PhD Thesis booklet

Superconducting double quantum dot hybrids in parallel InAs nanowires

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Introduction

Nowadays, the field of quantum electronics intensively investigates quantum bit (qubit) concepts relying on various physical systems, such as spin qubits or different superconducting qubits. In general, their main drawback is their susceptibility to external noise, which leads to computational errors and loss of coherence. A promising solution to this problem could be the application of anyons suggested by A. Kitaev. His one-dimensional chain model is based on the interaction of superconductors and the atoms connected to each other in series. In such a chain the appearance of Majorana fermions is predicted, which are topologically protected against external environmental inhomogeneities. Due to the protection, the Majoranas are ideal candidates to perform fault-tolerant quantum algorithms, which makes them more favorable than any traditional qubits.

In recent years, many researches focused on the realization of Majorana fermions in semiconductor nanowires attached to a superconductor. Majorana fermions were expected to arise in these systems as a result of the interplay of the superconductivity, the magnetic field, and the spin-orbit interaction. Although the signatures of Majorana-type excitations have been reported in spectroscopic measurements, their origin and the presence of Majorana in such systems are still under debate in the scientific community. In addition, the lack of control parameters (for example, the chemical potential) is a serious limiting factor of this proposal.

A one-dimensional array of artificial atoms (namely quantum dots) and superconductors (constituting a Kitaev chain) serves as an alternative platform for the experimental implementation of Majorana fermions. The tunability of the energy levels of the quantum dots and the electron tunneling processes give a significantly greater experimental control, which allows to finetune the system to the appropriate parameter settings required for the Majoranas.

The main building block of the Kitaev chain is a double quantum dot connected by a joint superconductor, which, based on theoretical predictions, can already exhibit excitations with Majorana statistics. In this reduced system, the hybridization of the quantum dots mediated by the superconductor can be studied, which can maintain a long-range interaction in a longer chain. The superconducting coupling of the dots can be manifested in different limits: in the case of a weak coupling, Cooper pair splitting is present, while for strong interaction, a so-called An Andreev molecular state can be formed. If the impact of these processes is explored and controlled, the system can be integrated into a longer chain, in which the topologically protected Majorana states are bound to the end of the chain.

Objectives

The target of my PhD research and the thesis is the experimental investigation of parallel quantum dots coupled by a joint superconductor in different limits as outlined in the introduction. In the experiments, I examine nanocircuits built from parallel InAs nanowires which are connected by an epitaxial superconducting layer. In this platform, the strength of the interaction between the quantum dots formed in the wires can be maximized since their distance is minimal.

In case of a weak coupling between the quantum dots and the superconductor, Cooper pair splitting can be dominant as a manifestation of the interaction. However, as a result of the close vicinity of the dots, the Coulomb repulsion between them also becomes considerable limiting the pair-splitting processes. One of the goals of the thesis is to present and quantify the competition between the two phenomena. Despite the unfavorable Coulomb repulsion, I demonstrate the presence of a high-efficient Cooper pair splitting by measuring the correlation of the current flowing through the quantum dots.

In the strong coupling limit, the quantum dots can host so-called Andreev bound states. When these sub-gap states are assisted by the same superconductor, they can hybridize and constitute an Andreev molecule. Another main objective of the thesis is the realization of a level-tunable Andreev molecular state with spectroscopic measurements, which I also confirm by numerical simulations.

The superconducting-double quantum dot hybrid can also be studied in a third limit where the superconducting electrode is replaced by a finite-size superconducting island which also acts as a quantum dot. In this case, the quantum dots form such an artificial 3-atomic molecule, where superconducting correlations are present on the central atom. In the thesis, by investigating the stability diagram of the superconducting island systematically, I demonstrate the presence of the 3-atom molecule, which I also approve with simple calculations.

Thesis points

1. **I detected high-efficient Cooper pair splitting in the presence of strong Coulomb repulsion.** In a double InAs nanowire-based nanocircuit, I formed parallel quantum dots electrostatically with side gate electrodes defined in the vicinity of the nanowires. I coupled the quantum dots to a joint superconductor and two separate normal electrodes, and I studied the Cooper pair splitting signal via low-temperature transport measurements. Due to the small geometrical distance between the quantum dots, the splitting efficiency is expected to be enhanced. On the other hand, the strong Couplumb interaction between the quantum dots penalizes such transport processes where the two dots are charged simultaneously, i.e. Cooper pair splitting. I analyzed the impact of the Coulomb repulsion and in my measurements, I found a significantly higher splitting efficiency compared to the previous ones from literature performed on single InAs nanowires. According to theoretical calculations, the double nanowire geometry is said to be preferred regarding the splitting efficiency. (T1)
2. **I constructed a 2-atomic Andreev molecule in a superconductor-parallel double quantum dot hybrid.** In parallel quantum dots embedded in double InAs nanowires and coupled to superconducting electrodes, I demonstrated the hybridization of two Yu-Shiba-Rusinov bound states mediated by crossed Andreev reflection and elastic cotunneling. I studied the excitation spectra of the interacting Yu-Shiba-Rusinov states as a function of the quantum dot level positions and distinguished the spectral peculiarities originating from distinct interactions (e.g. capacitive coupling, crossed Andreev reflection). To verify the presence of the Andreev molecule, I compared the experimental results with numerical simulations, which reproduced the main properties of the spectra. (T2)
3. **I created a 3-atom Andreev molecule by the interaction of two artificial atoms connected to a superconducting island.** In a multi-terminal, double InAs nanowire-based circuit, I explored the interaction between a superconducting island and a parallel double quantum dot system coupled to it. By fine-tuning the energy levels of the island and semiconductor quantum dots, I formed Coulomb-assisted Yu-Shiba-Rusinov bound states, which I captured in the electron occupation-dependent stability diagram of the island. Examining the resonance distance of the superconducting island, I have shown that if a single quasi-particle is present in the superconducting island and both quantum dots have an unpaired electron, they bind to the quasi-particle and share it with each other. This hybridization constitutes such a 3-atomic Andreev molecule, where superconductivity is present in the central atom. (T3)

Publications related to the thesis points

(T1) **Kürtössy, O.**, Scherübl, Z., Fülöp, G., Lukács, I., Kanne, T., Nygård, J., Makk, P., Csonka, S.: *Parallel InAs nanowires for Cooper pair splitters with Coulomb repulsion*, Nature PJ Quantum Mater. 7, 88 (2022), IF: 7.14

(T2) **Kürtössy, O.**, Scherübl, Z., Fülöp, G., Lukács, I., Kanne, T., Nygård, J., Makk, P., Csonka, S.: *Andreev molecule in parallel InAs nanowires*, Nano Lett. 21, 19, 7929–7937 (2021), IF: 11.62

(T3) **Kürtössy, O.**, Bodócs, M., Scherübl, Z., Kanne, T., Nygård, J., Makk, P., Csonka, S.: *Polyatomic Andreev molecule in a superconducting island-double quantum dot hybrid*, manuscript under preparation (2024)

Other publications

(1) Elalaily, T., **Kürtössy, O.**, Zannier, V., Scherübl, Z., Lukács, I., Rossi, F., Srivastava, P., Sorba, L., Csonka, S., Makk, P.: *Probing proximity induced superconductivity in InAs nanowire using built-in barriers*, Phys. Rev. Applied 14, 044002 (2019), IF: 4.53

(2) Elalaily, T., **Kürtössy, O.**, Scherübl, Z., Berak, M., Fülöp, G., Lukács, I., Kanne, T., Nygård, J., Watanaba, K., Taniguchi, T., Makk, P., Csonka, S.: *Gate-controlled supercurrent in an epitaxial Al/InAs nanowires*, Nano Lett. 21, 22, 9684–9690 (2021), IF: 11.62