Andreev spectroscopy of the triplet superconductivity state in Bi/Ni bilayer system

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We calculate the Andreev spectroscopy between a ferromagnetic lead and Bi/Ni bilayer system for three types of superconducting states, including ABM state, ABM state mixing with $S$-wave state, ABM state mixing with $p_z$-wave state. Among them, ABM state and ABM state mixing with $S$-wave state can obtain the Andreev conductance consistent with the point contact experiment [G. J. Zhao, et al, arXiv:1810.10403], but failed to explain the experiment of time-domain THz spectroscopy experiment [Prashant Chauhan, et al, Phys. Rev. Lett. 122, 017002(2019)]. Only the ABM state mixing with $p_z$-wave state can explain both experiments. Besides, we reveal the conductance peak near the zero energy is induced by the surface state of the ABM phase. Our work may provides helpful clarification for understanding of recent experiments.

I. INTRODUCTION

The triplet $p$-wave superconductors receive a large amount of research interest\cite{1}, which provide new insight for topological superfluidity\cite{1,2}, superconductivity, and new applications in spintronics\cite{3,4}. Among them, the topological $p$-wave superconductors\cite{5,6} attract intensive attention due to potential applications in quantum computing such as the Majorana fermions locating at the edges and the vortex cores\cite{7,8}. Furthermore, the realization of the topological $p$-wave superfluid has been suggested for $\text{He}_3$\cite{9} and superconductivity has been suggested for $\text{Sr}_2\text{RuO}_4$\cite{10,11}. Another peculiar feature of topological materials is the gapless surface states\cite{12,13}. Experimentally, the surface state can be detected by the Andreev spectroscopy\cite{14,15,16}.

Recently, the point contact experiment report the observation of triplet superconductivity in epitaxial Bi/Ni bilayers\cite{17,18,19,20,21,22,23,24}. The zero bias peak on the Andreev conductance between the epitaxial Bi/Ni bilayer and the ferromagnetic metal implies the existence of triplet $p$-wave superconductivity. Furthermore, the quantitative analysis of Andreev conductance show that there may be a triplet $p$-wave Anderson-Brinkman-Morel (ABM) state\cite{25,26}, which have two Weyl node. However, the recent time-domain THz spectroscopy experiment\cite{27} reports a nodeless bulk superconductivity in epitaxial Bi/Ni bilayer. In addition, the inversion symmetry of Bi/Ni bilayer is broken, give rise to the possibility of the mixing of different pairing such as $s$-wave and $p$-wave\cite{28,29}. There are two natural questions associated with the Bi/Ni bilayer system: (1) Is there any superconducting paring other than ABM state at the interface, when inversion symmetry is broken? And (2) Since the behavior of surface states is widely concerned in topological superconductors, what are the contributions of surface states and bulk states of ABM state to transport properties?

We build a model to calculate the Andreev spectroscopy and local density of states of the superconducting materials i.e. the ABM state, the ABM state mixture with $S$-wave pairing and the ABM state mixture with $p_z$-wave pairing. Firstly, we consider the pure ABM state, we calculate the conductance of Andreev reflection using BTK method\cite{30,31} and local density of states by surface Green’s function method\cite{32,33}. We find that the conductance is consistent with the experimental results. Besides, we calculate the local density of states of the unconventional superconductivity state in different crystal directions, and we find that the conductance peak near zero energy comes from the contribution of surface state. Secondly, we consider the ABM state mixture with the $S$-wave superconductivity, and we find that the Andreev conductance is similar with that of pure ABM state when $S$-wave component is small. This is due to the energy band of ABM mixture with $S$-wave still contain two...
nodes. Then, we consider the ABM state mixture with \( p_z \)-wave superconductivity, and we find the Andreev conductance changes from a peak to a bimodal structure due to the energy band of this type of superconductors have an gap.

The paper is organized as follows. In Section II, we build a model to calculate the conductance. In Section III, we calculate the conductance and the surface state of ABM state. In Section IV, we calculate the conductance and surface state of an unconventional superconductivity state, which consist of ABM state and \( S \)-wave state. In Section V, we calculate the conductance and surface state of an unconventional superconductivity state, which contain the ABM state and the \( p_z \)-wave state.

II. MODEL

We consider a normal-metal-superconductor (N-S) junction, and the surface is located at \( x = 0 \) for \( x > 0 \) is the superconductor, \( x < 0 \) is normal metal as shown in FIG. (I a).

The effective Hamiltonian in Nambu representation reads:

\[
H_S = \begin{pmatrix}
\hat{H}_0(k) & \hat{\Delta}(k) \\
-\hat{\Delta}^*(k) & -H_0^*(k)
\end{pmatrix},
\]

with \( \hat{H}_0(k) = \xi_k, \xi_k = \frac{k^2}{2m}k^2 - \mu, \hat{\Delta}(k) = i\Delta \sigma_y \) for singlet pairing or \( \hat{\Delta}(k) = [d(k) \cdot \sigma] \sigma_y \) for triplet pairing

Firstly, we consider the superconducting order parameter of the pure ABM state \( p_z \)-wave superconductor: \( \Delta(k) = \begin{pmatrix} -\Delta_p \sin \theta_k & 0 \\ 0 & -\Delta_p \sin \theta_k \end{pmatrix} \).

where \( \Delta_p \) is superconducting order parameter of \( p_z \)-wave, \( \theta_k \equiv \frac{k_F}{k_F} \) with \( k_F \) is fermi-momentum and \( k_{Fz} \) is \( z \) component of \( k_F \). According to the BTK theorem, the wave function of superconductor \( \Psi_s \) reads:

\[
e^{ik_Fy} [c_1 \psi_1 e^{i\eta_1 x} + c_2 \psi_2 e^{-i\eta_2 x} + c_3 \psi_3 e^{i\eta_3 x} + c_4 \psi_4 e^{-i\eta_4 x}],
\]

where \( \eta_1(2) \) are \( \sqrt{q_{1(2)}^2} \pm k_{Fy}^2 \), \( q_{1(2)}^2 \approx k_F^2 \). Here, \( \psi_{1(2)} = [u_{\psi}(h), 0, -v_{\psi}(h)]^T \) denotes the electron(hole) like state for spin index \( \uparrow \), \( \psi_{3(4)} = [0, u_{\psi}(h), 0, v_{\psi}(h)]^T \) denotes the electron(hole) like state for spin index \( \downarrow \),

\[
u_e = \sqrt{\frac{1}{2}(1 + \frac{\varepsilon_e}{|E|})}, \quad v_h = \sqrt{\frac{1}{2}(1 + \frac{\varepsilon_h}{|E|})}, \quad v_e = \alpha_e \sqrt{\frac{1}{2}(1 - \frac{\varepsilon_e}{|E|})}, \quad v_h = \alpha_h \sqrt{\frac{1}{2}(1 - \frac{\varepsilon_h}{|E|})}, \text{ with } \alpha_e(h) = \alpha_e(h) = \text{sign}(\sin \theta_k) \text{.}
\]

Here, \( \varepsilon_e(h) = \varepsilon_e(h) = \sqrt{\frac{|E|}{4} - \Delta_e(h)^2} \), with \( \Delta_e(h) = \Delta_p \sin \theta_k \), \( \theta_e = \theta_k - \phi \) and \( \theta_h = \pi - \theta_k - \phi \) denote the different effective pair potentials for electronlike quasiparticle and holelike quasiparticle, with \( \theta_q \) depicts the electron incident angle and \( \phi \) represents the angle between the \( x \) axis of the \( p \)-wave and the normal direction of interface as shown in FIG. (I b) (similar with angle \( \alpha \) of \( d \)-wave superconductor).

Secondly, we consider the mixing of \( S \)-wave pairing and ABM state, and its superconducting order parameter has the following form: \( \Delta(k) = -\Delta_p \sin \theta_k \sigma_z + \Delta_h \sigma_y \). Then, the superconducting order parameters split into two independent order parameters: \( \Delta_p - \Delta_h = \Delta_p \sin \theta_k - \Delta_h \) and \( \Delta_e(h) = \Delta_p \sin \theta_k - \Delta_h \) respectively. In this case, the wave function changes to \( \psi_1 = [u_e^+, u_e^-, v_e^+, v_e^-]^T, \psi_2 = [u_h^+, u_h^-, v_h^+, v_h^-]^T, \psi_3 = [u_e^-, u_e^+, v_e^-, v_e^+]^T \) and \( \psi_4 = [u_h^-, u_h^+, v_h^-, v_h^+]^T \). Here, \( u_{e(h)}^+(-)^\dagger \) and \( v_{e(h)}^+(-)^\dagger \) have the same form as the former case, with \( \varepsilon_{e(h)}^\pm = \sqrt{(|E|)^2 - (\Delta_e(h))^2}, \alpha_e(h) = \text{sign}(\Delta_e(h)) \).

Furthermore, we study the influence of \( p_z \)-wave pairing (a type of \( p \)-wave superconductivity that \( \Delta(k) = \Delta_p \hat{z} \)) mixing with ABM phase. In this case, an energy gap can be opened in the energy band of the ABM state. Here, the gap can also be opened by mixing ABM state with \( ip_y \) pairing. Its superconducting order parameter has the following form: \( \Delta(k) = -\Delta_p \sin \theta_k \sigma_z + \Delta_h \sigma_x \). Then, the wave function of superconductor becomes: \( \psi_1 = [u_e^+, u_e^-, v_e^+, v_e^-]^T, \psi_2 = [u_h^+, u_h^-, v_h^+, v_h^-]^T, \psi_3 = [0, u_e^+, \beta_e v_e^+, \beta_e v_e^-]^T \) and \( \psi_4 = [0, u_h^+, \beta_e v_h^+, \beta_e v_h^-]^T \) with \( \alpha_e(h) = 1, \beta_e(h) = \frac{\Delta_p \sin \theta_k}{\sqrt{\Delta_p^2 \sin^2 \theta_k + \Delta_h^2}}, \beta_e(h) = \frac{\Delta_p \sin \theta_k}{\sqrt{\Delta_p^2 \sin^2 \theta_k + \Delta_h^2}} \), and \( \varepsilon_{e(h)}^\pm = \sqrt{(|E|)^2 - \Delta_p \sin \theta_k^2 - \Delta_h^2} \).

The wave function of the lead region from the Hamiltonian: \( \hat{H}_N(k) = \xi_k - \mu \cdot \hat{V} \), where \( \xi_k, \mu \) denote the kinetic energy and the chemical potential respectively. The plane wave at normal metal side can be expressed by a four-component wave function in Nambu representation:

\[
\Psi_N = \begin{pmatrix} e^{ik_Fy} & b_\uparrow & e^{-ik_Fy} & c_\uparrow & e^{-ik_Fy} & a_\uparrow \\
\end{pmatrix} \begin{pmatrix} e^{i(k_Fy)} & b_\uparrow & e^{-i(k_Fy)} & c_\uparrow & e^{-i(k_Fy)} & a_\uparrow \\
\end{pmatrix}.
\]

Here, the first row \( e^{ik_Fy} + b_\uparrow e^{-ik_Fy} \) represents the electron with spin up incident plane wave and normal reflection wave. The second row \( b_\downarrow e^{-ik_Fy} \) represents the electron with spin down wave. The third row \( a_\downarrow e^{ik_Fy} \) represents the hole with spin up Andreev reflection wave. The fourth row \( a_\uparrow e^{i(k_Fy)} + a_\uparrow e^{-i(k_Fy)} \) denotes the evanescent wave. It’s worth noting that we only consider the case of spin-up electron incidence. For fully polarized ferromagnetic electrodes, there are only spin-up electrons in the material, while for non-magnetic electrodes, spin-up and spin-down electrons are
the same, so it is sufficient to consider spin-up electrons only.

Then, we study the transport properties of the N/S junction. We assume that the N/S interface located at \( x = 0 \) along the y axis has an infinitely narrow insulating barrier described by the delta function \( U = U_\delta(x) \). Solving the following boundary conditions

\[
\Psi_S(0) = \Psi_N(0) \]

\[
\frac{\partial \Psi_S(x)}{\partial x}|_{x=0} - \frac{\partial \Psi_N(x)}{\partial x}|_{x=0} = U \Psi_S(0). \tag{5}
\]

we can get the \( a_{\uparrow, \downarrow}(\theta) \) and the \( b_{\uparrow, \downarrow}(\theta) \). The normalized conductance with a bias voltage is

\[
\sigma(eV) = \frac{\int_{-\pi/2}^{\pi/2} g^T(eV) \cos \theta d\theta}{\int_{-\pi/2}^{\pi/2} g^T(\infty) \cos \theta d\theta} \tag{6}
\]

where \( g^T(eV) = \int_0^1 g(|eV + \frac{1}{3}\beta \ln \frac{1-e^{-2}}{1-e^{-2}}|) \), \( g(E) = [1 + \frac{1}{2} \sum_{\rho=\uparrow, \downarrow} |a_{\rho}(\theta, E)|^2 - |b_{\rho}(\theta, E)|^2] \), \( \beta = \frac{1}{2\pi} \). Here, the parameter \( \Gamma \) represents the energy broadening.

### III. THE CONDUCTANCE AND SURFACE STATE OF ABM STATE

First, we calculate the normalized Andreev conductance between ferromagnetic/non-magnetic lead and ABM state at different incident plane which denoted by \( \phi \). Here, we use the interface parameters obtained by fitting the experimental results on the c plane. The experimental results of the c plane are close to the result of when \( \phi \) is equal to 60°, we mainly analyze the case that \( \phi \) is equal to 0° and 60°. Detail information about experimental fitting are given in the appendix.

As shown in FIG. 2(a) and (b), we find that the conductance near zero energy changes from a valley to a peak as \( \phi \) increase. When \( \phi \) is zero, the conductivity near zero energy shows the shape of a valley. With the increase of \( \phi \), the conductance at zero energy gradually increases. It is worth noting that with the increase of \( \phi \), the peak of conductance increases gradually.

Compare the density of states localized on the surface with the energy band of the ABM state, the conductivity at the zero energy comes from the projection of the surface state between the two Weyl points at the zero energy on the incident plane. First of all, we find that the local density of states on the surface is consistent with the conductivity spectrum, so the conductivity comes from the strength of the density of states. Then, as shown in the FIG. 2(c), we find the density of states forms a funnel-like shape, resulting in a valley of conductivity when \( \phi \) is zero. Moreover, as shown in the FIG 2(d)-(f), there is a state which more and more obvious at zero energy, which leads to the formation of a peak value of conductance with the increase of \( \phi \). However, according to FIG 2(b), the band structure of the ABM state is similar to that of the Weyl semimetal, with only two Weyl points at zero energy. According to previous work, there should be a Fermi arc between the two Weyl points. After comparing the density of states with the band structure, the zero energy state is the projection of the Fermi arc on the incident plane.

Here, the conductance spectroscopy of Andreev reflection between ferromagnetic/non-magnetic lead and ABM state at different incident plane is consistent with the density of states. Detail information about the density of states and conductance spectrum are given in the appendix.

### IV. MIXTURE OF ABM STATE AND S-WAVE STATE

The mixing of S-wave and p-wave states is allowed in Bi/Ni bilayer due to the inversion symmetry of Bi/Ni bilayer is broken. Next, we study the Andreev re-
reflection of unconventional superconductors composed of ABM state and S-wave superconductors.

As shown in FIG 3(a) and (b), the Andreev conductance is qualitatively consistent with that of the pure ABM state in case of $\Delta_s < \Delta_p$. However, the Andreev conductance is qualitatively consistent with that of the pure S-wave state in case of $\Delta_s \geq \Delta_p$. Since the conductivity at zero energy mainly comes from the zero energy surface state, then we will study the effect of S-wave component on the surface state.

With the increase of S-wave component, the surface state and bulk state near zero energy gradually weaken and disappear as shown in FIG 3(c) (h). When $\phi = 0^\circ$, the S-wave component will split the density of state of the previous funnel type into two parts: the left and the right. The S-wave component can increase the split. So, the two nodes at zero energy will gradually move away and disappear, resulting in a decrease in the conductance at zero energy. Besides, the overlapping parts of the two after the split have a larger density of states. With the increase of the S-wave component, the higher density region gradually moves away from the zero energy, resulting in the increase of the conductance grain width. However, when the $\phi = 60^\circ$, as the S-wave component increases from 0 to equal to the p-wave component, the surface state will gradually weaken and disappear. When the S-wave component is larger than the p-wave component, the S-wave component will split the density of states into two parts. In this case, as the S-wave component increases, the distance between the two parts and the zero energy increases gradually, resulting in a gradually wider valley of conductance.

In summary, the S-wave component will reduce the surface state and the conductivity at zero energy. When the S-wave component is less than the p-wave component, the conductivity can appear in a shape similar to that of the pure ABM state. However, the energy band still have nodes at zero energy. When the S-wave component is larger than the p-wave component, the conductivity will become the shape of the valley. Therefore, this model should not be able to fully explain the experimental results of Bi/Ni bilayer films. Moreover, in this case, the S-wave component induced decrease of conductance in NM lead is smaller than that of FM lead. Details about the influence of S-wave component on the surface states, conductance as well as conductance spectrum in different incident face in case of FM/NM lead are given in appendix.

V. MIXTURE OF ABM STATE AND $p_z$-WAVE PAIRING

The inversion symmetry broken can induce the mixing of different pairing such as ABM state mixing with $p_z$-wave pairing. This kind of mixing will lead to the opening of an energy gap similar to the experimental results. There are many similar ways to open the energy gap in the energy band, such as adding a small $ip_p$ component to the superconducting order parameter. Next, we focus on the Andreev reflection conductance of an unconventional superconductor composed of ABM state and $p_z$ pairing.

As shown in FIG 4(a) and (b), the $p_z$ component...
FIG. 4: The conductance with different $\Delta p_z$, when (a) $\phi = 0^0$ and (b) $\phi = 60^0$ and the density of states with different $\Delta$, with (c) $\Delta p_z = 0.1\Delta$, (e) $\Delta p_z = 0.2\Delta$ and (g) $\Delta p_z = 0.4\Delta$ when $\theta = 0^0$ and (d) $\Delta p_z = 0.1\Delta$, (f) $\Delta p_z = 0.2\Delta$ and (h) $\Delta p_z = 0.4\Delta$ when $\theta = 60^0$. When the $\phi$ is 0, with the increase of the $p_z$ component, the conductance at the will form a valley which is wider and deeper due to the density of states has a wider and wider energy gap. When the $\phi$ is 60, with the increase of $p_z$ component, the density of states will become a more and more wide energy gap. At this point, the conductance will also gradually form a bimodal structure.

can also decrease the conductance near the zero energy. When the $\phi$ is equal to 0, as the $p_z$ component increases, the depth and width of the conductance valley near the zero energy increase. However, when $\phi = 60^0$, the $p_z$ component affects conductance in two ways. When the $p_z$ component is small, the $p_z$ component can decrease the Andreev reflection spectrum and the normalized conductance at zero energy. In this case, the conductance remains in the shape of a peak. However, when the $p_z$ component is large, the $p_z$ component can make the conductance peak gradually forms a bimodal structure with gradually wider width.

Meanwhile, we find that the density of states splits into two parts that are gradually farther away from each other as the $p_z$ component increase, as shown in FIG 4(c)-(h). In addition, the energy band of superconductor will appear a larger and larger energy gap with the increase of $p_z$ component. Here, the different between the density of states and the Andreev reflection spectrum is due to the broadening of the density of states denoted by $\Gamma$ and interfacial parameter $Z$.

In summary, the Andreev conductance of the unconventional superconductivity state which consist of ABM state and $p_z$ pairing in the limit of lower $\Delta p_z$ and bigger $\Gamma$ is consist with the experiment of the Bi/Ni bilayer. Details about the influence of $\Delta p_z$ on the density of states, the conductance and the conductance spectrum in different incident angle in case of FM lead or NM lead are given in appendix.

VI. SUMMARY

We study the conductance of Andreev reflection in the Bi/Ni bilayer system including the pure ABM state superconductor, ABM state and $S$-wave mixed type superconductor and ABM state and $p_z$ mixed type superconductor. The conductance of Andreev reflections between ferromagnetic or non-magnetic lead and unconventional superconductors and the local state density of the unconventional superconductor surface. Firstly, we find that the conductance of the ABM state is consistent with the experimental results. In addition, the conductance at zero energy is originates from the surface state os ABM phase. Secondly, when the small $S$-wave component is considered, the result is consistent with the pure ABM state qualitatively. Lastly, after considering the influence of the $p_z$ component, the energy band of the superconductor opens the energy gap. With the increase of $p_z$ component, the conductance with large $\phi$ gradually becomes a bimodal structure. Our work provides some complementary explanations for recent experiments.

VII. ACKNOWLEDGMENTS

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Hamiltonian reads:

$$H = \begin{pmatrix} H_{01,01} & H_{01,11} \\ H_{11,01} & H_{01,11} \end{pmatrix}$$

where $H_{il,i'l}$ denote the coupling between $i$ and $i'$ layer. After discretizing the Hamiltonian, the surface green's function can be obtained by the following procedure:

Firstly, we define the parameters:

$$\alpha_0 = (\omega - H_{01,01})^{-1} H_{01,01}$$

$$\beta_0 = (\omega - H_{01,01})^{-1} H_{01,11}$$

(8)

Secondly, we repeat the iteration until $\alpha_i \to 0$, $\beta_i \to 0$

$$\alpha_i = (1 - \alpha_{i-1}\beta_{i-1} - \beta_{i-1}\alpha_{i-1})^{-1}\alpha_{i-1}^2$$

$$\beta_i = (1 - \alpha_{i-1}\beta_{i-1} - \beta_{i-1}\alpha_{i-1})^{-1}\beta_{i-1}^2$$

(9)

Thirdly, Define $T = \alpha_0 + \beta_0 \alpha_1 + \cdots + \beta_0 \beta_1 \cdots \beta_{n-1} \alpha_n$. The surface green function is $\hat{g}_{00} = (\omega - H_{01,01} - H_{01,11}T)^{-1}$. Therefore, we can get the state density on the surface of the superconductor using the surface green's function.

**IX. APPENDIX B: FITTING OF EXPERIMENTAL RESULTS**

Here, we use our model to fit the experimental results of Andreev reflection normalized conductance in both ferromagnetic and non-magnetic lead as FIG 5 shows. For the experimental results of ferromagnetic or non-magnetic lead at different incident surfaces, we adopt different interface parameters and different $\phi$.

For the results of non-magnetic lead, we adopted the following parameters: $\Delta_0 = 2.2$, $Z = 2.2$, $\Gamma = 0.2$, $T = 1.43K$, $\phi = 0.25\pi$ for a plan, $\Delta_0 = 2.2$, $Z = 0.64$, $\Gamma = 0.33$, $T = 1.43K$, $\phi = 0.0\pi$ for b plan, and $\Delta_0 = 2.2$, $Z = 1.8$, $\Gamma = 0.2$, $T = 1.43K$, $\phi = 0.3\pi$ for c plan. For the results of ferromagnetic lead, we adopted the following parameters: $\Delta_0 = 2.0$, $Z = 1.8$, $\Gamma = 0.005$, $T = 1.43K$, $\phi = 0.3\pi$ for a plan, $\Delta_0 = 2.0$, $Z = 0.698$, $\Gamma = 0.02\pi$ for b plan, $\Delta_0 = 2.0$, $Z = 0.608$, $\Gamma = 0.04\pi$ for c plan.

**FIG. 6:** The conductance with different incidence plane. The conductance varies slowly with the change of incident plane.

0.6, $T = 1.43K$, $\phi = 0.0\pi$ for b plan, $\Delta_0 = 2.0$, $Z = 2.6$, $\Gamma = 0.28$, $T = 1.43K$, $\phi = 0.21\pi$ for c plan.

**X. APPENDIX C: THE CONDUCTANCE WITH DIFFERENT INCIDENCE PLANE**

Here, we use our model to calculate the Andreev reflection normalized conductance with different incidence plane using the non-magnetic lead as FIG 6 shows. We find that the conductance changes slowly with the change of incident plane.

**XI. APPENDIX D: THE INFLUENCE OF S-WAVE COMPONENT AND $p_z$ COMPONENT ON ENERGY BAND, CONDUCTANCE AND SURFACE STATES**

Firstly, we calculate the density of states with different $S$-wave component and different incident plane. We find the $S$-wave component have huge influence on energy and density of states.

We find the $S$-wave component can induce a split in the energy band and density of states. As shown in FIG 7(a)-(c), we find that the $S$-wave component can causes the original energy band split in two part. Meanwhile, the $S$-wave component can causes the original hourglass to split in two part. As shown in FIG 7(e)-(g).

Besides, as shown in FIG 7(i)-(k), (m)-(o) and (q)-(s), we find the $S$-wave component can decrease the surface state. When $\Delta_s = \Delta_p$, the surface states disappears completely.

Moreover, we find the $S$-wave component created a growing gap in both of energy band and density of states with different incident plane as shown in FIG 7(c)-(d), (k)-(l), (o)-(p) and (s)-(t).
FIG. 7: Influence of $\Delta_s$ on the surface state in different incident face between lead and superconductor. (a)-(d) is the schematic diagram of energy band of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$. (e)-(h) is the local density of state of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ when $\phi = 0^\circ$. (i)-(l) is the local density of state of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ when $\phi = 30^\circ$. (m)-(p) is the local density of state of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ when $\phi = 60^\circ$. (q)-(t) is the local density of state of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ when $\phi = 90^\circ$. $\Delta_s$ will decrease the conductance near the zero energy and suppress the surface state. When $\Delta_s \geq \Delta_p$ the surface state and conductance peak vanished in case of $\phi > 0$. 
FIG. 8: Influence of $\Delta_s$ on the conductance as well as conductance spectrum in different incident plane between FM lead and superconductor. (a)-(d) is the schematic diagram of energy band of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$. (e)-(h) is the conductance of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ with different $\phi$. (i)-(l) is the conductance spectrum of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ when $\phi = 0^\circ$. (m)-(p) is the conductance spectrum of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ when $\phi = 30^\circ$. (q)-(t) is the conductance spectrum of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ when $\phi = 60^\circ$. (u)-(x) is conductance spectrum of pure ABM states, $\Delta_s = 0.5\Delta_p$, $\Delta_s = \Delta_p$ and $\Delta_s = 2\Delta_p$ when $\phi = 90^\circ$. $\Delta_s$ will decrease the conductance near the zero energy. When $\Delta_s \geq \Delta_p$ the conductance peak vanished in case of $\phi > 0$. 


Secondly, we calculate the influence of $S$-wave component on the conductance in different incident plane between FM lead and superconductor. We find that the $S$-wave component can decrease the conductance near the zero energy.

As shown in FIG 8(e)-(h), we find that the $S$-wave component can decrease the conductance near the zero energy. When $\Delta_s < \Delta_p$, the conductance line still similar to the Andreev conductance of pure ABM state. When $\Delta_s \geq \Delta_p$, the conductance is similar to the Andreev conductance of pure $S$-wave superconductor.

Besides, the influence of $S$-wave component on the conductance spectrum with different incident plane is shown in FIG 8(e)-(x). We find that the conductance spectrum is similar to the local density of states. When $\Delta_s < \Delta_p$ and non-zero $\phi$, the $S$-wave component can decrease the conductance near the zero energy due to the decrease of the surface state near the zero energy. However, when $\Delta_s < \Delta_p$ and $\phi = 0$, the $S$-wave component can decrease the conductance near the zero energy due to the spilt of the density of states. When $\Delta_s \geq \Delta_p$, the $S$-wave component can decrease the conductance far from the zero energy due to the growing gap of the density of states.

It’s worth noting that the conductance spectrum are consistent with the density of states at very small energy expansions ($\Gamma$).

Next, we calculate the influence of $S$-wave component on the conductance in different incident plane between NM lead and superconductor. The conductance and conductance spectrum are different but qualitatively consistent with the situation of the FM lead.

**XII. APPENDIX E: THE INFLUENCE OF $p_z$ COMPONENT ON ENERGY BAND, CONDUCTANCE AND SURFACE STATES**

Firstly, we calculate the density of states with different $p_z$ component and different incident plan. We find the $p_z$ component have huge influence on energy and density of states.

As shown in FIG 9(a)-(o), the $p_z$ component can induce a gap in energy band and density of states.

Secondly, we calculate the influence of $p_z$ component on the conductance in different incident plane between FM lead and superconductor. We find that the $p_z$ component can decrease the conductance near the zero energy.

As shown in FIG 10(d)-(f), the $p_z$ component can decreases the conductance at zero energy and eventually the conductance forms a bimodal structure. Besides, the influence of $S$-wave component on the conductance spectrum with different incident plane is shown in FIG 10(g)-(r). The $p_z$ component can gradually induce a gap in the conductance spectrum. After comparing with the local state density, we find that the difference between the conductance spectrum and density of states mainly comes from the broadening of energy.

Next, we calculate the influence of $p_z$ component on the conductance in different incident plane between NM lead and superconductor. The conductance and conductance spectrum are different but qualitatively consistent with the situation of the FM lead.
FIG. 9: Influence of $\Delta_{p_z}$ on the surface state in different incident face. (a)-(c) is the schematic diagram of energy band of pure ABM states, $\Delta_{p_z} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$. (d)-(f) is the local density of state of pure ABM states, $\Delta_{p_z} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ when $\phi = 0^\circ$. (g)-(i) is the local density of state of pure ABM states, $\Delta_{p_z} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ when $\phi = 30^\circ$. (j)-(l) is the local density of state of pure ABM states, $\Delta_{p_z} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ when $\phi = 60^\circ$. (m)-(o) is the local density of state of pure ABM states, $\Delta_{p_z} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ when $\phi = 90^\circ$. $\Delta_{p_z}$ will open a gap on the energy band and density of states.
FIG. 10: Influence of $\Delta_{pz}$ on the conductance as well as the conductance spectrum in different incident face between FM lead and superconductor. (a)-(c) is the schematic diagram of energy band of pure ABM states, $\Delta_{pz} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$. (d)-(f) is the conductance of pure ABM states, $\Delta_{pz} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ with different $\phi$. (g)-(i) is the conductance spectrum of pure ABM states, $\Delta_{pz} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ when $\phi = 0^\circ$. (j)-(l) is the conductance spectrum of pure ABM states, $\Delta_{pz} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ when $\phi = 30^\circ$. (m)-(o) is the conductance spectrum of pure ABM states, $\Delta_{pz} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ when $\phi = 60^\circ$. (p)-(r) is conductance spectrum of pure ABM states, $\Delta_{pz} = 0.2\Delta_p$ and $\Delta_s = 0.4\Delta_p$ when $\phi = 90^\circ$. $\Delta_{pz}$ will open a gap on the energy band. However, the conductance peak at zero energy still exits due to the interfacial effect.