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Transport properties of ferromagnet-d-wave superconductor ferromagnet double junctions

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Abstract

We investigate transport properties of a trilayer made of a d-wave superconductor connected to two ferromagnetic electrodes. Using Keldysh formalism we show that crossed Andreev reflection and elastic cotunnelling exist also with d-wave superconductors. Their properties are controlled by the existence of zero-energy states due to the anisotropy of the d-wave pair potential.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Transport in superconductor–ferromagnetic hybrid systems has received great attention in the last few years due to the progress in nanotechnology which made possible the fabrication and characterization of various heterostructures [1–5].

During the last few years phase-sensitive tests have shown that the order parameter in cuprate superconductors is predominantly of a d-wave symmetry [6–9]. In d-wave superconductors the zero bias conductance peak (ZBCP) observed in the tunnelling spectra results from zero-energy states (ZES) that are formed due to the sign change of the order parameter in orthogonal directions in k space. The ZBCP depends on the orientation of the surface and does not exist for s-wave superconductors [10–15].

In d-wave superconductor ferromagnet junctions the ZBCP is suppressed by the increase of the exchange field of the ferromagnet [16–19]. This can be understood from the fact that increasing spin polarization in the ferromagnetic electrode suppresses Andreev reflection and therefore suppresses the ZBCP, which is due to the fact that the transmitted quasiparticles are subject to the sign change of the order parameter. Moreover, in ferromagnet/d-wave superconductor/ferromagnet double junctions, the quasiparticle current is enhanced compared

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to the normal state because of ZES [20]. Very recently a circuit theory of unconventional superconductors has been presented [21].

Keldysh formalism has been applied to normal metal-s-wave superconductor junctions [22] and in multiterminal configurations where one s-wave superconductor is connected to several ferromagnetic electrodes [23–27]. The conductance of multiterminal hybrid structures is due to two types of processes:

- (i) crossed Andreev reflection in which Cooper pairs are extracted from the superconductor. The spin-up electron of the Cooper pair tunnels in a spin-up ferromagnet and the spin-down electron tunnels in a spin-down ferromagnet;
- (ii) elastic cotunnelling in which a spin- σ electron from one electrode is transferred as a spin- σ electron in another electrode.

The purpose of the present work is to investigate transport properties of a ferromagnet/d-wave superconductor/ferromagnet double junction via Keldysh formalism. We find that crossed Andreev reflection and elastic cotunnelling are influenced by the d-wave symmetry of the order parameter in the sense that both processes are mediated by ZES formed for certain orientations of the d-wave order parameter.

This paper is organized as follows. In section 2 we introduce surface Green functions. In sections 3 and 4 we describe transport theory and present the results. Concluding remarks are given in the last section.

2. Surface Green functions

The quasiparticle properties of d-wave superconductors are influenced by interfaces and surfaces: due to the anisotropy of the order parameter the quasiparticles that are reflected from the surface or transmitted through the interface are subject to the sign change of the order parameter. Therefore surface properties are different from bulk properties and we use in transport theory the surface Green functions that take into account the contributions of all waves that propagate close to the surface [28, 29]. Green function techniques have been used to calculate the conductance of d-wave superconductors near impurities [30, 31]. Also surface quasiclassical Green functions have been used in the calculation of the Josephson current between d-wave superconductors [32–35]. In our case this Green function is inserted in a three-node ballistic circuit that is used to describe the transport properties of the hybrid structure containing a d-wave superconductor.

The form of the local retarded surface Green function matrix for a d-wave superconductor is the following, for smooth interface, with momentum conservation in the plane of the interface:

$$\hat{g}^{xx,R}(E, \theta) = \begin{pmatrix} g & f \\ \bar{f} & g \end{pmatrix}. \quad (1)$$

It obeys the Eilenberger equation [36] and satisfies the normalization condition $\hat{g}^2 = 1$. It can be parametrized as follows:

$$g = \frac{1 - ab}{1 + ab}, \quad f = \frac{2a}{1 + ab}, \quad \bar{f} = \frac{2b}{1 + ab}, \quad (2)$$

where the $a(x, \theta)$ and $b(x, \theta)$ satisfy the Riccati equations [37]

$$\hbar v_F \cos(\theta) \frac{da}{dx} - 2iEa + \Delta^* a^2 - \Delta = 0 \quad (3)$$

$$\hbar v_F \cos(\theta) \frac{db}{dx} + 2iEb - \Delta b^2 + \Delta^* = 0, \quad (4)$$

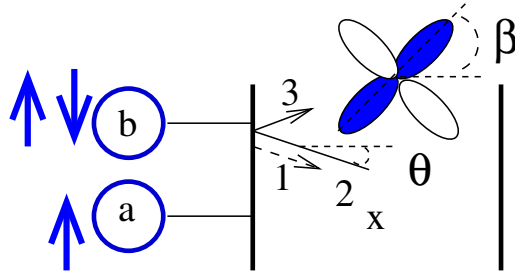


Figure 1. The geometry of the junction involving the d-wave superconductor and two ferromagnetic electrodes of full spin polarization as indicated in the figure by up and down arrows. The orientation of the magnetization of the ferromagnetic electrodes can be parallel or antiparallel. The excitation at x gives rise to several outgoing trajectories θ . In the figure only one of these trajectories is presented. β is the orientation of the d-wave order parameter shown also in the figure with respect to the direction x . The electron like quasiparticle 2 is reflected as a hole like quasiparticle 1 and an electron like quasiparticle 3. The labels a and b in the figure correspond to the electrodes a and b , respectively.

where v_F is the Fermi velocity. We assume for simplicity that the gap function Δ is constant. Then the spatially independent a, b functions are found as

$$a(0, \theta) = \frac{i(E - \epsilon_+ \operatorname{sgn} E)}{\Delta_+(\theta)} \quad (5)$$

$$b(0, \theta) = \frac{i(E - \epsilon_- \operatorname{sgn} E)}{\Delta_-^*(\theta)}, \quad (6)$$

where θ is the angle between the normal to the interface and the trajectory of the quasiparticle, $\Delta_+(\theta) = \Delta(\theta)$ ($\Delta_-(\theta) = \Delta(\pi - \theta)$) is the pair potential experienced by the quasiparticle along the trajectory θ ($\pi - \theta$) and $\epsilon_{\pm} = \sqrt{E^2 - \Delta_{\pm}^2(\theta)}$. In the case of $d_{x^2-y^2}$ -wave superconductor

$$\Delta(\theta) = \Delta_0 \cos[2(\theta - \beta)], \quad (7)$$

where β denotes the angle between the normal to the interface and the x axis of the crystal. Then g and f Green functions are calculated from equations (2).

In fact, in the transport equations we should average over the Fermi surface in order to include the details of the order parameter symmetry. We have calculated the density of states averaged over the Fermi surface $\rho_g^{xx} = \langle \operatorname{Re} g^{xx,R}(E, \theta,) \rangle$. In figure 2 the density of states ρ_g^{xx} is plotted for different orientations of the order parameter $\beta = 0$ and $\pi/4$. A ZEP is formed for $\beta = \pi/4$ due to sign change of the pair potential. A small imaginary or effectively dissipative term ($\delta = 0.01$) was added in the energy in order to make this peak visible.

In order to study the effect of the angular dependence of the transmission coefficient we calculate the Fermi surface averaged density of states $\rho_g^{xx,D}$ defined as

$$\rho_g^{xx,D} = \int_{-\pi/2}^{\pi/2} d\theta D(\theta) (\operatorname{Re} g^{xx,R}(E, \theta)),$$

where $D(\theta) = \sin^2(\theta)$ [38]. We see that the density of states is suppressed when this coefficient is included in the calculation (see figure 2). However, we do not expect the transport properties to change qualitatively compared to the case where the transmission is independent of the angle (see figure 2). In the following we use $D(\theta) = 1$. Transport can probe the symmetry of the d-wave order parameter if we consider the orientation of the d-wave order parameter β as a variable.

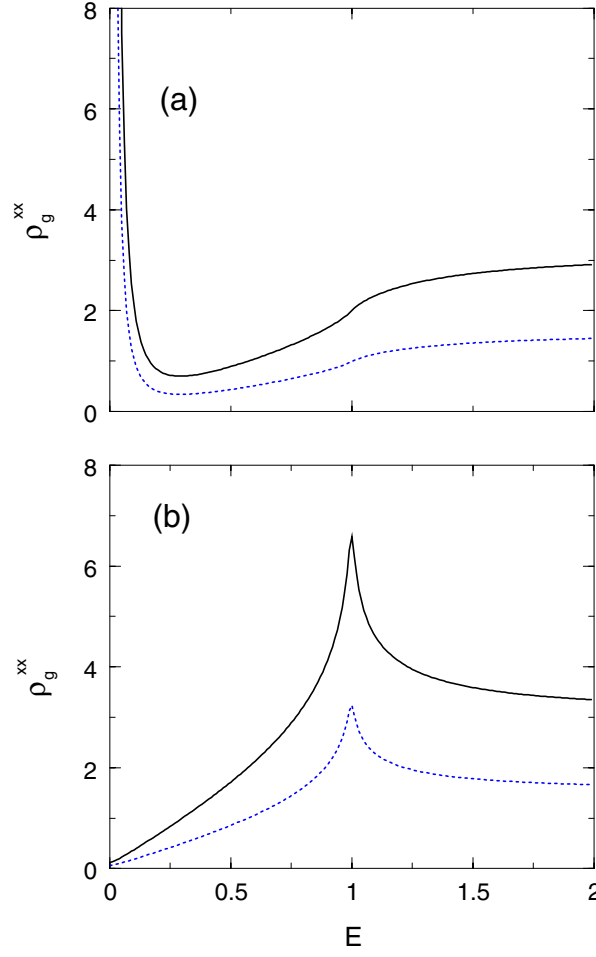


Figure 2. (a) The full curve represents averaging over the Fermi surface density of states ρ_g^{xx} for $\beta = \pi/4$. A well defined ZEP exists. We have put a small imaginary part $\delta = 0.01$ in the energy ω of the Green function. The broken curve represents the ρ_g^{xx} averaged over the Fermi surface with an angular depended transmission coefficient. (b) The same as in (a) but for $\beta = 0$.

The ferromagnetic electrodes are described by the Green function

$$\hat{g}^{R,A} = \mp i\pi \begin{bmatrix} \rho_{1,1} & 0 \\ 0 & \rho_{2,2} \end{bmatrix}, \quad (8)$$

where $\rho_{1,1}$ and $\rho_{2,2}$ are, respectively, the spin-up and spin-down densities of states.

3. Transport theory

We use a Green function method to describe transport in a system made of two ferromagnetic electrodes connected to a d-wave superconductor (see figure 1). We first solve the Dyson equation which, in a 2×2 Nambu representation, has the following form for the advanced ($\hat{G}^A$) and retarded ($\hat{G}^R$) Green functions [39, 40]:

$$\hat{G}^{R,A} = \hat{g}^{R,A} + \hat{g}^{R,A} \otimes \hat{\Sigma} \otimes \hat{G}^{R,A}. \quad (9)$$

$\hat{\Sigma}$ is the self-energy that contains the coupling of the tunnel Hamiltonian. The tunnel Hamiltonian associated to figure 1 takes the form

$$\mathcal{W} = \sum_{\sigma} [t_{a,x} c_a^{\dagger} c_x + t_{x,a} c_x^{\dagger} c_a + t_{b,x} c_b^{\dagger} c_x + t_{x,b} c_x^{\dagger} c_b].$$

$\hat{g}$ in equation (9) is the Green functions of the disconnected system (i.e. with $\hat{\Sigma} = 0$). The symbol $\otimes$ includes a summation over the nodes of the network and a convolution over time arguments. Since we consider stationary transport this conclusion is transformed into a product by Fourier transform. $\hat{G}$ is the Green functions of the connected system (i.e. with $\hat{\Sigma} \neq 0$). The Keldysh component is given by [40]

$$\hat{G}^{+, -} = [\hat{I} + \hat{G}^R \otimes \hat{\Sigma}] \otimes \hat{g}^{+, -} \otimes [\hat{I} + \hat{\Sigma} \otimes \hat{G}^A]. \quad (10)$$

The current is related to the Keldysh Green function [40] by the relation

$$I_{a,x} = \frac{e}{h} \int d\omega [\hat{t}_{a,x} \hat{G}_{x,a}^{+, -} - \hat{t}_{x,a} \hat{G}_{a,x}^{+, -}] \sigma^z. \quad (11)$$

At this stage of the calculation no explicit angular form of the tunnelling matrix elements was assumed. The effect of the angular dependence of the transmission coefficient in the transport properties was already discussed in the previous section. The elements of the differential conductance matrix that we want to calculate are given by

$$\mathcal{G}_{a_i, a_j}(V_a, V_b) = \frac{\partial I_{a_i}}{\partial V_{a_j}}(V_a, V_b). \quad (12)$$

The principle of the calculation of $\mathcal{G}_{a_i, a_j}(V_a, V_b)$ is similar to the s-wave case [23]. Depending on the orientation of the magnetizations in the two ferromagnetic electrodes we can distinguish the following cases.

3.1. Antiparallel magnetizations

If the two ferromagnetic electrodes have an antiparallel spin orientation we find for the elements of the conductance matrix

$$\mathcal{G}_{a,a} = +4\pi^2 |t_{a,x}|^2 \rho_{1,1}^{a,a} \rho_g^{x,x} \times \frac{1}{\mathcal{D}^A \mathcal{D}^R} [1 - |t_{b,x}|^2 g_{2,2}^{b,b,A} g^{x,x,A}] [1 - |t_{b,x}|^2 g_{2,2}^{b,b,R} g^{x,x,R}] \quad (13)$$

$$- 2i\pi |t_{a,x}|^2 |t_{b,x}|^2 \rho_{1,1}^{a,a} g_{2,2}^{b,b,A} \times \frac{1}{\mathcal{D}^A \mathcal{D}^R} f^{x,x,A} f^{x,x,A} [1 - |t_{b,x}|^2 g_{2,2}^{b,b,R} g^{x,x,R}] \quad (14)$$

$$+ 2i\pi |t_{a,x}|^2 |t_{b,x}|^2 \rho_{1,1}^{a,a} g_{2,2}^{b,b,R} \times \frac{1}{\mathcal{D}^A \mathcal{D}^R} f^{x,x,R} f^{x,x,R} [1 - |t_{b,x}|^2 g_{2,2}^{b,b,A} g^{x,x,A}], \quad (15)$$

and

$$\mathcal{G}_{a,b} = -4\pi^2 |t_{a,x}|^2 |t_{b,x}|^2 \frac{1}{\mathcal{D}^A \mathcal{D}^R} \rho_{1,1}^{a,a} \rho_{2,2}^{b,b} f^{x,x,R} f^{x,x,A}. \quad (16)$$

The expression of the determinant $\mathcal{D}_R$ is the following:

$$\mathcal{D}_R = 1 - |t_{b,x}|^2 g_{2,2}^{b,b,R} g^{x,x,R} - |t_{a,x}|^2 g_{1,1}^{a,a,R} g^{x,x,R} + |t_{b,x}|^2 |t_{a,x}|^2 g_{1,1}^{a,a,R} g_{2,2}^{b,b,R} (g^{x,x,R^2} - f^{x,x,R^2}), \quad (17)$$

and a similar expression holds for $\mathcal{D}_A$. $\rho_{1,1}^{a,a}, \rho_{2,2}^{b,b}, \rho_g^{x,x}$ are the density of states of electrodes a, b and the superconductor, respectively. Contrary to the s-wave case $\rho_g^{x,x}$ is not zero for $E < \Delta_0$ and the term equation (13) contributes also to the quasiparticle current even below the superconducting gap. In the s-wave case there are simple relations between the conductance matrix elements (for instance $\mathcal{G}_{a,a} = \mathcal{G}_{a,b}$), which means that the transport is mediated only by Cooper pairs [23]. In the d-wave case such relations are no longer valid because of the quasiparticle tunnelling. Also, depending on the trajectory angle θ the different terms contribute to the Andreev current and the quasiparticle current. Moreover in the present case the propagators $f^{x,x,A,(R)}, g^{x,x,A,(R)}$ have a d-wave symmetry. In equation (16) $\mathcal{G}_{ab}$ depends on $f^{x,x,R} f^{x,x,A}$ and therefore the corresponding matrix element is associated with crossed Andreev reflections.

3.2. Parallel magnetizations

If the electrodes have a parallel spin orientation, we find

$$\mathcal{G}_{a,a} = +4\pi^2 |t_{a,x}|^2 \rho_{1,1}^{a,a} \rho_g^{x,x} \quad (18)$$

$$\begin{aligned} & \times \frac{1}{\mathcal{D}^A \mathcal{D}^R} [1 - |t_{b,x}|^2 g_{1,1}^{b,b,A} g^{x,x,A}] [1 - |t_{b,x}|^2 g_{1,1}^{b,b,R} g^{x,x,R}] \\ & - 2i\pi |t_{a,x}|^2 |t_{b,x}|^2 \rho_{1,1}^{a,a} g_{1,1}^{b,b,A} \\ & \times \frac{1}{\mathcal{D}^A \mathcal{D}^R} g^{x,x,A} g^{x,x,A} [1 - |t_{b,x}|^2 g_{1,1}^{b,b,R} g^{x,x,R}] \\ & + 2i\pi |t_{a,x}|^2 |t_{b,x}|^2 \rho_{1,1}^{a,a} g_{1,1}^{b,b,R} \end{aligned} \quad (19)$$

$$\times \frac{1}{\mathcal{D}^A \mathcal{D}^R} g^{x,x,R} g^{x,x,R} [1 - |t_{b,x}|^2 g_{1,1}^{b,b,A} g^{x,x,A}], \quad (20)$$

and

$$\mathcal{G}_{a,b} = -4\pi^2 |t_{a,x}|^2 |t_{b,x}|^2 \frac{1}{\mathcal{D}^A \mathcal{D}^R} \rho_{1,1}^{a,a} \rho_{1,1}^{b,b} g^{x,x,R} g^{x,x,A}. \quad (21)$$

The determinant $\mathcal{D}_R$ is given by

$$\mathcal{D}_R = 1 - |t_{b,x}|^2 g_{2,2}^{b,b,R} g^{x,x,R} - |t_{a,x}|^2 g_{1,1}^{a,a,R} g^{x,x,R}. \quad (22)$$

In equation (21) $\mathcal{G}_{ab}$ depends on $g^{x,x,R} g^{x,x,A}$ and therefore the corresponding matrix element is associated to cotunnelling processes. The elements $\mathcal{G}_{b,a}, \mathcal{G}_{b,b}$ of the conductance matrix which describe transport through electrode *b* are derived from the corresponding expressions for $\mathcal{G}_{a,a}, \mathcal{G}_{a,b}$ by the substitution $a \leftrightarrow b$ for the parallel alignment. For the antiparallel alignment the following set of substitutions should be made: $g_{2,2}^{b,b,A,(R)} \leftrightarrow g_{1,1}^{a,a,A,(R)}, t_{a,x} \leftrightarrow t_{b,x}, \mu_a \leftrightarrow \mu_b$.

4. Results

4.1. Antiparallel magnetizations

We consider the ferromagnet/d-wave superconductor/ferromagnet double junction shown in figure 1. For the antiparallel alignment of the magnetizations in the two ferromagnetic electrodes the conductance depends on the orientation β as well as on the transparencies of the interfaces $t_{a,x}, t_{b,x}$. For $\beta = \pi/4$ (see figure 3(a)) the surface Green function has a pole at $E = 0$ and the conductance (both $\mathcal{G}^{aa}$ and $\mathcal{G}^{ab}$) acquires a ZEP. The conductance $\mathcal{G}^{aa}$ above the gap depends only on the density of states ρ_g^{xx} and for large energies it has a finite value. $\mathcal{G}^{ab}$ depends only on crossed Andreev reflection processes and is zero above the gap.

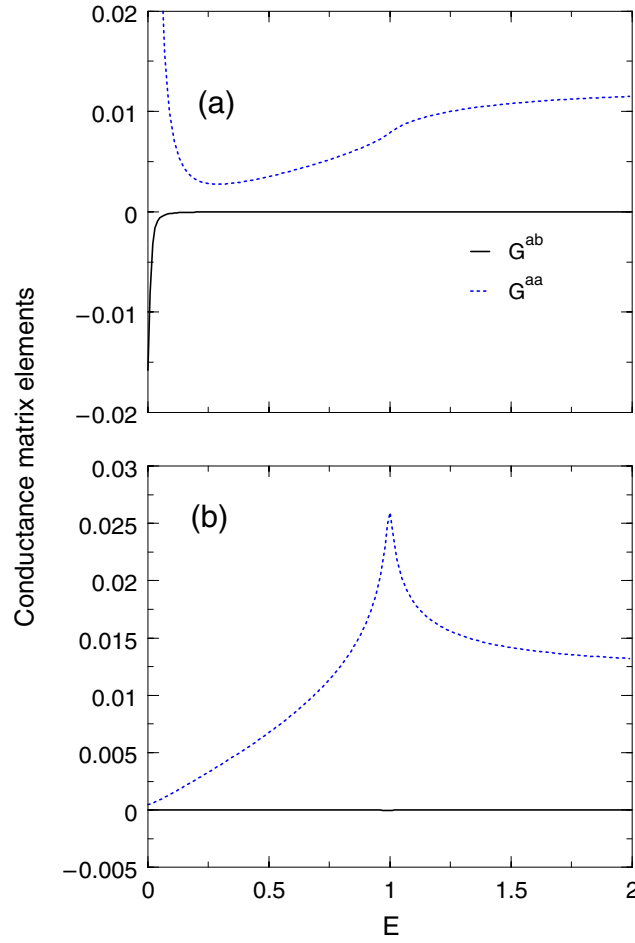


Figure 3. Conductance $\mathcal{G}^{ab}$, $\mathcal{G}^{aa}$ for the antiparallel spin orientation of the ferromagnetic electrodes, as a function of E (in units of Δ_0) for different orientations of the d-wave order parameter: (a) $\beta = \pi/4$, (b) $\beta = 0$. The hopping element is 0.01.

For $\beta = 0$ (see figure 3(b)) similarly to the s-wave case no ZES are formed at the interface and both $\mathcal{G}^{aa}$ and $\mathcal{G}^{ab}$ take relatively small values. However the line shape of the conductance is V and is determined by ρ_g^{xx} . In the s-wave case the line shape of the conductance is U and a peak just below the energy gap exists [23]. In this sense the results for s-wave are qualitatively different than for d-wave with $\beta = 0$ due to the anisotropy of the d-wave order parameter.

To summarize, transport for antiparallel magnetizations is due to crossed Andreev reflection in which a spin-up electron from one electrode is transferred as a spin-down hole in the other electrode, and is influenced by ZES that are formed at the interface due to the sign change of the order parameter. The enhancement of the quasiparticle current at $E = 0$ for $\beta = \pi/4$ in the ferromagnet/d-wave superconductor/ferromagnet double junction has also been found recently using the scattering approach [20].

4.2. Parallel magnetizations

The results concerning the ZES are not modified qualitatively when the orientation of the magnetizations is parallel (see figure 1). The conductance above the gap is determined mainly

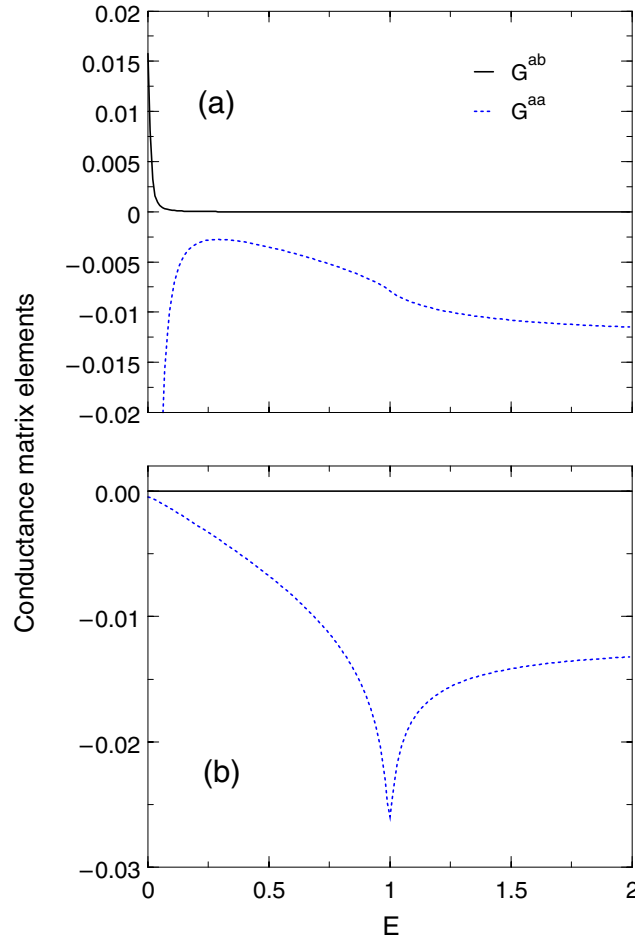


Figure 4. Conductance G^{ab} , G^{aa} for the parallel spin orientation of the ferromagnetic electrodes, as a function of E (in units of Δ_0) for different orientations of the d-wave order parameter: (a) $\beta = \pi/4$, (b) $\beta = 0$. The hopping element is 0.01.

by ρ_g^{xx} . For $\beta = 0$ (see figure 4(b)) the results are similar to the case for the antiparallel alignment.

To summarize, transport for parallel magnetizations is due to elastic cotunnelling in which an electron from electrode a is transmitted as an electron in electrode b, and is influenced by the ZES that are formed for certain orientations of the d-wave order parameter. For $\beta = \pi/4$ the interface at large values of the barrier strength becomes transparent due to bound states formed because of the sign change of the order parameter in orthogonal directions in k -space. This property does not exist for s-wave superconductors.

5. Relevance to experiment

Multiterminal superconductor ferromagnet structures can be used to test the specific physics associated with the symmetry of a d-wave superconducting order parameter, because transport through the ferromagnetic electrodes has a strong directional dependence. The orientation of the electrodes can be used to probe the symmetry of the order parameter.

The line shape of the conductance spectra is V-like which is a fingerprint of d-wave systems. This has already been tested in experiments [11].

Moreover we used a theoretical description that is valid not only in the tunnel regime but also for large interface transparencies. We have found a ZEP in the conductances $\mathcal{G}_{a,b}$, $\mathcal{G}_{a,a}$ in the tunnel regime in the two cases of parallel and antiparallel spin orientations, for the $\beta = \pi/4$ orientation.

6. Conclusions

Using a Keldysh formalism we have shown that in the ferromagnet/d-wave superconductor/ferromagnet double junction, transport is due to crossed Andreev reflection and elastic cotunnelling and is mediated by ZES that are formed at the interface due to the sign change of the order parameter.

We have used the local surface Green function given by equation (1) and we find no particular relation between the conductances in the parallel and antiparallel alignments. In the s-wave case and for extended contacts it is possible to show that the average current due to crossed Andreev reflection in the antiparallel alignment is equal to the average current due to elastic cotunnelling in the parallel alignment [23, 26]. Discussing multichannel effects for d-wave superconductors is left as an important open question.

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