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Spin-resolved crossed Andreev reflection in ballistic heterostructures

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Abstract

We theoretically analyze non-local effects in electron transport across three-terminal ballistic normal–superconducting–normal (NSN) structures with spin-active interfaces. Subgap electrons entering S-electrode from one N-metal may form Cooper pairs with their counterparts penetrating from another N-metal. This phenomenon of crossed Andreev reflection (CAR) is highly sensitive to electron spins and yields a rich variety of properties of non-local conductance which we describe non-perturbatively at arbitrary interface transmissions, voltages and temperatures. Our results can be applied to hybrid structures with normal, ferromagnetic and half-metallic electrodes and can be directly tested in future experiments.

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1. Introduction

Andreev reflection (AR) [1] is the main mechanism of low energy electron transport between a normal metal and a superconductor. This mechanism results in a number of interesting effects causing, e.g. a non-zero subgap conductance [2] of such hybrid structures. In systems with one superconducting (S) and several normal (N) terminals, e.g. normal-superconducting-normal (NSN) hybrid structures, electrons may suffer AR at each of NS interfaces. Provided the distance between two NS interfaces L strongly exceeds the superconducting coherence length ξ, AR processes at these interfaces are independent. If, however, the distance L becomes comparable with ξ, two additional *non-local* processes should be taken into account (see Fig. 1). Firstly, an electron with subgap energy can directly penetrate from one N-metal into another through a superconductor. Since the subgap density of states in the superconductor vanishes, the probability of this process should be suppressed by the factor $\sim\exp(-L/\xi)$. Secondly, an electron penetrating into the superconductor from the first N-terminal may form a Cooper pair together with another electron from the second N-terminal. In this case a hole goes into the second N-metal and AR becomes a non-local effect. The probability of this process—usually called crossed Andreev reflection (CAR) [3,4]—also decays as $\sim\exp(-L/\xi)$ and, in combination with direct electron transfer between normal electrodes, determines non-local conductance in hybrid multi-terminal structures. This non-local conductance can be directly measured in experiments and it has recently become a subject of intensive investigations.

Several experiments [5–7] allowed to clearly detect the non-local conductance in three-terminal NSN structures and demonstrated a rich variety of different features whose unambiguous and detailed interpretation remains an important task for the future. At this point we note that in addition to CAR a number of other physical effects may considerably influence the observations. Among such effects we mention, e.g. charge imbalance (relevant close to the superconducting critical temperature [5,7]) and zero-bias anomalies in the Andreev conductance due to both disorder-enhanced interference of electrons [8–10] and Coulomb effects [10–12].

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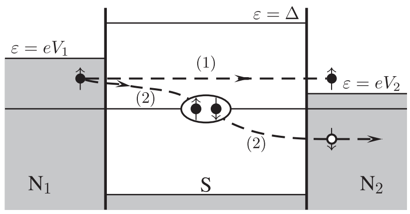

Fig. 1. Two elementary processes contributing to non-local conductance of an NSN device: (1) direct electron transfer and (2) crossed Andreev reflection.

Theoretically CAR was analyzed within the perturbation theory in the transmission of NS interfaces in Refs. [13,14] where it was demonstrated that in the lowest order in the interface barrier transmission and at $T = 0$ CAR contribution to cross-terminal conductance is exactly canceled by that from elastic electron cotunneling (indicated as (1) in Fig. 1), i.e. the non-local conductance turns out to vanish in this limit. Recently a non-trivial interplay between normal reflection, tunneling, local AR and CAR in three-terminal ballistic NSN devices was non-perturbatively analyzed to all orders in the interface transmissions [15]. This analysis allowed to determine an explicit dependence of the non-local conductance both on the transmissions of NS interfaces and on the length L, to set the maximum scale of the effect and to consider various important limits. The effect of disorder on CAR was recently studied in Refs. [16] (perturbatively in tunneling) and [17] (non-perturbatively in tunneling, for a device with normal terminals attached to a superconductor via an additional normal island). The interplay between CAR and Coulomb interaction effects was recently addressed in Refs. [18,19].

It is also important to mention that both AR and CAR should be sensitive to magnetic properties of normal electrodes because these processes essentially depend on spins of scattered electrons. First experiments on ferromagnet–superconductor–ferromagnet (FSF) structures [5] illustrated this point by demonstrating the dependence of non-local conductance on the polarization of ferromagnetic terminals. Hence, for better understanding of non-local effects in multi-terminal hybrid proximity structures it is desirable to construct a theory of *spin-resolved* CAR. In the lowest order in tunneling this task was accomplished in Ref. [13]. For FSF structures higher orders in the interface transmissions were considered in Refs. [20,21].

In this paper we are going to generalize our quasiclassical approach [15] and construct a theory of spin-resolved CAR to all orders in the interface transmissions. Instead of dealing directly with FSF devices we will consider NSN structures with spin-active interfaces. This model allows to distinguish spin-dependent contributions to the non-local conductance and to effectively mimic the situation of ferromagnetic and/or half-metallic electrodes.

The structure of the paper is as follows. In Section 2 we will introduce our model and discuss the quasiclassical formalism supplemented by the boundary conditions for Green–Keldysh functions which account for electron scattering at spin-active interfaces. Non-local electron transport in NSN structures with such interfaces will be analyzed in Section 3. Our main conclusions will be briefly summarized in Section 4. Technical details related to boundary conditions will be outlined in Appendix A.

2. The model and formalism

Let us consider three-terminal NSN structure depicted in Fig. 2. We will assume that all three metallic electrodes are non-magnetic and ballistic, i.e. the electron elastic mean free path in each metal is larger than any other relevant size scale. In order to resolve spin-dependent effects we will assume that both NS interfaces are spin-active, i.e. we will distinguish "spin-up" and "spin-down" transmissions of the first ($D_{1\uparrow}$ and $D_{1\downarrow}$) and the second ($D_{2\uparrow}$ and $D_{2\downarrow}$) SN interface. All these four transmissions may take any value from zero to one. The effective cross-sections of the two interfaces will be denoted, respectively, as $\mathcal{A}_1$ and $\mathcal{A}_2$. The distance between these interfaces L as well as other geometric parameters are assumed to be much larger than $\sqrt{\mathcal{A}_{1,2}}$, i.e. effectively both contacts are metallic constrictions. In this case the voltage drops only across SN interfaces and not inside large metallic electrodes. Hence, nonequilibrium (e.g. charge imbalance) effects related to the electric field penetration into the S-electrode can be neglected. In what follows we will also ignore Coulomb effects [10–12].

For convenience, we will set the electric potential of the S-electrode equal to zero, $V = 0$. In the presence of bias voltages V_1 and V_2 applied to two normal electrodes (see Fig. 2) the currents I_1 and I_2 will flow through SN_1 and SN_2 interfaces. These currents can be evaluated with the aid of the quasiclassical formalism of nonequilibrium Green–Eilenberger–Keldysh functions $\hat{g}^{R,A,K}$ [22] which we briefly specify below.

2.1. Quasiclassical equations

In the ballistic limit the corresponding equations take the form

$$[\varepsilon\hat{\tau}_3 + eV(\boldsymbol{r},t) - \hat{\Delta}(\boldsymbol{r},t), \hat{g}^{R,A,K}(\boldsymbol{p}_F,\varepsilon,\boldsymbol{r},t)] + i\boldsymbol{v}_F\nabla\hat{g}^{R,A,K}(\boldsymbol{p}_F,\varepsilon,\boldsymbol{r},t) = 0, \quad (1)$$

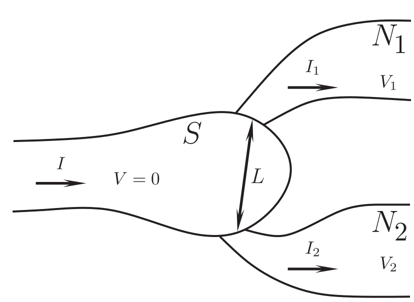

Fig. 2. Schematics of our NSN device.