Parity-Sensitive Measurements Based on Ferromagnet/Superconductor Tunneling Junctions

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A method for identifying the parity of unconventional superconductors based on tunneling spectroscopy is proposed. For a model of calculation, we adopt a ferromagnet/superconductor (F/S) junction, the tunneling current of which is spin polarized. The tunneling conductance spectra are shown to be quite sensitive to the direction of the magnetization axis in the ferromagnet only when the superconductor has odd parity. Therefore, it is possible to distinguish the parity of the superconductor by performing tunneling spectroscopy in F/S junctions.

KEYWORDS: tunneling conductance, triplet superconductor, parity of the superconductor, Andreev reflection, ferromagnet

The discovery of superconductivity in Sr\textsubscript{2}RuO\textsubscript{4}\textsuperscript{1,2} aroused our interest in triplet pairing states in metals. To date, the spin triplet pairing states have been proposed to be realized in UPt\textsubscript{3}\textsuperscript{3} (TMTSF)\textsubscript{2}PF\textsubscript{6} and UGe\textsubscript{2}\textsuperscript{4,5}. In triplet superconductors, Cooper pairs have a rich internal degree of freedom as compared to those in singlet ones. One of the important quantities for identifying the basic properties of triplet superconductors is the $d$-vector, which characterizes the odd parity of a Cooper pair. It is an interesting problem to develop a novel method for distinguishing the parity of the superconductors based on the dependence of the direction of the $d$-vector in tunneling spectroscopy.

The tunneling effect in normal metal / insulator / unconventional superconductor (N/I/S) junctions markedly reflects the symmetry of the pair potential of unconventional superconductors. In particular, the sign change in the pair potential induces a significant effect, i.e., a zero-bias conductance peak (ZBCP) in tunneling experiments of high-$T\textsubscript{C}$ superconductors\textsuperscript{6-9}. Using a tunneling conductance formula in normal metal / insulator / unconventional singlet superconductor junctions, the origin of the ZBCP is explained in terms of the formation of the zero-energy Andreev bound states (ZES) at the interface of a superconductor.\textsuperscript{10-12} Applying this formula to triplet superconductor junctions, ZBCPs are also obtained\textsuperscript{13}. Since the ZBCP is a universal phenomena expected to exist for unconventional superconductors with the sign change in the pair potential on the Fermi surface regardless of the parity, we cannot distinguish the parity of the superconductor using only tunneling spectroscopy in the N/I/S junctions. The tunneling effect in ferromagnet / insulator / superconductor junctions (F/I/S) has also been studied\textsuperscript{14-16}. Since the retro-reflectivity of the Andreev reflection\textsuperscript{17} is broken due to the exchange potential in the ferromagnet, the height of ZBCP is suppressed when the superconductor is singlet. With regard to triplet superconductor junctions, the situation becomes much more complex. It is revealed that whether the magnitude of ZBCP is suppressed or not strongly depends on the direction of the $d$-vector. However, there is no systematic study to clarify the influence of the ferromagnet on the tunneling conductance in triplet superconductor junctions at this stage. To more clearly reveal the difference between singlet superconductors and triplet ones through tunneling conductance in F/I/S junctions, we must propose a new idea.

In this study, we calculate the tunneling conductance for ferromagnet / insulator / superconductor (F/I/S) junctions with arbitrary direction of the magnetization axis. It is clarified that the tunneling conductance for triplet superconductors depends on the angle between the magnetization axis and the $d$-vector, while that for singlet ones does not because the total spin angular momentum of the Cooper pair is zero. Through the change in the tunneling conductance as a function of the direction of the magnetization axis, we can identify much more detailed features of a triplet superconducting Cooper pair. With this idea, we can clarified detailed features of the pair potential of Sr\textsubscript{2}RuO\textsubscript{4}.

We assume a two-dimensional F/I/S junction with semi-infinite double-layered structures in the clean limit. A flat interface is perpendicular to the $x$-axis and is located at $x = 0$. The insulator is modeled as a delta-functional form $V(x) = H\delta(x)$, where $H$ and $\delta(x)$ are the height of the barrier potential and $\delta$ function, respectively. The Fermi energy $E_F$ and the effective mass $m$ are assumed to be equal in both the ferromagnet and the superconductor. As a model of the ferromagnet, we apply the Stoner model using the exchange potential $U$. The magnitude of momentum in the ferromagnet for the majority ($\uparrow$) or minority ($\downarrow$) spin is denoted...
by $k_{\uparrow(\downarrow)} = \sqrt{2m(E \pm U)}$. The wave functions $\Psi(r)$ are obtained by solving the Bogoliubov-de Gennes (BdG) equation applying the quasi-classical approximation

$$
\begin{pmatrix}
\hat{H}(r) & \hat{\Delta}(\theta_S, x) \\
\hat{\Delta}^\dagger(\theta_S, x) & -\hat{H}^\dagger(r)
\end{pmatrix}
\begin{pmatrix}
\begin{pmatrix}
\upsilon_\uparrow(r) \\
\upsilon_\downarrow(r)
\end{pmatrix}
& \begin{pmatrix}
\upsilon_\uparrow(r) \\
\upsilon_\downarrow(r)
\end{pmatrix}
\end{pmatrix} = E
\begin{pmatrix}
\begin{pmatrix}
\upsilon_\uparrow(r) \\
\upsilon_\downarrow(r)
\end{pmatrix}
& \begin{pmatrix}
\upsilon_\uparrow(r) \\
\upsilon_\downarrow(r)
\end{pmatrix}
\end{pmatrix}

(1)
$$

where $E$ is the energy of the quasiparticle, $\hat{H}(r) = h_0 \hat{1} - \hat{U}(r) \cdot \sigma(r)$, $h_0 = -\frac{e^2}{2m} \nabla^2 + V(x) - E_F$, $\hat{U}(r) = \Theta(-x) \hat{n}$, $\hat{1}$ and $\sigma$ are the $2 \times 2$ identity matrix and Pauli matrix, respectively. The quantity $\theta_S$ denotes the direction of the motion of quasiparticles in the superconductor. The quantity $\hat{n}$ is the direction of the magnetization axis, and $\Theta(x)$ is the Heaviside step function. The indices $\uparrow, \downarrow$ denote the up and down spin in the superconductor, respectively. The configuration of the magnetization axis of the ferromagnet and the $c$-axis of the superconductor is expressed by a polar coordinate $(\theta_M, \phi_M)$ (see Fig. 1.), where we assume that the quantization axis of the triplet superconductor is parallel to the $c$-axis. The effective pair potential $\hat{\Delta}(\theta_S, x) = \Delta(\theta_S) \Theta(x)$ is given by

$$
\hat{\Delta}(\theta_S) = \begin{pmatrix}
\Delta_{\uparrow\uparrow}(\theta_S) & \Delta_{\uparrow\downarrow}(\theta_S) \\
\Delta_{\downarrow\uparrow}(\theta_S) & \Delta_{\downarrow\downarrow}(\theta_S)
\end{pmatrix}
$$

(2)

It is comprehensive to rewrite the pair potential in the coordinate of spin space in the ferromagnet, $\Delta_{\sigma\sigma'}(\theta_S) = \hat{U}^\dagger \Delta_{\sigma\sigma'}(\theta_S) \hat{U}$, where the unitary operator $\hat{U}$ is given by

$$
\hat{U} = \begin{pmatrix}
\gamma_1 & -\gamma_2^s \\
\gamma_2 & \gamma_1
\end{pmatrix},
\gamma_1 = \cos \frac{\theta_M}{2} e^{-i\phi_M/2}, \gamma_2 = \sin \frac{\theta_M}{2} e^{i\phi_M/2}.

(3)
$$

Here, the spin indices $\sigma, \sigma' = \uparrow, \downarrow$ correspond to the majority and minority spin in the ferromagnet, respectively, and $s, s' = \uparrow, \downarrow$. In general, we should consider the following four kinds of reflection processes with arbitrary $H$ and $\theta_M$ for an electron with majority spin injection: i) Andreev reflection of majority spin ($a_{\uparrow\uparrow}$) ii) Andreev reflection of minority spin ($a_{\uparrow\downarrow}$) iii) normal reflection of majority spin ($b_{\uparrow\uparrow}$) and iv) normal reflection of minority spin ($b_{\uparrow\downarrow}$).

Similar reflection processes also exist for minority-spin injection. Here, $a_{\sigma\sigma'}$ and $b_{\sigma\sigma'}$ are reflection coefficients of the Andreev and normal reflections, respectively. The wave function of the quasiparticle for majority- and minority-spin injections is denoted by the coefficients $a_{\sigma\sigma'}$ and $b_{\sigma\sigma'}$ for $x < 0$. The coefficients $a_{\sigma\sigma'}$ and $b_{\sigma\sigma'}$ are determined by solving the BdG equation with quasi-classical approximation under the boundary condition. The normalized tunneling conductance for zero temperature is given by

$$
\sigma_T(eV) = \frac{\int_{-\pi/2}^{\pi/2} d\theta_S \cos \theta_S \left( \sigma_{SS\uparrow}(\theta_S) + \sigma_{SS\downarrow}(\theta_S) \right)}{\int_{-\pi/2}^{\pi/2} d\theta_S \cos \theta_S \left( \sigma_{SS\uparrow}(\theta_S) + \sigma_{SS\downarrow}(\theta_S) \right)}

(4)
$$

$$
\sigma_{SS\uparrow} = 1 + |a_{\uparrow\uparrow}|^2 - |b_{\uparrow\uparrow}|^2 + \left( \frac{\eta_{\uparrow}}{\eta_{\uparrow}} |a_{\uparrow\uparrow}|^2 - \frac{\eta_{\downarrow}}{\eta_{\downarrow}} |b_{\uparrow\downarrow}|^2 \right) \times \Theta(\theta_C - |\theta_S|)

(5)
$$

$$
\sigma_{SS\downarrow} = 1 + |a_{\uparrow\downarrow}|^2 - |b_{\uparrow\downarrow}|^2 + \left( \frac{\eta_{\uparrow}}{\eta_{\uparrow}} |a_{\uparrow\downarrow}|^2 - \frac{\eta_{\downarrow}}{\eta_{\downarrow}} |b_{\uparrow\downarrow}|^2 \right) \times \Theta(\theta_C - |\theta_S|)

(6)
$$

$$
\sigma_{N\uparrow\uparrow} = \frac{4\eta_{\uparrow}}{(1 + \eta_{\uparrow})^2 + 2\eta_{\uparrow}^2} \Theta(\theta_C - |\theta_S|),

\sigma_{N\downarrow\downarrow} = \frac{4\eta_{\downarrow}}{(1 + \eta_{\downarrow})^2 + 2\eta_{\downarrow}^2} \Theta(\theta_C - |\theta_S|),

(7)
$$

with $Z_{\theta_S} = Z/\cos \theta_S$, $Z = 2mH/\hbar^2 k_F$ and $\eta_{\uparrow(\downarrow)} = \sqrt{1 \pm X \cos^2 \theta_S}$. Here, we define the polarization parameter $X = U/E_F$. The quantity $\sigma_{SS\uparrow}(\theta_S)$ is the tunneling conductance for electron injection with a majority (minority) spin in the superconducting state, and $\sigma_{N\uparrow\uparrow}(\theta_S)$ denotes that in the normal state. For $|\theta_S| > \theta_C = \cos^{-1} \sqrt{X}$, the reflected wave function with a minority spin for majority-spin injection cannot exist as a propagating wave. Therefore, these reflection processes do not contribute to the tunneling conductance. In the above equation, $\theta_M$ dependence of the tunneling conductance appears only through pair potentials. In general, for singlet superconductors, since $\Delta_{\sigma\sigma'}(\theta_S) = \Delta_{\sigma\sigma'}(\theta_S)$ is satisfied for any $\theta_M$, $\sigma_{SS\uparrow}$ are independent of $\theta_M$. Thus, the $\theta_M$ dependence of tunneling conductance never occurs.

As the prototype of triplet superconductors, we consider one of the unitary pairing states presented in Sr3RuO4 given by $\Delta_{\uparrow\downarrow}(\theta_S) = \Delta_{\uparrow\uparrow}(\theta_S) = \Delta_0 e^{i\theta_2}$ and $\Delta_{\downarrow\uparrow}(\theta_S) = \Delta_{\downarrow\downarrow}(\theta_S) = 0$, where the $d$-vector is along a $c$-axis. $\Delta_F(\theta_S)$ in the unitary case is given by

$$
\Delta_F(\theta_S) = \begin{pmatrix}
\Delta_{\uparrow\uparrow}(\theta_S) & \Delta_{\uparrow\downarrow}(\theta_S) \\
\Delta_{\downarrow\uparrow}(\theta_S) & \Delta_{\downarrow\downarrow}(\theta_S)
\end{pmatrix} = \begin{pmatrix}
\sin \theta_M & \cos \theta_M \\
\cos \theta_M & -\sin \theta_M
\end{pmatrix} \Delta_0 e^{i\theta_S}.

(9)
$$

In particular, for $\theta_M = 0$ or $\pi (\theta_M = \pi/2)$, the relation $a_{\uparrow\downarrow} = b_{\uparrow\downarrow} = 0$ holds. The voltage dependence of $\sigma_T(eV)$ is plotted for $Z = 0$ with $X = 0.999$ (see Fig. 2(a)), where only an injected electron with a majority spin can contribute to the tunneling conductance in both the superconducting and normal states. As a reference, the corresponding quantity for $X = 0$ is plotted in curve $d$, where $\sigma_T(eV) = 2$ is satisfied for $0 < eV < \Delta_0$ due to the complete Andreev reflection. For $\theta_M = 0$ or $\pi$, since a reflected hole has a minority spin for an electron injection with a majority spin, the Andreev reflection does not exist as a propagating wave for $|\theta_S| > \theta_C \sim \pi/100$. Consequently, $\sigma_T(eV)$ is drastically suppressed for $0 < eV < \Delta_0$. For $\theta_M = \pi/2$, since a reflected hole has a majority spin for an electron injection with a majority spin, wave function of the Andreev reflected hole is a propagating wave for arbitrary $\theta_S$. Then, the magnitude of $\sigma_T(eV)$ does not decrease.

In Fig. 2(b), $\theta_M$ dependence of the normalized tunneling conductance $\sigma_T(eV = 0)$ is plotted against various magnitudes of $Z$ with $X = 0.9$. The magnitude of $\sigma_T(eV = 0)$ is significantly influenced by $\theta_M$. The same calculation for the $d_{x^2-y^2}$-wave superconductor is also
plotted in curve d for $Z = 1$ with $X = 0.9$ as a typical example of a singlet superconductor. The resulting $\sigma_T(eV = 0)$ is independent of $\theta_M$, since total spin angular momentum of the singlet Cooper pair is zero. It is a unique property that using the $\theta_M$ dependence of $\sigma_T(eV = 0)$, we can distinguish the parity of the superconductor in the $F/I/S$ junction.

Next, we observe the energy dependence of the $\sigma_T(eV)$ plotted for $Z = 10$ with $X = 0.9$ and 0.999 (see Fig. 3). The magnitude of $\sigma_T(eV)$ for $\theta_M = 0$ or $\pi$ is smaller than that for $\theta_M = \pi/2$, as in the case of Fig. 2(a) (see curves $a$, $b$, and $c$, $d$). For all curves, there is a change in the curvature at a certain energy $eV = E_C$. In order to explain this property, we consider the relationship between bound states and $\theta_C$. When the transparency of the junction is low, i.e., the magnitude of $Z$ is large, $\sigma_T(eV)$ is expressed by the surface density of states (SDOS) of the superconductor and the energy levels of the bound state crucially determine the low-energy properties of SDOS. The energy levels of the bound states in the present unitary triplet pair potential are obtained by solving the following equation:

$$1 = -e^{2i\theta_S} E + i \sqrt{\Delta^2 - E^2} \overline{E - i \sqrt{\Delta^2 - E^2}},$$

and the calculated results are plotted in the inset of Fig. 3. The bound states exist only for $\theta_S \geq 0$ and not for $\theta_S < 0$ due to the effect of the broken time reversal symmetry of the pair potential. Here, we consider the contribution of bound states to $\sigma_T(eV)$ in the $F/I/S$ junctions in relation to the wave function of the Andreev reflected hole and the critical angle $\theta_C$ for $0 < eV < \Delta_0$. The magnitude of $\sigma_T(eV)$ is determined based on the magnitude of the Andreev reflection coefficient through the energy level of the bound state. For $\theta_M = 0$ or $\pi$, when an electron with a majority spin is injected, the Andreev reflected hole has a minority spin and its wave function becomes a propagating wave for $|\theta_S| < \theta_C$, and an evanescent wave for $|\theta_S| > \theta_C$. At the same time, an electron injection with a minority spin is prohibited for $|\theta_S| > \theta_C$. Therefore, an injected electron with both majority and minority spin does not contribute to $\sigma_T(eV)$ through the bound state for $|\theta_S| > \theta_C$. Due to the vanishing of the contribution of bound states for $|\theta_S| > \theta_C$, the change in the curvature at $eV = E_C$ in $\sigma_T(eV)$ occurs as in the case in which $\theta_M = 0$ or $\pi$.

Finally, we discuss the tunneling conductance for the non-unitary case presented in Sr$_2$RuO$_4$, i.e., $\Delta_{1 \uparrow} = \Delta_{3 \downarrow} e^{i\theta_S}$, otherwise $= 0$, where the $d$-vector is parallel to the $ab$-plane of triple superconductors. In this superconducting state, only an electron injection with an up spin feels the pair potential. In the present non-unitary case, the pair potential written in the coordinate of spin space in the ferromagnet is given by

$$\Delta^P(\theta_S) = \left( \frac{\cos^2 \theta_M / 2 - \frac{1}{2} \sin \theta_M / 2}{\sin \theta_M / 2} \right) e^{-i\phi_M} \Delta_0 e^{i\theta_S}$$

The $\theta_M$ dependence of $\sigma_T(eV = 0)$ is plotted in Fig. 4 with $Z = 5$. For $\theta_M = 0$ ($\theta_M = \pi$), since the relation $a_{1 \uparrow} = a_{3 \downarrow} = 0$ ($a_{2 \uparrow} = a_{1 \downarrow} = 0$) holds, the Andreev reflection with only a majority (minority) spin exists for an electron injection with a majority (minority) spin. Therefore, $\sigma_T(eV = 0)$ for $\theta_M = 0$ is larger than that for $\theta_M = \pi$. It is a significant fact that $\sigma_T(eV = 0)$ has a different period as a function of $\theta_S$ as compared to that in the unitary pairing. Using these properties, we can distinguish the unitary and non-unitary states which are presented as a promising symmetry of Sr$_2$RuO$_4$.

In conclusion, we have studied tunneling conductance in $F/I/S$ junctions by changing the angle $\theta_M$ between the direction of the magnetization axis of the ferromagnet and the $c$-axis of the superconductor. The $\theta_M$ dependence appears only in the triplet superconducting junctions and its dependence is sensitive to the direction of the $d$-vector in triplet superconductors. From these properties, tunneling spectroscopy of $F/I/S$ junctions for various directions of the magnetization axis becomes a powerful method for identifying the parity of the superconductor. Moreover, we can identify detailed profiles of the triplet superconducting pair potentials. In the present paper, we neglected the spin-orbit coupling in triplet superconductors. If the magnitude of spin-orbit coupling is not strong, we expect the obtained results will not be changed qualitatively.

In actual experiments, we propose a SrRuO$_3$ / Sr$_2$RuO$_4$ junction as a promising candidate for a $F/I/S$ junction, where SrRuO$_3$ is known as a ferromagnet with a Curie temperature $T_C$ much higher than the transition temperature of Sr$_2$RuO$_4$ ($T_Q$). The direction of the magnetization axis of SrRuO$_3$ is fixed at $T_C < T < T_Q$, and by decreasing the temperature below $T_C$ we can realize $F/I/S$ junctions with an arbitrary direction of the magnetization axis. The response of conductance spectra discussed in the present paper is easily accessible in actual experimental situations. We hope that the present theoretical predictions will be validated in future experiments.

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Figure Captions
Fig. 1. Schematic illustration of ferromagnet / superconductor junction. The direction of the magnetization axis is denoted by a polar coordinate $(\theta_M, \phi_M)$.

Fig. 2. (a) Energy dependence and (b) $\theta_M$ dependence of the normalized conductance for unitary symmetry. In Fig. 2(a), $a$: $\theta_M = 0$, $b$: $\theta_M = \pi/4$ and $c$: $\theta_M = \pi/2$ with $Z = 0$, $X = 0.999$, and $d$: $Z = 0$ with $X = 0$. In Fig. 2(b), $a$: $Z = 0$, $b$: $Z = 1$ and $c$: $Z = 5$ with $X = 0.9$, $eV = 0$. $d$: The $d_{x^2-y^2}$ state for $Z = 1$ with $X = 0.9$ in the case of the existence of ZES.

Fig. 3. Energy dependence of the normalized conductance for unitary symmetry. $a$: $\theta_M = 0$, $b$: $\theta_M = \pi/2$ for $X = 0.9$, and $c$: $\theta_M = 0$, $d$: $\theta_M = \pi/2$ for $X = 0.999$ with $Z = 10$. The inset shows $a$: bound states formed at the surface of the triplet superconductor in the unitary case, and $b$: bound states for $0 \leq \theta_S < \theta_C$ in the ferromagnet / insulator / triplet superconductor junction with $X = 0.9$.

Fig. 4 $\theta_M$ dependence of the normalized conductance for non-unitary symmetry. $a$: $X = 0.7$, $b$: $X = 0.9$ and $c$: $X = 0.999$ with $Z = 5$, $eV = 0$. 
The diagram illustrates the relationship between a ferromagnet and a superconductor. The angles $\theta_M$ and $\phi_M$ represent specific parameters related to the orientation of the magnetic field within the ferromagnet. The notation $U$ likely denotes a vector or scalar quantity associated with the system. The Cartesian coordinates $a$, $b$, and $c$ represent different axes within the superconductor and ferromagnet, respectively.
Normalized conductance $\sigma_T(eV)$ as a function of normalized energy $eV/\Delta_0$. The graph shows four distinct regions labeled $a$, $b$, $c$, and $d$. The y-axis represents $\sigma_T(eV)$, and the x-axis represents normalized energy $eV/\Delta_0$. The graph indicates a transition at a specific energy level.
The graph illustrates the dependence of the normalized conductance $\sigma_T(eV=0)$ on the magnetization angle $\theta_M/\pi$. The conductance varies with different curves labeled as a, b, c, and d, indicating distinct properties across the range of magnetization angles from 0 to $\pi$. The x-axis represents the magnetization angle $\theta_M/\pi$, while the y-axis shows the normalized conductance. The specific behavior and implications of these curves are critical for understanding the system's electronic properties under magnetic influence.
-normalized energy $\frac{E}{\Delta_0}$

-normalized conductance $\sigma$

Injection angle $\theta$

$E_C/\Delta_0$

$(X=0.9)$

$E_C=\Delta_0$

$(X=0.999)$

$eV=\Delta_0$

$\theta_S/\pi$

$\theta_C$
$\sigma_T(eV=0)$

normalized conductance

magnetization angle

$\theta_M/\pi$

$\frac{M}{\pi}$

$\sigma_T(eV=0)$

magnetization angle

$\theta_M/\pi$