Bilayer junction with chiral $p$-wave superconductor and itinerant ferromagnet: role of distinct mechanisms for the generation of spin imbalance

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Abstract. We have investigated the behavior of a bilayer junction made of a $p$-wave chiral superconductor and an itinerant ferromagnet, under the assumption of high barrier transparency and in the clean limit. For the ferromagnet two distinct mechanisms for the generation of spin imbalance have been taken into account: a Stoner-like one originated by the presence of a constant exchange field, and a mass asymmetry one generated by a narrowing of the bandwidth of the minority spin carriers with respect to the majority ones. By solving the Bogoliubov-de Gennes equations, we show that the two mechanisms for ferromagnetism lead to different features as concerns the formation at the interface of dominant and sub-dominant superconducting components as well as their propagation in the ferromagnetic side.

1. Introduction
The rich physics characterizing the boundary regions between superconducting (S) and ferromagnetic (F) materials has recently been probed in a series of important experiments. Their relevance stems not only from the verification of earlier theoretical predictions, but also from the possibility to provide deep insight into the coexistence of the two types of order, also inspiring new ideas in the emerging field of the spin electronics [1].

In the boundary region, typical correlations known from the proximity effect in normal metals are induced, but superimposed to the usual decay a peculiar oscillating behavior manifests itself, with a characteristic frequency related to the degree of magnetization in the F layer. It is well-known that the ferromagnet acts at the interface as a source of spin polarization for Cooper pairs in the superconductor. This may result in a boundary layer with coexisting singlet and triplet amplitudes, extending over a distance of the order of the coherence length into the superconductor. Conversely, in the F side there is a penetration of the pair wave function and the penetration depth of the superconducting condensate is considerably reduced by the pair breaking effect due to the exchange field tending to align spins in the Cooper pair. The relative shift of the electronic bands of the two spin species makes the wavevectors of two paired electrons different, so that the pair acquires a finite momentum and correspondingly its wave function oscillates in space in the F layer.

In this paper we analyze some aspects of the proximity phenomena between an unconventional superconductor and a ferromagnet, in the case where the magnetization in the F side is due either to a standard Stoner-like mechanism associated with the presence of an exchange field,
or to an asymmetry between the hopping amplitudes for electrons with opposite spins, which produces a relative change in the bandwidths for the two spin species. Moreover, we consider a superconductor with p-wave character with broken parity and broken time reversal symmetry. We find that the presence of a finite magnetization in the F side leads to a pairing amplitude in the s- and in the d-wave channel at the interface. By suitably tuning the amplitude of the exchange field and that of the hopping asymmetry ratio it is possible to control the leaking distance of these induced pairing components and the profile of their amplitude [2]. It is worth noticing that this analysis may turn out to be relevant, and possibly experimentally probed, when referred to recent studies on the eutectic system Sr$_2$RuO$_4$-Sr$_3$Ru$_2$O$_7$, where an internal anomalous proximity effect is induced in Sr$_3$Ru$_2$O$_7$ by Sr$_2$RuO$_4$ p-wave superconducting macrodromains [3].

The outline of the paper is as follows. In Sec. 2 we introduce the model Hamiltonian and briefly describe the technique of solution. In Sec. 3 we present the results for the case of an itinerant ferromagnet of the Stoner type or of the spin-dependent bandwidth type, in contact with a chiral superconductor through an interface barrier; we also illustrate similarities and differences in the results obtained with the two kinds of ferromagnetic mechanism. Finally, Sec. 4 is devoted to the conclusions.

2. The model Hamiltonian

The system under study is constituted by a two-dimensional bilayer with a ferromagnetic and a superconducting layer on the left and the right side, respectively, separated by a highly transparent interface. The microscopic model adopted here is an extended version of the Hubbard model on a square lattice [2], that we investigate at zero temperature within the Hartree-Fock approximation to describe magnetism and superconductivity.

The explicit form of the Hamiltonians $H_F$ and $H_S$ for the F and the S layer is

$$H_A = -\sum_{(ij),\sigma} t_{A\sigma} (c_{i\sigma}^\dagger c_{j\sigma} + \text{h.c.}) + \sum_i U_A n_{i\uparrow} n_{i\downarrow} + \sum_{(ij)} V_A (n_{i\uparrow} n_{j\downarrow} + n_{i\downarrow} n_{j\uparrow}) - \mu \sum_{i,\sigma} n_{i\sigma} - \hbar A \sum_{i,\sigma} (n_{i\uparrow} - n_{i\downarrow}) \quad A = F, S$$

(1)

where $c_{i\sigma}$ is the annihilation operator of an electron with spin $\sigma$ at site $i \equiv (i_x, i_y)$, $n_{i\sigma} = c_{i\sigma}^\dagger c_{i\sigma}$ is the corresponding number operator, and $\langle i,j \rangle$ denotes nearest-neighbor sites. The magnetic field, which in this context can be equivalently seen either as an external or an intrinsic one, is assumed to be non-vanishing only in the F side ($h_F \neq 0, h_S = 0$), while for the hopping amplitudes we choose $t_{S\uparrow} = t_{S\downarrow} \equiv t_S$. Moreover, we also assume $t_{F\uparrow} \neq t_{F\downarrow}$ when the spin-dependent mass asymmetry mechanism for ferromagnetism is considered. Finally, $\mu$ is the common chemical potential, the parameter $U_A (A = F, S)$ represents the on-site repulsion for the A side ($U_F, U_S > 0$), whereas the nearest neighbour attraction $V_A$ is chosen to be non-vanishing only on the S side ($V_F = 0, V_S < 0$).

The coupling between the two sides of the junction is ensured by a term $H_T$, describing the transmission of electrons at the interface. It is given by

$$H_T = -t_T \sum_{(lm)\sigma} (c_{i_{\sigma}^\dagger} c_{m\sigma} + \text{h.c.}) \quad ,$$

(2)

where $l$ ($m$) denotes sites at the surface for the left (right) layer. Here we assume that the position of the interface corresponds to the coordinate $i_x = 0$ (all the lengths are in units of the interatomic lattice spacing $a$).
The interaction terms in $H_F$ and $H_S$ are decoupled by means of a standard Hartree-Fock approximation such that the magnetic and the pairing channels originate from the on-site and the intersite interactions, respectively. To determine the self-consistent solution of the mean-field problem, we follow a standard iterating procedure. We start with an initial set of values for the order parameters, hence, we solve the Bogoliubov-de Gennes equations, and finally, we redetermine the amplitudes for the order parameters, proceeding by iteration until the required accuracy is reached.

3. Results for chiral p-wave

![Figure 1](image_url)

Figure 1. Variation close to the interface of the dominant chiral $p$-wave superconducting order parameter. The left panels show the real part for the $p_x$ symmetry and the imaginary part for the $p_y$ one as functions of the exchange field. In the right panels the same quantities are reported as functions of the spin bandwidth asymmetry $1-t_F^-/t_F^+$.  

We discuss the outcome of the proximity within the F/S bilayer assuming a value of the chemical potential equal to $\mu = 1.6$, with $U_F = 2$, $V_F = 0$ for the F side, and $U_S = 1.5$, $V_S = -2.5$ for the S side, all the energies being expressed in units of $t_S^+ = t_S^- = t_F^+ = t_T = 1$. We notice that for the adopted choice of $\mu$ and the other physical parameters, the S side exhibits a bulk OP with triplet $p_x + ip_y$ symmetry [4].

In Fig. 1 we report the results for the triplet order parameter components near the interface as functions of both the exchange field and the spin bandwidth asymmetry. Our main findings can be summarized in the following way. When the Stoner mechanism is considered and the exchange field is increased, the real part of the $p_x$ order parameter and the imaginary part of the $p_y$ one both decrease in the F side (site -1), eventually vanishing. A different behavior is found in the S side (site 1): whereas the real part of $p_x$ increases, the imaginary part of $p_y$ decreases when $h$ increases. Looking at the effect introduced by the spin bandwidth asymmetry, we find in the F side a similar behavior, but in the S side the real part of $p_x$ and the imaginary part of $p_y$ stay almost constant.

For the case under consideration of bulk chiral $p$-wave symmetry, the presence of a finite magnetization in the F side leads to a finite pairing amplitude at the interface in the $s$- as well as in the $d$-wave channel. We find a behavior for the real part of the $s$-wave component which is qualitatively the same regardless of whether the spin polarization is due to the exchange field or to the asymmetry in the spin bandwidth. From Fig. 2, we see that while in the F side it first grows reaching a maximum and then tends to zero at high field or large asymmetry, in the
S side its absolute value monotonically increases as the system gets more and more polarized. The situation is different for the real part of d-wave order parameter. In the F side it tends to vanish after passing through a minimum in the Stoner case as well as in the spin-dependent mass case. On the other hand, in the S side while the exchange field produces a smooth increase of the order parameter, the reduction of the minority spin bandwidth leads to a non-monotonic behavior accompanied by a change in sign. For completeness, we also notice that the imaginary parts of both the s- and the d-wave components, not shown here for brevity, are appreciable at the interface but decay very quickly as one moves away from it, in a way which is essentially insensitive to the degree of magnetization in the F layer.

![Figure 2](image)

Figure 2. Variation close to the interface of the sub-dominant superconducting components. The left panels show the real part of the s-wave and the d-wave order parameters as function of the exchange field, while in the right panels the same quantities are reported as functions of the spin bandwidth asymmetry $1-t_{F↓}/t_{F↑}$.

4. Conclusions
We have investigated the behavior of a bilayer junction made of a chiral $p$-wave superconductor and an itinerant ferromagnet, considering two distinct mechanisms for the generation of spin imbalance, that is, a Stoner-like one originated by the presence of a constant exchange field, and a mass asymmetry one generated by a narrowing of the bandwidth of the minority spin carriers with respect to the majority ones. In particular, the real and the imaginary parts of the $p$-wave components behave differently for the two types of ferromagnetism considered here: in the exchange field case the $p_x$ ($p_y$) component grows (decreases), while in the spin-dependent mass case they do not exhibit significant variations. As concerns the subdominant pairing components, the main distinctive features occur in the $d$-wave channel. Such features can eventually be taken into account for distinguishing the microscopic mechanism generating the ferromagnetism.

References
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