

Unambiguous probe of parity mixing of Cooper pairs in noncentrosymmetric superconductors

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We propose an experimental scheme to detect unambiguously parity mixing of Cooper pairs in noncentrosymmetric superconductors, which utilizes crossed Andreev reflection processes between two oppositely spin-polarized normal-metal leads and a noncentrosymmetric superconductor. It is demonstrated that a nonlocal conductance exhibits a clear signature of parity breaking of Cooper pairs and, thus, can be a direct probe of the parity mixing.

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In noncentrosymmetric superconductors (NCSs), which lack inversion symmetry in their crystal structure, antisymmetric spin-orbit (SO) interactions give rise to various exotic effects on superconducting states.^{1–30} In particular, pairing states cannot be classified according to parity but, instead, the admixture of spin-singlet and spin-triplet pairings generally occurs.^{7,10,11,22} This most striking effect, however, unfortunately has not been detected so far by experimental studies. The difficulty of detecting parity mixing of Cooper pairs is partly due to the fact that conventional experimental approaches, which are utilized for the determination of parity of Cooper pairs in centrosymmetric superconductors, such as NMR Knight shift measurements, do not provide any useful information concerning parity mixing. That is, in centrosymmetric superconductors, the change in the Knight shift below the transition temperature T_c tells us whether the pairing state is spin singlet or spin triplet. By contrast, in NCS, if the SO interaction is much larger than the energy scale of the superconducting gap, the behavior of the Knight shift below T_c is mainly governed by the strong SO interaction and does not yield any information on pairing states.^{12,22,23,31,32} Thus, a novel experimental approach is required for the detection of parity mixing of Cooper pairs. There have been several proposals for this aim, which use, for instance, tunneling characteristics,^{33–36} accidental gap-node structures,³⁷ and a fractional vortex scenario.³⁸

In this Rapid Communication, we propose another method to probe parity mixing of Cooper pairs in an unambiguous way. In this scheme, we utilize crossed Andreev reflection (CARE) between two ferromagnetic normal-metal leads and a NCS. CARE is a nonlocal reflection process; an electron injected from one lead to a superconductor is converted to a hole in another lead, when the distance between two leads is smaller than the coherence length ξ .^{39–44} To illustrate the basic idea, we consider a setup consisting of two oppositely spin-polarized leads and a NCS with the Rashba SO interaction⁴⁵ $H_{SO} = \alpha \mathcal{L}(k) \cdot \boldsymbol{\sigma}$ with $\mathcal{L}(k) = (k_y, -k_x, 0)$, α as the SO coupling constant, and $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ as the Pauli matrices (Fig. 1). In the NCS, the SO interaction splits the electron band into two parts, $\varepsilon_{k\pm} = \varepsilon_k \pm \alpha|k|$, each of which is the eigenstate of spin chirality. We assume that the SO split is sufficiently larger than the superconducting gap, and that there are only intraband Cooper pairs formed between electrons in the same band. For instance, in the ε_{k-} band, an electron with momentum k and spin \uparrow and an electron with momentum $-k$ and spin \downarrow form a

Cooper pairing state $|k\uparrow\rangle|k\downarrow\rangle$, while in the ε_{k+} band an electron with momentum k and spin \downarrow and an electron with momentum $-k$ and spin \uparrow form a Cooper pairing state $|k\downarrow\rangle|k\uparrow\rangle$. Here, we have chosen the spin-quantization axis parallel to $\mathcal{L}(k) = (k_y, -k_x, 0)$. When the density of states in each band is different from each other, the superposition between these two pairing states is impossible. Then, the pairing state in each band is the admixture of spin-singlet and spin-triplet states, e.g., $|k\uparrow\rangle|k\downarrow\rangle = \frac{1}{2}(|k\uparrow\rangle|k\downarrow\rangle - |k\downarrow\rangle|k\uparrow\rangle) + \frac{1}{2}(|k\uparrow\rangle|k\downarrow\rangle + |k\downarrow\rangle|k\uparrow\rangle)$.^{7,10,11,22,23} The superconducting gap of the parity-mixed pairing state is generally given by $\Delta_{\sigma\sigma'}(k) = \Delta_s(k) i(\sigma_y)_{\sigma\sigma'} + \mathbf{d}(k) \cdot (\boldsymbol{\sigma} i \boldsymbol{\sigma}_y)_{\sigma\sigma'}$. We assume that the \mathbf{d} vector of the triplet pairing is constrained by the Rashba SO interaction, i.e., $\mathbf{d}(k) = |\mathbf{d}(k)|(\sin \phi_k, -\cos \phi_k, 0)$ with $\phi_k = \tan^{-1}(k_y/k_x)$.^{7,10,11} Then, the superconducting gaps on the ε_{k+} and the ε_{k-} bands are, respectively, $\tilde{\Delta}_+(k) = [\Delta_s(k) + |\mathbf{d}(k)|]t_k$ and $\tilde{\Delta}_-(k) = [\Delta_s(k) - |\mathbf{d}(k)|]t_k^*$, where t_k is an odd-parity phase factor given by $t_k = ie^{-i\phi_k}$. Actually, the structure of the \mathbf{d} vector is determined not only by the SO interaction, but also by the detail of the pairing interaction.^{25,46} The generalization of our argument to the case with more complex structure of \mathbf{d} vector is straightforward. In the following, for simplicity, we focus on one-dimensional (1D) scattering problem where currents flow only along the x axis which is perpendicular to the interface between the leads and the NCS (see Fig. 1). A qualitative feature which is important for the detection of parity-mixing is not largely affected by this simplification. In

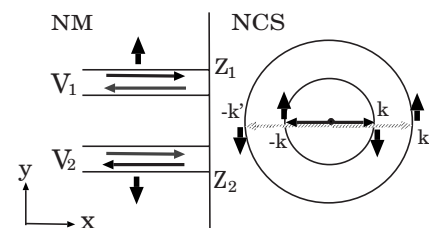


FIG. 1. Setup for crossed Andreev reflection between a NCS and two spatially separated NM leads with opposite spin polarizations and bias voltages V_1 and V_2 , respectively. Short arrows represent the directions of electron spins. In the NCS side, the circular Fermi surface split by the Rashba SO interaction is depicted. Cooper pairs are formed within the same band. Black (gray) long arrows in the leads represent the flow of injected electrons and reflected holes for process A (B).

fact, the degrees of freedom along the z axis are irrelevant for our argument. Effects of tilting alignment of the leads on the xy plane will be discussed later. In this setup, we assume that two leads are oppositely spin polarized with the spin-quantization axis parallel to the y axis.

An important observation here is that the parity-broken structure of the Cooper pair $|k\uparrow\rangle|k\downarrow\rangle$ (or $|k\downarrow\rangle|k\uparrow\rangle$) is directly related to the parity mixing, as explained above. The parity breaking of Cooper pairs can be detected by CARE as asymmetric reflection processes; a process in which an injected electron with spin \uparrow in lead 1 is converted to a hole with spin \downarrow in lead 2 is not equivalent to a process in which an injected electron with spin \downarrow in lead 2 is converted to a hole with spin \uparrow in lead 1 because of broken inversion symmetry of the NCS. In the former process (denoted as process A), the Andreev-reflected hole is associated with the superconducting gap Δ_- , while, in the latter process (denoted as process B), the relevant superconducting gap is Δ_+ . As mentioned above, in the parity-mixed pairing state, the amplitudes of these two gaps are different, which can be clearly observed as a characteristic bias-voltage dependence of the nonlocal conductance. Thus, the parity mixing of Cooper pairs can be detected directly without ambiguity.

The nonlocal conductance, which characterizes the CARE, is given by $G_{12}(V_1) = dI_2/dV_1$ and $G_{21}(V_2) = dI_1/dV_2$, where $I_{1(2)}$ and $V_{1(2)}$ are, respectively, a current and a bias voltage in lead 1 (2). The nonlocal conductance is expressed in terms of the reflection probabilities A_{ij}^σ for the process that an injected electron with spin σ in the lead i is converted to a hole with spin $-\sigma$ in the lead j , i.e., when the electron spin in each lead is fully polarized,

$$G_{12}(V_1) = G_N A_{12}^\uparrow/2, \quad G_{21}(V_2) = G_N A_{21}^\downarrow/2. \quad (1)$$

Here G_N is the conductance in the normal state. To obtain the probabilities, we solve the Bogoliubov-de Gennes (BdG) equation for the CARE. In the representation where σ_y is diagonal, the Hamiltonian is decoupled into two parts \hat{H}_+ and \hat{H}_- , each of which corresponds to the pairing state in one of two SO split bands. The BdG equation for the 1D scattering problem depicted in Fig. 1 is

$$\hat{H}_\nu \Psi_\nu = E \Psi_\nu, \quad (2)$$

$$\hat{H}_\nu = \begin{pmatrix} \varepsilon(\hat{k}) + \nu \alpha \hat{k}_x + V(x) & -i\nu \Delta_\nu(\hat{k}) \\ i\nu \Delta_\nu(\hat{k}) & -\varepsilon(\hat{k}) - \nu \alpha \hat{k}_x - V(x) \end{pmatrix}, \quad (3)$$

with $\nu = \pm$. Here $\varepsilon(\hat{k}) = -\frac{1}{2m} \nabla^2 - \mu$ with μ as a chemical potential and $\hat{k}_x = -i\partial_x$. The gap functions are $\Delta_\pm(\hat{k}) = \Delta_s(\hat{k}) \pm |\mathbf{d}(\hat{k})|$. We assume that a barrier at the interface between lead 1 (2) and the NCS is given by a Dirac-type potential, $V(x) = \frac{k_F}{m} Z_{1(2)} \delta(x)$. Here Z_1 and Z_2 are dimensionless parameters for the strength of the barrier potentials and k_F is defined by $k_F^2/2m = \mu$, i.e., the Fermi momentum in the case without the SO split. To simplify the analysis, we consider the case of an $(s+p)$ -wave pairing state and neglect k dependence of Δ_\pm . The following argument can be easily extended to the case with more general pairing states such as a $(d$

$+f$)-wave state, a $(g+h)$ -wave state etc. After a straightforward calculation,⁴⁷ we obtain the probability A_{ij}^σ ,

$$A_{12}^\uparrow(E) = \frac{\Delta_-^2 s_\nu^2}{4E^2 |\gamma_\nu(E)|^2}, \quad (4)$$

with $\nu = -$ and $s_\nu = 1 - \nu m \alpha / k_F$. Here, for $E < \Delta_\nu$,

$$4E^2 |\gamma_\nu(E)|^2 = [s_\nu E - (Z_1 - Z_2) \sqrt{\Delta_\nu^2 - E^2}]^2 + [\sqrt{\Delta_\nu^2 - E^2} (s_\nu + 2Z_1 Z_2) + s_\nu (Z_1 - Z_2) E]^2, \quad (5)$$

and, for $E > \Delta_\nu$,

$$4E^2 |\gamma_\nu(E)|^2 = [s_\nu E + (s_\nu + 2Z_1 Z_2) \sqrt{E^2 - \Delta_\nu^2}]^2 + (Z_1 - Z_2)^2 (s_\nu E + \sqrt{E^2 - \Delta_\nu^2})^2. \quad (6)$$

The probability $A_{12}^\downarrow(E)$ is given by Eq. (4) with $\nu = +$. One can obtain the probability A_{21}^σ by interchanging Z_1 and Z_2 in the expression of A_{12}^σ . In the derivation of A_{ij}^σ , we have used the approximation that the Fermi momentum for $\varepsilon_{k\pm}$ is $k_{F\pm} \approx k_F \mp m\alpha$, which is valid when the SO split is much smaller than the Fermi energy. In fact, within this approximation, the shift of the Fermi momentum due to the SO split does not change qualitatively the feature of the nonlocal conductance that is important for the detection of parity mixing of Cooper pairs, as will be shown below.

We, first, consider the case that leads 1 and 2 are fully spin polarized in the opposite directions, and the nonlocal conductance is given by Eq. (1). Although the spin polarization in the leads induces exchange fields in the NCS region, which may affect the amplitude of the superconducting gap in a nontrivial way, we neglect this effect because it may not change our argument qualitatively. Because of the parity-broken structure of Cooper pairs mentioned above, $G_{12}(eV)$ and $G_{21}(eV)$ exhibit asymmetric behaviors as functions of V even when $Z_1 = Z_2$, i.e., for $G_{12}(eV)$ a peak structure appears at $eV = \Delta_-$, while for $G_{21}(eV)$ it appears at $eV_2 = \Delta_+$. When there is the admixture of spin-singlet and spin-triplet pairings, $\Delta_+ \neq \Delta_-$ holds. Thus, the parity mixing can be detected unambiguously from the measurement of the nonlocal conductance. Also, we can derive the BCS gap magnitudes for the spin-singlet and spin-triplet pairs from $\Delta_s = (\Delta_+ + \Delta_-)/2$ and $|\mathbf{d}(k)| = (\Delta_+ - \Delta_-)/2$. Typical behaviors of the nonlocal conductance as functions of bias voltages are shown in Fig. 2(a). It is noted that even in the case of $Z_1 \neq Z_2$, the origin of this asymmetric behavior of G_{12} and G_{21} can be clearly attributed to the result of parity mixing, since the most important factor which yields the asymmetric behavior of the nonlocal conductance is the existence of two gaps Δ_+ and Δ_- associated with, respectively, opposite spin chiralities of the two SO split Fermi surfaces. We emphasize that the two different gap structures which appear in G_{12} and G_{21} shown in Fig. 2(a) are obviously different from conventional multi-gap behaviors of centrosymmetric superconductors with multibands. From this point of view, the CARE experiment is more advantageous than the conventional Andreev reflection experiment³³⁻³⁶ as a probe of parity mixing, although its realization is still challenging with current nanotechnology.

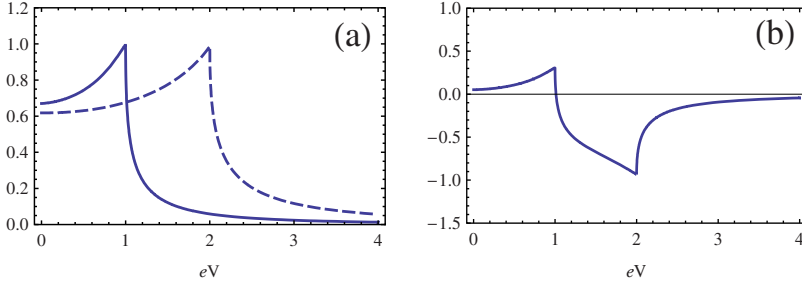


FIG. 2. (Color online) (a) Typical behaviors of the nonlocal conductance as functions of a bias voltage eV . $G_{12}(eV)$ (solid line) and $G_{21}(eV)$ (broken line) for $\Delta_- = 1.0$ (energy unit), $\Delta_+ = 2.0$, $Z_1 = 0.3$, $Z_2 = 0.4$, and $m\alpha/k_F = 0.1$. Unit of the conductance is $G_N/2$. (b) $(G_{12}^{H>0} - G_{12}^{H<0})/(1 - C_0)$ as a function of a bias voltage for the same parameters as (a).

In the above argument, a crucial assumption for the gap function is that there are no interband Cooper pairs or, if they exist, the gap amplitude for the interband pairs is negligibly small. This assumption is valid as long as the SO split of the Fermi surface is sufficiently smaller than the Fermi energy.

An apparent drawback of the above scheme is that in the setup shown in Fig. 1, one needs to know beforehand the spin structure on the Fermi surfaces of the NCS determined by the SO interaction to align the direction of the spin polarization in two leads properly. Generally, this task is not so easy, because the structure of the SO interaction for real NCSs is a quite complicated function of momentum k .^{48–50} For the purpose of extending our scenario to such realistic cases with the non-Rashba SO interactions, we consider a setup a bit different from that depicted in Fig. 1; in two normal-metal leads, there is no spontaneous magnetization but, instead, spin polarization is induced by an external weak magnetic field H which is smaller than H_{c1} . We neglect effects of the magnetic field on the NCS, since it does not change our argument qualitatively. A main effect of a sufficiently small magnetic field on the Andreev reflection processes is to raise an imbalance of spin population in two normal-metal leads. Suppose the Rashba SO interaction for a while. We will discuss more general cases later. Then, when the magnetic field is parallel to the positive direction of the y axis, the nonlocal conductance $G_{12}^{H>0}$ is

$$\frac{2G_{12}^{H>0}}{G_N} = A_{12}^{\uparrow} + C_0 A_{12}^{\downarrow}, \quad (7)$$

where $C_0 = N_{\downarrow}/N_{\uparrow}$ with $N_{\uparrow(\downarrow)}$ as the total number of electrons with up (down) spin in lead 1 and $A_{12}^{\uparrow(\downarrow)}$ in Eq. (7) is the reflection probability in the case without a magnetic field. In the derivation of Eq. (7), we have taken into account the Zeeman effect up to the lowest order in $\mu_B H/\mu$ but neglected the change in the Fermi momentum due to the Zeeman shift in the leads. Thus, the suppression of the Andreev reflection due to the spin polarization is not included in Eq. (7) up to $O(\mu_B H/\mu)$. This approximation does not affect an important feature of the nonlocal conductance relevant to the detection of parity mixing for a sufficiently small H , as will be clarified later. In a similar way, the nonlocal conductance in the case with a magnetic field parallel to the negative direction of the y axis is obtained as $G_{12}^{H<0}/G_N = C_0 A_{12}^{\uparrow} + A_{12}^{\downarrow}$. From the difference between the conductance for $H>0$ and that for $H<0$, $G_{12}^{H>0} - G_{12}^{H<0} = (1 - C_0)(A_{12}^{\uparrow} - A_{12}^{\downarrow})$, we can clearly see whether the parity of Cooper pairs is broken ($A_{12}^{\uparrow} \neq A_{12}^{\downarrow}$) or not ($A_{12}^{\uparrow} = A_{12}^{\downarrow}$). We show a typical behavior of $(G_{12}^{H>0} - G_{12}^{H<0})/(1 - C_0)$ as a function of a bias voltage in

Fig. 2(b). This quantity exhibits distinct peak structures at $eV = \Delta_+$ and Δ_- as a signature of the parity mixing and thus can be a useful probe of the admixture of spin-singlet and spin-triplet pairs. It is noted that the peak height at $eV = \Delta_{\pm}$ is not affected by the Zeeman shift of the Fermi momentum in the NM leads up to the first order in $\mu_B H/\mu$ since, up to this order, the magnetic field H enters into the expression of A_{ij}^{σ} in the form of $(\mu_B H/\mu) \sqrt{|\Delta_{\pm}^2 - E^2|}$. Thus, the approximation used in the derivation of Eq. (7) and the equation for $G_{12}^{H<0}$ is valid for our purpose. This scheme which uses field-induced spin polarization in the leads can be utilized for the detection of parity mixing in the general case that the structure of the antisymmetric SO interaction, $H_{SO} = \alpha \mathcal{L}(k) \cdot \sigma$, is unknown. Even in this case, when a magnetic field is applied, one can observe the asymmetry between the nonlocal conductance for a magnetic field with a certain direction, $G_{12}^{H>0}$, and the nonlocal conductance for a field antiparallel to it, $G_{12}^{H<0}$, quite generally except in the case with $\vec{H} \perp \mathcal{L}(k)$. Thus, it is not difficult to find a direction of the magnetic field for which the asymmetric behavior of the nonlocal conductance is observed, and the conductance difference $G_{12}^{H>0} - G_{12}^{H<0}$ is nonzero. Then, one can detect parity mixing of Cooper pairs.

Finally, we comment on effects of inversion-symmetry breaking caused by the interface between the NCS and the NM leads. Generally, inversion symmetry is broken at a surface. However, this extrinsic inversion-symmetry breaking does not affect our proposal because of the following reason. For the (100) interface depicted in Fig. 1, the SO interaction due to the interface is typically the Rashba type with the Hamiltonian $H' = \alpha'(k_x \sigma_y - k_y \sigma_x)$. On the other hand, CARE processes for this geometry are dominated by electrons and holes with momentum parallel to the x axis, i.e., $k_y = k_z = 0$. Thus, effects of the extrinsic Rashba interaction on the CARE are negligible.

Recently, we have become aware of the paper by Wu and Samokhin,⁵¹ in which the conductance for conventional Andreev reflection between a ferromagnetic metal and a NCS is calculated in a thorough way. It is important to generalize the current study to more realistic situations as considered by Wu and Samokhin for quantitative comparison between theory and experiments. In summary, it is proposed that a crossed Andreev reflection experiment can be utilized as an unambiguous probe of parity mixing of Cooper pairs in NCSs.

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