Solid State Communications 258 (2017) 25–32

Contents lists available at ScienceDirect

Solid State Communications

journal homepage: www.elsevier.com/locate/ssc

Communication

Noise cross-correlation and Cooper pair splitting efficiency in multi-teminal superconductor junctions

J.A. Celis Gil[a,b], S. Gomez P.[b,c,*], William J. Herrera[b]

[a] Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands
[b] Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
[c] Departamento de Física, Universidad El Bosque, Bogotá, Colombia

ARTICLE INFO

Communicated by: F. Peeters

Keywords:
Superconductivity
Pairing symmetries
Iron pnictides
Andreev reflection
SN junctions
Nanostructures
Nanocontacts

ABSTRACT

We analyze the non-local shot noise in a multi-terminal junction formed by two Normal metal leads connected to one superconductor. Using the cross Fano factor and the shot noise, we calculate the efficiency of the Cooper pair splitting. The method is applied to *d*-wave and iron based superconductors. We determine that the contributions to the noise cross-correlation are due to crossed Andreev reflections (CAR), elastic cotunneling, quasiparticles transmission and local Andreev reflections. In the tunneling limit, the CAR contribute positively to the noise cross-correlation whereas the other processes contribute negatively. Depending on the pair potential symmetry, the CAR are the dominant processes, giving as a result a high efficiency for Cooper pair split. We propose the use of the Fano factor to test the efficiency of a Cooper pair splitter device.

1. Introduction

Entanglement states between photons have been very well developed [1]. However, entanglement between electrons in solid system is difficult to create because the electrons are immersed in a macroscopic ground state, which prevents the straightforward generation of entangled pairs of electrons.

The use of a superconductor to produce entangled electrons has been proposed [2–8] because its ground state is composed of Cooper pairs. A Cooper pair in the superconductor can be break up into two nonlocal entangled electrons that enter into different normal metal leads via the Cooper pair splitting (CPS) [9–13]. The CPS has been studied theoretically and experimentally [14–18], opening a door to test Bell inequalities in the solid state [19,20].

The Cooper pair splitting process is analog to CAR, where an incoming electron from one of the leads is reflected as a hole in the other one, inducing a Cooper pair in the superconductor. Typically, to analyze the CAR, the electrical current has been used to test the Bell inequalities; it is important to analyze not only the currents through every lead, but also the correlations between them, which can be determined through the noise.

According to its origin, the noise is classified into two types: one due to thermal fluctuations, which is known as Nyquist-Johnson noise [21], and the other due to the discrete behavior of the electric charge, known as shot noise [22]. It is possible to obtain with shot noise measurements information not commonly obtained with conductance measurements. In high T_C superconductors, the shot noise has been studied for plain junctions where shot noise is affect by the pair potential symmetry [23,24].

The nonlocal shot noise or noise cross-correlation between two electrodes connected to a superconductor reveals a change of the sign in the correlation between currents [25–27]. For example, for two electrodes connected to a normal metal, the nonlocal shot noise shows a negative crossed correlation, which indicates that when the electrical current in one lead increases, the current in the other lead decreases [28–30]. However the nonlocal shot noise for two leads connected to a superconductor can exhibits positive values [31,32] that is, the electrical current in the two leads could increase or decrease at the same time.

The noise cross-correlation has been studied for two quantum point leads connected to a superconductor [33–38]; nevertheless, the nonlocal shot noise has not been studied for two electrodes connected to *d*-wave or iron based superconductors, where the pair potential symmetry can affect the transport properties of the system. In the present paper we show an analytic approach that allows us to find the current-current correlation and separate the contributions due to the different processes. In particular we analyze the Cooper pair split contribution. For this, we use the Hamiltonian approach and the non-equilibrium Green functions in Keldysh formalism. We consider typical pair potential symmetries for cuprates and iron based superconductors

---

[*] Corresponding author at: Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia.
E-mail addresses: sgomezp@unal.edu.co (S. Gomez P.), jherreraw@unal.edu.co (W.J. Herrera).

http://dx.doi.org/10.1016/j.ssc.2017.04.009
Received 10 January 2017; Received in revised form 13 April 2017; Accepted 17 April 2017

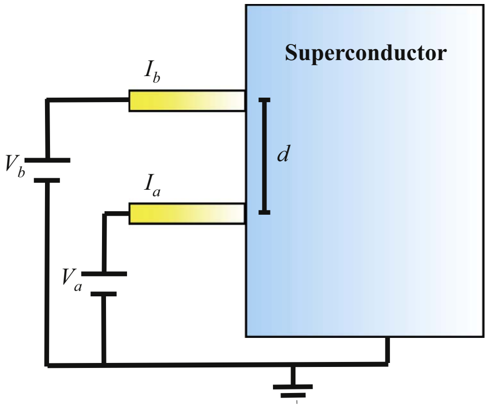

Fig. 1. Diagram of two electrodes $a(b)$ separated by a distance d and connected to a superconductor. The superconductor is grounded and the leads are at voltages V_a and V_b respectively.

which means d, s_{++} and s_{+-} symmetries [39–46]. In addition, we consider a s-wave compound added to the d-wave superconductors, thus we study how the magnitude and phase of the pair potential affect the noise cross-correlation. We analyze the symmetric case when the two leads are connected to the same voltage ($V_a = V_b = V$) and the non-symmetric case when the two leads are connected to a voltage difference V ($V_a = 0$, $V_b = V$). We find that the positive noise cross-correlation is favored by symmetric applied voltages.

2. Shot noise cross-correlation

The system considered is formed by two one-dimensional normal metal leads connected to a semi-infinite superconducting region Fig. 1. The lead $a(b)$ is connected to voltage $V_{a(b)}$, while the superconductor is grounded. It has been demonstrated that there are two processes that contribute to the cross conductance; the CAR and the elastic cotunneling (EC) [47], see Fig. 2. When the $V_a = 0$ and $V_b = V$ the nonlocal differential conductance is given by

$$\sigma_{ab} = \frac{dI_a}{dV_b} = \frac{2e^2}{h}(T_{CAR} - T_{EC}), \tag{1}$$

where T_{CAR} and T_{EC} are the transmission coefficients of the CAR and EC respectively and that can be written in terms of the Green function as

$$T_{CAR} = 4t^4|\check{G}^r_{ab,eh}(E)|^2, \tag{2}$$

$$T_{EC} = 4t^4|\check{G}^r_{ab,ee}(E)|^2, \tag{3}$$

where t is the hopping parameter coupling the leads and the superconductor, $\check{G}^r_{ab}(E)$ is the nonlocal green function in the superconducting region between a and b, the subindex $ee(h)$ denotes the electron-electron (hole) component. The contributions of T_{CAR} and T_{EC} processes decrease when the distance between the leads increases and depend on the symmetry of the pair potential [47].

Our aim is to obtain the noise cross-correlations and the Fano factor. For s-wave superconductors, the nonlocal shot noise has been calculated [32], showing that, whereas the CAR contribute positively to the crossed correlation between the currents in the two leads [48–50], the EC contributes negatively [51]. Local processes like the Andreev reflections (AR) and quasiparticles transmission (Q) contribute negatively to the nonlocal shot noise (see Fig. 2). Whereas the AR are equivalent to Cooper pair tunneling in one lead, the CAR are equivalent to CPS [52,53]; hence, we are interested in analyzing the positive contributions to the nonlocal shot noise (see Fig. 3).

We use the Hamiltonian approach to study this system and the Green functions, and Keldysh formalism [54] in order to find the nonlocal shot noise between the leads β and β' at frequency ω (for details see Appendix A),

$$S_{\beta\beta'}(\omega) = \frac{2e^2t^4}{h}\int dE\,[K_{\beta\beta'}(E,\,\varepsilon)+K_{\beta'\beta}(\varepsilon,\,E)], \tag{4}$$

where

$$\varepsilon = E + \hbar\omega.$$

The kernel $K_{\beta\beta'}(E,\,\varepsilon)$ can be rewritten as

$$K_{\beta\beta'}(E,\,\varepsilon) = K^1_{\beta\beta'}(E,\,\varepsilon) + K^2_{\beta\beta'}(E,\,\varepsilon) + K^3_{\beta\beta'}(E,\,\varepsilon) + K^4_{\beta\beta'}(E,\,\varepsilon), \tag{5}$$

where

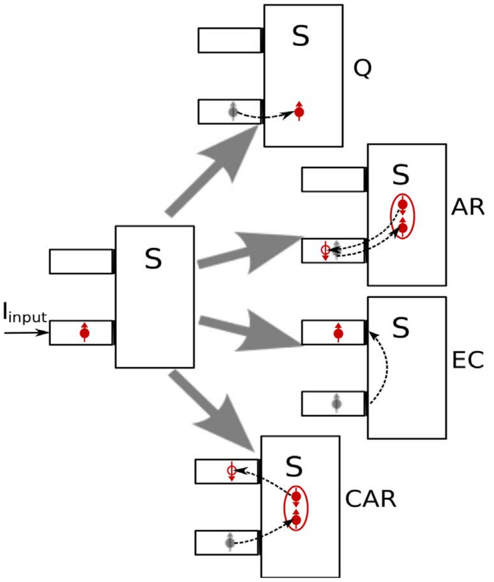

Fig. 2. Diagram of the different processes considered. An incoming electron from a lead could be: transmitted as a quasiparticle (Q); reflected as a hole in the same lead inducing a Cooper pair in the superconductor (AR); reflected as an electron in the other lead (EC); or reflected as a hole in the other lead inducing a Cooper pair in the superconductor (CAR).

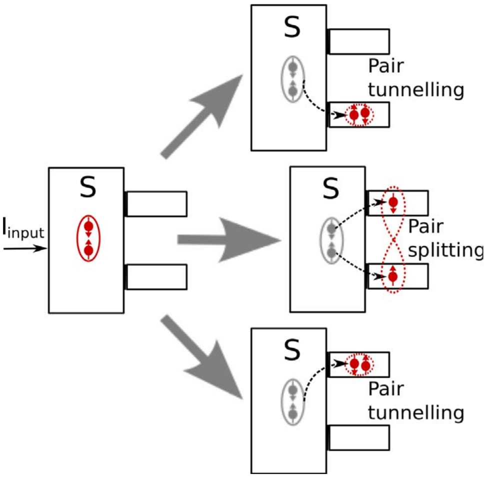

Fig. 3. Basic transport processes in a Cooper pair splitter: the electrons of a Cooper pair either leave the superconductor into the same arm (pair tunneling) or split up into different arms (pair splitting).