-simply connected structure, where isolated non-topological regions are surrounded by connected topological ones. This is possible by allowing both a non-uniform pairing amplitude and a tilted Zeeman field. Non-contractible pumping paths in parameter space can thus be identified within the topological phase. Quantised pumping is very important in view of its metrological applications. In general the quantisation condition requires some fine tuning of the parameters. If, however, quantisation stems from topology, pumping will be immune from errors and robust to unavoidable perturbations and therefore it might lead to current standards of unprecedent accuracy.



In the figure above we show the cumulative pumped charge (in units of e) as a function of time t (in units of the pumping period T) in the presence of a quantum point contact at a distance from the NS interface. At the end of the cycle the final pumped charge is quantized. Results for different trajectories in parameter space are denoted with distinct line styles. In the inset we have sketched the setup with a QPC at a distance d from the NS boundary in order to restrict the number of propagating modes.

References

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