Spontaneous spin current near the interface between ferromagnets and unconventional superconductors

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Abstract

Proximity effects between ferromagnets (F) and superconductors (S) with broken time-reversal symmetry (T) are studied theoretically. For the S side we consider a chiral ($p_x \pm ip_y$)-wave, and a $d_{x^2-y^2}$-wave superconductor, the latter of which can form T-breaking surface state, i.e., ($d_{x^2-y^2} \pm is$)-state. The Bogoliubov de Gennes equation which describes the spatial variations of the superconducting order parameter and the magnetization is derived and solved numerically. It is found that a spontaneous spin current flows along the interface between the ($p_x \pm ip_y$)-wave superconductor and the ferromagnet. On the contrary, in the case of a [110] interface of the $d_{x^2-y^2}$-wave SC, the surface state has a ($d \pm p_x \pm p_y$)-wave (or ($d_{x^2-y^2} \pm is$)-wave) symmetry, and thus no (only charge) spontaneous current arises.

Key words: proximity effect; unconventional superconductor; spin current; broken time-reversal symmetry

Recently proximity effects between superconductors (S) and ferromagnets (F) attract much attention,[1] especially when S side is an unconventional superconductor. In this paper we examine these effects theoretically.

We consider two-dimensional S/F bilayer models at zero temperature. The Hamiltonian for each layer is given by

$$H_{\rm L} = -t_{\rm L} \sum_{<i,j>\sigma} (c^\dagger_{i,\sigma} c_{j,\sigma} + h.c.) + U_{\rm L} \sum_i n_{i\uparrow} n_{i\downarrow} - V_{\rm L} \sum_{<i,j>} \left[n_{i\uparrow} n_{j\downarrow} + n_{j\uparrow} n_{i\downarrow} \right], \quad ({\rm L} = {\rm S}, {\rm F}) \tag{1}$$

where $\langle i,j \rangle$ and σ denote the nearest-neighbor pairs on a square lattice and the spin index, respectively. Parameters $t_{\rm L}$, $U_{\rm L}$ and $V_{\rm L}$ are the transfer integral, the on-site repulsive and the nearest-neighbor attractive interactions, respectively, for the ${\rm L}(= {\rm S}, {\rm F})$ side. The transmission of electrons at the interface is described by the following tunneling Hamiltonian: $H_{\rm T} = -t_{\rm T} \sum_{<l,m>\sigma} (c^\dagger_{l,\sigma} c_{m,\sigma} + h.c.)$, where l (m) denotes the surface sites of S (F) layer. Then the total Hamiltonian of the system is $H = H_{\rm S} + H_{\rm F} + H_{\rm T} - \mu \sum_{i\sigma} c^\dagger_{i\sigma} c_{i\sigma}$ with μ being the chemical potential. The interaction terms are decoupled within the Hartree-Fock approximation: $U n_{i\uparrow} n_{i\downarrow} \rightarrow U\langle n_{i\uparrow}\rangle n_{i\downarrow} + U\langle n_{i\downarrow}\rangle n_{i\uparrow} - U\langle n_{i\uparrow}\rangle\langle n_{i\downarrow}\rangle$, $V n_{i\uparrow} n_{j\downarrow} \rightarrow V\Delta_{ij} c^\dagger_{j\downarrow} c^\dagger_{i\uparrow} + V\Delta^*_{ij} c_{i\uparrow} c_{j\downarrow} - V|\Delta_{ij}|^2$ with $\Delta_{ij} \equiv \langle c_{i\uparrow} c_{j\downarrow}\rangle$. The magnetization $m_i = \langle n_{i\uparrow} - n_{i\downarrow}\rangle/2$ and Δ_{ij} are the order parameters (OP's) to be determined self-consistently. The direction perpendicular (parallel) to the interface is denoted as x (y), and we assume that the system is uniform along the y-direction. Along the y-direction we carry out the Fourier transformation, and the Bogoliubov de Gennes (BdG) equation which describes the x-dependences of OP's is derived and solved numerically. The system size we treat is $N_x = N_y = 120$, and we take $t_{\rm S} = t_{\rm F} = 1$ as the unit of energy. The parameters $U_{\rm L}$, $V_{\rm L}$ and μ are chosen such that the superconducting (SC) and the ferromagnetic order occurs in each layer. [2–4] Depending on the electron density, $d_{x^2-y^2}$-wave, extended s-wave and chiral ($p_x + ip_y$)-wave superconducting (SC) states are

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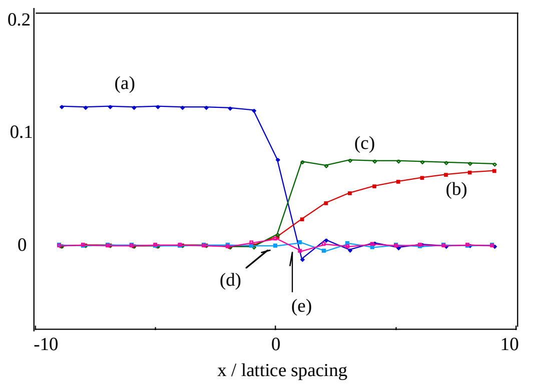

Fig. 1. Spatial variations of order parameters. The region $x < 0$ is a ferromagnet. (a) m, (b) ReΔ_{px}, (c) ImΔ_{py}, (d) ReΔ_d and (e) ReΔ_s. Note all OP's are non-dimensional. Parameters used are $t_{\rm T} = 1, U_{\rm F} = 12, U_{\rm S} = 1.5, V_{\rm S} = 2.5, V_{\rm F} = 0$ and $\mu = -1.6$.

stabilized.

Here we consider $d_{x^2-y^2}$-wave and $(p_x + ip_y)$-wave SC states for the S layer. It is known that near the [110] surface of the former the system may break time-reversal symmetry (T) by introducing second component of SCOP (is) and that a spontaneous (charge) current flows along the surface. [5] The chiral SC states also break T and the spontaneous current can flow along the edge of the system.[6] When S and F layers are connected, the magnetization (spin-triplet SCOP) may be induced in the former (latter) due to the proximity effect.[7] Then it may be possible to have a spontaneous spin current (defined as $J_{\rm spin}(x) \equiv J_{y\uparrow}(x) - J_{y\downarrow}(x)$) along the interface of a T-breaking S layer and a F layer, because of the imbalance of the electron densities of spin-up and spin-down electrons.

First we investigate the case of a bilayer composed of a chiral $(p_x \pm ip_y)$-wave superconductor and a ferromagnet. In Fig.1 we show the spatial variations of OP's for the case of [100] interface. (We have also studied the case of [110] surface, and the results were qualitatively the same.) It is seen that p_x and p_y-wave components (denoted as Δ_{px} and Δ_{py}, respectively) are suppressed near the interface, while d-wave (Δ_d) and s-wave (Δ_s) components are induced. The magnetization penetrates into the S layer and it coexists with SCOP's. We can see that a spontaneous spin current actually flows (Fig.2).

Next we consider the $d_{x^2-y^2}$-wave SC state. We consider the [110] interface, since a T-breaking surface state associated with a spontaneous current can be formed in this case, but not in the case for a [100] surface. The results are qualitatively different depending on the value of $t_{\rm T}$. When $t_{\rm T}$ is comparable to $t_{\rm S}$ $(= t_{\rm F} = 1)$, the magnetization penetrates into the S layer and then the p-wave components are induced. However, the complex component (is) is not induced in contrast to the case of a [110] surface exposed to the vacuum. The

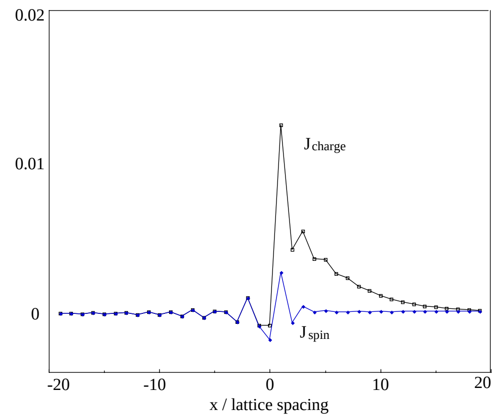

Fig. 2. Spontaneous charge and spin currents along the interface, in units of $eta/\hbar$ (a being the lattice constant).

resulting state has a $(d_{x^2-y^2} \pm p_x \pm p_y)$-symmetry, and no spontaneous current arises. When the value of $t_{\rm T}$ is reduced the magnetization does not penetrate into the S layer (and thus p-wave OP's are absent), and the state has a $(d_{x^2-y^2} \pm is)$-symmetry. In this case a spontaneous charge current flows along the interface, but not the spin current because the electron densities of spin-up and spin-down electrons are the same. The transition between the above two states seems to be of first order, and we did not find states with spontaneous spin currents.

In summary we have studied the states near the interface between unconventional superconductors and ferromagnets. Spontaneous spin currents are found in the case of chiral $(p_x \pm ip_y)$-wave superconductors. For $d_{x^2-y^2}$-wave superconductors the resulting states have either $(d_{x^2-y^2} \pm is)$- or $(d_{x^2-y^2} \pm p_x \pm p_y)$ -symmetry, so that only charge (no) current appears in the former (latter).

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