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Reprint of : Quantum interference in a Cooper pair splitter: The three sites model

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ABSTRACT

New generation of Cooper pair splitters defined on hybrid nanostructures are devices with high tunable coupling parameters. Transport measurements through these devices revealed clear signatures of interference effects and motivated us to introduce a new model, called the 3-sites model. These devices provide an ideal playground to tune the Cooper pair splitting (CPS) efficiency on demand, and displays a rich variety of physical phenomena. In the present work we analyze theoretically the conductance of the 3-sites model in the linear and non-linear regimes and characterize the most representative features that arise by the interplay of the different model parameters. In the linear regime we find that the local processes typically exhibit Fano-shape resonances, while the CPS contribution exhibits Lorentzian-shapes. Remarkably, we find that under certain conditions, the transport is blocked by the presence of a dark state. In the non-linear regime we established a hierarchy of the model parameters to obtain the conditions for optimal efficiency.

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1. Introduction

Producing and detecting entangled electronic states in nanoscale circuits is a prominent goal which is still under development. Among his many contributions to the field of quantum transport, Markus Büttiker participated in the intense search for manifestations of quantum entanglement in transport experiments which took place at the beginning of 2000 [1–11]. Markus and his group extensively explored the characterization of the degree of entanglement by cross correlations of the electrical current [6,12,13]. Within the early theoretical proposals for producing entanglement in transport, the ones based on superconducting correlations [3,5,4] have acquired a particular relevance with the first experimental realizations of Cooper pair splitters (CPS) in semiconducting nanowires [14–16] and carbon nanotubes [17–19]. These experiments, although providing evidence of CPS through conductance measurements, have not yet achieved the goal of demonstrating entanglement. In connection to these developments there have also appeared some proposals for detecting entanglement from conductance measurements [20,21].

Ideally, the basic mechanism for enforcing CPS in these devices is the presence of a large intradot Coulomb repulsion and a large gap for quasiparticle excitations in the superconductor. In actual devices, however, geometrical and/or parameter constraints complicate the analysis but, at the same time, give rise to interesting new phenomena. In this sense, while in an ideal CPS device it is assumed that Cooper pairs are injected at a slow rate and extracted at a faster rate in order to avoid overlap between subsequent pairs, in an actual device the injected pairs can dwell within the device and interference effects due to the superposition of different electronic paths can emerge. In fact, as shown first in the experiments of Ref. [22] for QDs inserted in a Aharonov–Bohm ring and analyzed theoretically by Markus Büttiker et al. [23–25], the phase of the transmission through a QD can be well defined even when the system is deep in the Coulomb blockade (CB) regime, thus leading to interference effects. should be replaced by: In fact, as shown first in the experiments of Ref. [22] for quantum dots (QDs) placed in a Aharonov–Bohm ring and analyzed theoretically by Markus In fact, as shown first in the experiments of Ref. [22] for QDs inserted in a Aharonov–Bohm ring and analyzed theoretically by Markus Büttiker et al. [23–25], the phase of the transmission through a QD can be well defined even when the system is deep in the Coulomb blockade (CB) regime, thus leading to interference effects. Such effects have been reported in a recent experiment on CPS devices based on InAs nanowires coupled to a Nb superconducting lead [26]. These experiments have motivated the model that we analyze in detail within the present work.

Another motivation for our work is the extension of the CPS analysis to the finite bias regime. While most theoretical analysis and measurements concerning CPS have been restricted to the linear regime where the applied bias voltage is negligible compared to all

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energy scales (temperature, charging energy and the superconducting gap), the applied bias to each lead is an additional parameter to play with, which can be easily controlled experimentally. It has also been argued [3] that a finite bias voltage together with an antisymmetric detuning of the dot resonances can be used to increase the CPS efficiency by enhancing the non-local with respect to the local processes. Again, the validity of these arguments for the actual experimental geometries and parameter regimes should be tested.

The rest of the paper is organized as follows: in Section 2 we present the 3-sites model used to describe the interference effects in a Cooper pair splitter (see Ref. [26]). Then, in Section 3, we introduce the Keldysh formalism used to calculate the conductance. Furthermore, we explain the self-consistent approach used here to calculate the current in the presence of Coulomb interactions. In Section 4 we present the conductance results in the linear regime, and we analyze the evolution of the conductance profiles varying the rest of the model parameters in two different limits: one in which the central system is fully hybridized and another in which it is partially hybridized. Finally in Section 5, we show some representative conductance calculations in the non-linear regime. We focus our attention on the case in which the energy levels of the dots are tuned symmetrically and antisymmetrically. Furthermore, we establish a hierarchy of the 3-sites model parameters to obtain the optimal conditions to enhance the CPS efficiency.

2. Description of the 3-sites model

In the recent experiments of Ref. [26] the conductance through the QDs exhibited Fano-like resonances when operated in the Cooper pair splitting mode. A qualitative description of the experimental results requires to go beyond previous incoherent models with independent transport mechanisms only coupled by the QD dynamics [16,18] or the simpler coherent two-dot models considered in Refs. [17,27,28]. The 3-sites model introduced in Ref. [26] is schematically depicted in Fig. 1.

The system can be decomposed in two parts: a coherent central region and the electronic reservoirs. The coherent part is given by three discrete spin levels coupled coherently. We will assume that the part of the wire that separates the quantum dots can be effectively described by a single discrete level. This approximation can be done when the energy separation between the levels of the central part ($\delta\epsilon$) is much higher than the coherent tunnel between the central part and the dots, i.e. $\delta\epsilon \gg t_{im}$. We will assume that the Coulomb interaction in the central part is negligible because it is screened by the nearby superconducting electrode. Thus, we can write the central part by the Hamiltonian

$$H_{3s} = \sum_{i,\sigma} \epsilon_{i,\sigma}\hat{n}_{i,\sigma} + U_i\hat{n}_{i\uparrow}\hat{n}_{i\downarrow} + \sum_{i\neq m,\sigma} t_{im}\, d^{\dagger}_{i,\sigma}d_{m,\sigma} + \text{h. c.} \quad (1)$$

with $i = 1, m, 2$, and $d^{(\dagger)}_{i,\sigma}$ destroys (creates) an electron with σ-spin in the site i, $\hat{n}_{i,\sigma}$ is the number operator, ϵ_i are the site energies, t_{im} are the tunnel coupling amplitudes between the site i and the central site, and U_i are the Coulomb interaction constants. As we mentioned above we set $U_m=0$. It has been shown experimentally [16,26] that the energies $\epsilon_{i,\sigma}$ and the tunnel couplings $t_{i,m}$ can be tunned by several nearby gate electrodes. We describe the normal leads $l=1,2$ using non-interacting (normal) Fermi liquids, described by the Hamiltonian

$$H_{lead-l} = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} a^{\dagger}_{l\mathbf{k}\sigma}a_{l\mathbf{k}\sigma}, \quad (2)$$

where $a^{(\dagger)}_{l\mathbf{k}\sigma}$ is the annihilation (creation) operator of an electron in the l-lead. On the other hand, the superconducting lead is described by the BCS-Hamiltonian

$$H_S = \sum_{\mathbf{k},\sigma} \xi_k c^{\dagger}_{\mathbf{k}\sigma}c_{\mathbf{k}\sigma} - \sum_{\mathbf{k}} \left(\Delta_k c^{\dagger}_{\mathbf{k}\uparrow}c^{\dagger}_{-\mathbf{k}\downarrow} + \text{h. c.}\right), \quad (3)$$

where $c^{\dagger}_{\mathbf{k},\sigma}$ creates a fermion with k momentum and spin $\sigma = \uparrow, \downarrow$. The coupling to the leads is given by

$$H_\tau = \sum_{i,\mathbf{k},\sigma} \left(t_i d^{\dagger}_{i,\sigma}a_{i,\mathbf{k},\sigma} + t_m d^{\dagger}_{i,\sigma}c_{\mathbf{k},\sigma} + \text{h. c.}\right). \quad (4)$$

Here, tunneling from the dot to the state **k** in the lead is described by the tunel amplitude $t_{1,m,2}$. We assume that the **k**-dependence of the tunel amplitudes can be neglected. These tunel amplitudes lead to the tunel rates defined by $\gamma_i = \pi\rho_i t_i^2$, being ρ_i the density of states of the ith-lead.

3. Transport properties

The mean current through the j-lead is defined as

$$I_j = i\frac{e}{\hbar}\sum_{k,\sigma} t_j\left(\langle a^{\dagger}_{k,j,\sigma}d_{j,\sigma}\rangle - \langle d^{\dagger}_{j,\sigma}a_{k,j,\sigma}\rangle\right). \quad (5)$$

In order to calculate the current, it is convenient to express this quantity in terms of Keldysh Green's functions (GFs)

$$I_j = \frac{e}{\hbar}\int\frac{d\omega}{2\pi}\,\text{Tr}\left\{\hat{\tau}_j\left(\hat{G}^{+-}_{DL}(\omega) - \hat{G}^{+-}_{LD}(\omega)\right)\sigma_z\right\}, \quad (6)$$

where $\hat{\tau}_j = t_j\sigma_z P_j$, and P_j projects on the j-subspace, with $j = 1, m, 2$. In this expression $\hat{G}^{\alpha\beta}_{DL}(\omega)$, with $\alpha, \beta = +, -$, is the Fourier transform

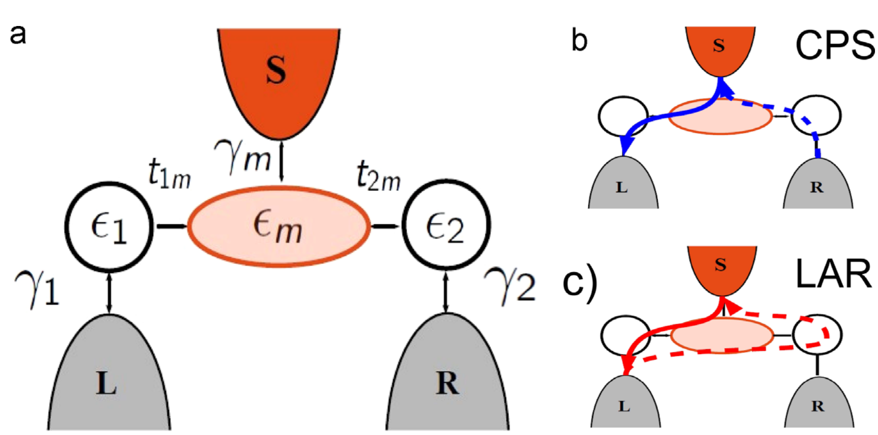

Fig. 1. Panel a: we show the schematic representation of the 3-sites model, with the model parameters. Panels b and c show the electronic (solid line) and the hole (dashed line) paths that the Cooper pairs may take depending on the process, CPS and local Andreev reflexion (LAR), respectively.

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