Andreev bound states in normal and ferromagnet/high-\(T_c\) superconducting tunnel junctions

Mario Freamati and K.-W. Ng

Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, U.S.A.

(Dated: November 6, 2018)

Ag/BSCCO and Fe/Ag/BSCCO planar tunnel junctions were constructed in order to study experimentally the effect of an exchange potential on the spin polarized current transported through Andreev bound states appearing at the interface with a superconductor with broken time reversal pairing symmetry. The zero bias conductance peak (ZBCP) resulting from the Andreev bound states (ABS) is split into two symmetric peaks shifted at finite energies when the counter electrode is normal. Four asymmetric peaks are observed when the ferromagnetic spin polarized charge reservoir is added, due to the combined effect of a spin-filtering exchange energy in the barrier, which is a spin dependent phenomenon, and the spin independent effect of a broken time reversal symmetry (BTRS). The polarization in the iron layer leads to asymmetry. Due to the shift of ABS peaks to finite energies, the conductance at zero energy behaves as predicted by recent theoretical developments for pure \(d\)-wave junctions without Andreev reflections.

PACS numbers: 74.45.+c, 74.50.+r, 75.70.-i

I. INTRODUCTION

Tunneling conductance spectroscopy performed on \(d\)-wave superconductor-insulator-counterelectrode junctions is one of the most powerful experimental tools in the study of pairing properties of high \(T_c\) superconductors (SC) which are still incompletely understood. The tunnel spectra provide a direct measurement of the energy resolved density of states (DOS). One of the most suggestive spectral contributions is due to the Cooper pairs transmitted into the SC as result of the low energy Andreev reflections, leading to spectral features influenced by the superconductive pairing symmetry. Since the Andreev reflection is phase sensitive, the onset and amplitude of Andreev bound states (ABS), manifested through the zero bias conductance peak (ZBCP), are a signature of the symmetry of order parameter (OP). In particular, for the case of cuprates, the \(d\)-wave symmetry of the order parameter was experimentally probed\(^5,6\) and theoretically modeled\(^7\) by analyzing the behavior of ZBCP when the current is injected under different angles of incidence in the ab-plane. The phase of quasiparticles experiencing multiple Andreev reflections by lobes of the OP with different sign may interfere constructively at low energies, resulting in charge-current carrying ABS close to the surface, represented by subgap DOS peaks in the tunneling spectra. The amplitude of the bound state, and hence the height of the ZBCP, is maximum when the injection is along the points of the OP, e.g. close from the [110] surface when the symmetry is \(d_{x^2-y^2}\).

However, while the time reversal symmetric \(d\)-wave OP predominates in the bulk of the SC, a nodeless broken time reversal symmetry (BTRS) state may appear\(^4\) at the junction interface. This is consistent with a \(d_{x^2+y^2}\)-is combination. Experimentally, this results in a split of the ZBCP proportional in magnitude and with an onset temperature dependent on the strength of the \(s\) subcomponent. A similar influence has an \(s\)-wave counter electrode, or may be induced by proximity effect\(^5\). In recent years much experimental\(^6,7,8\) and theoretical\(^9,10\) effort was directed toward understanding the effect of an exchange field on the spin polarized transport in hybrid ferromagnet/\(d\)-wave SC structures. The ZBCP splitting is in fact an energy shift of the ABS peaks and it can be correlated not only to BTRS, which is a spin independent phenomenon, but also to processes magnetic in nature. In this case, the spin distribution of the tunneling carriers becomes important. Thus, it was suggested\(^11,12\) that a spin filtering junction barrier, like a ferromagnet insulator, may also lead to splitting by determining an imbalance between the energy for up and down spin components transported through the junction. As result, the corresponding ABS peaks are shifted towards finite negative and positive energies. This phenomenon is observable as a split ZBCP, with the splitting magnitude dependent on the barrier strength and the spin filtering exchange energy in the barrier. Moreover, if the counterelectrode is a ferromagnet, the DOS spectrum is expected to be asymmetric due to the spin polarization which consequently can be calculated from the ratio of the two unequal peaks\(^5\).

In this paper we report our measurements on a planar Fe/Ag/Bi\(_2\)Sr\(_2\)Ca\(_2\)Cu\(_3\)O\(_8\) (BSCCO) junction where the BTRS splitting effect combines with a the spin dependent energy shift. Due to the Fe polarization, the peaks are asymmetric with the holelike branch (\(E < 0\)) more prominent than the electronlike one. We compare the spectral characteristics and their variation with temperature with an unpolarized junction, Ag/BSCCO.

II. EXPERIMENT AND DISCUSSION

Our junctions employ BSCCO monocrystals cleaved from samples prepared by the self-flux method. The thin film metallic counterelectrodes were evaporated normal
conductance spectra obtained on one of the Ag/BS-SCCO junctions. The $T_c \approx 85$ K and the ZBCP splits with the onset of the $s$-wave subcomponent, at $T_s \approx 20$ K, as shown in Fig. 1 where the splitting occurs at the intersection between conductance curves at $E = 0$ and $E = \pm \Delta_s$. The splitting is symmetric and the amplitude of the peaks is relatively large as in the unpolarized conditions the spin-up and spin-down wave vectors of the quasiparticles are equal, leading to a balanced, maximal contribution from Andreev reflections in both branches of the spectrum.

In Fig. 1 we fitted the subgap spectrum at $T = 4.2$ K, using a BTK-type model modified for anisotropic pairing symmetries. It calculates the DOS in terms of the probability amplitudes of different events occurring at the junction interface. Considering the tunneling conductance for the spin-up and spin-down quasiparticles separately, the total conductance for the charge current incident under angle $\theta$, at energy $E$, is $\sigma_\uparrow(E) = \sigma_{q\uparrow} + \sigma_{q\downarrow}$. The fitting parameters are the $d$-wave gaps $\Delta_{d,s}$, junction orientation $\beta$, barrier strength $Z$ and exchange amplitude $U$, and the ferromagnetic exchange potential $h$ of the counter electrode. To emulate the effect of temperature, a Gaussian smearing factor $\Gamma$ was introduced.

The fit results in a magnitude of 7.3% for the $s$-wave subcomponent. The peaks on the sides of the ZBCP are finite energy ABS and are not discussed in this paper and are not included in the fit. The effect of the BTRS on these peaks is also a shift at lower/higher energies correlated with the ZBCP shift, looking like an increasing inner gap. There is no spin dependent imbalance between the peaks resulting from the ZBCP since there is no exchange field ($h = 0$) and the two contributions $\sigma_{q\uparrow}$, $\sigma_{q\downarrow}$ are equal. Recently Ref. 9 calculated the temperature dependence of the zero bias conductance (ZBC, tunnel conductance at $E = 0$) in $d$ and $p$-wave SC structures. According to this reference, the $d$-wave ZBC is expected to increase with decreasing temperature at $\beta \neq 0$ and finite $Z$ due to the enhanced ZBCP. As shown in Fig. 1 in our case the ZBC decreases monotonically with decreasing temperature, but this contradiction is just apparent because of the splitting. Thus, our junction show a well developed ZBCP at high temperatures, which is common for $\beta \neq 0$ tunneling. If the junction were pure $d$-wave, the ZBCP would increase with decreasing temperature, following the theory outlined in Ref. 9. We explain the temperature dependence of ZBC by the effect of BTRS which flattens and then splits the ZBCP at lower temperatures, leaving the ZBC on the bottom of the inner gap to evolve as in the case of a $\beta = 0$, no ZBCP, junction. On the other hand, the conductance at $E = \pm \Delta_s$ behaves as Ref. 9 predicts for the ZBC of a junction with parameters similar to ours; it varies proportional to the inverse temperature (Fig. 1). Another possible explanation, i.e., the presence of a spin-triplet pairing like $p_y$, is improbable since it brakes the time reversal symmetry and hence the ZBCP would be already split at $T_c$. This is not the case in our experiment where the splitting occurs on the ab-plane of the cuprate (Fig. 1). Two types of junctions were built: Ag/BS-SCCO and Fe/Ag/BS-SCCO junctions. (The procedure is presented in more detail elsewhere.) The thickness of Fe layer was controlled to be $\approx 60$ Å. For approximately this thickness and junction orientation $\beta = 45^\circ$, the amplitude of the ABS at zero bias presents a maximum. The $30$ Å Ag layer in the ferromagnetic junction was intended to decrease the junction interface strength which, if too high, may suppress the spin splitting effect in the barrier. We collected I-V data by standard 4-point measurements, from which the differential conductance was calculated. In our experiment the junction orientation in the ab-plane (angle $\beta$ in Fig. 1) cannot be predetermined. Only some junctions show the ZBCP, indicating a predominant injection with $\beta \neq 0$. In Fig. 1 we present the temperature dependent
at $T \approx 20 \text{ K} < T_c \approx 85 \text{ K}$. The presence of an exchange field in the Fe/Ag/BSCCO junction and the appearance of a naturally induced exchange potential in the junction barrier, combines with the BTRS to influence the ABS, leading to a four-peak asymmetric splitting, marked in Fig. 2, with ABCD arrows. The B-C splitting is due to the spin filtering effect and the A-B, C-D splittings to the much smaller effect of BTRS state. The interface exchange energy filters the spins by lowering the barrier strength for the spin up current and raising it for spin down component, so that the corresponding Andreev peaks (initially located at zero bias, in the absence of BTRS) gain and lose energy, moving at different energy. This phenomenon depends on the quasiparticle trajectories, with the trajectories normal on the barrier experiencing the maximum spin splitting. As result, the ZBCP not only splits, but the resulting peaks broadens with growing exchange potential $U$. This broadening was observed in our experiment, as seen in Fig. 2a,c. The contribution of the barrier spin filtering leads to a peak-to-peak (B-C) splitting of $\approx 27 \text{ meV}$, much larger than the $s$-wave gap, $\Delta_s \approx 2.4 \text{ meV}$, which measures the splitting in case of Ag/BSCCO junction. The bumps on the sides of the peaks are traces of the BTRS effect, resulting in the four-fold splitting (A-B and C-D in Fig. 2c). We fitted the 4.2 K spectrum using the same model as above and obtained the parameters indicated in the figure. The $s$-wave sub-component is small, $\approx 6\%$, and the ABS peaks are broad and high in amplitude, consistent with the $\beta=45^\circ$ injection. The ZBCP splitting is asymmetric, since B-C splitting is spin dependent and hence influenced by the ferromagnet polarization. Consequently, the polarization can be estimated from the peak ratio, which in our case gives $P\approx 35\%$, measured at 4.2 K. For a clearer image of this effect, we plotted separately the peaks corresponding to $\sigma_{q\uparrow}$ shifted to lower (higher) energies. We observed that the splitting appears immediate under $T_c$, but the peaks are symmetric until down to $\approx 32 \text{ K}$ (Fig. 2a). This is visible in Fig. 2b, where we plotted the temperature variation of conductance at zero energy and at energies corresponding to the ingap maxima (ABS peaks). One can see that the peak asymmetry appears only at lower temperatures. This can be explained by the specific temperature dependence of the ferromagnetism of iron very thin layer. It was observed that, in function of layer thickness and temperature, the magnetization in thin ferromagnetic films can experience a reorientation transition from in-plane to perpendicular direction, due to the temperature dependence of perpendicular anisotropy in ultrathin magnetic films. Consequently, while at higher temperatures the peaks are symmetrical since the magnetization is mainly parallel with junction interface, starting with $\approx 32 \text{ K}$ the spins gradually switch to a direction perpendicular on the barrier, into BSCCO ab-plane, so that the iron polarization affects the ABS peaks symmetry.

It was proved that the ABS amplitude decreases with increasing exchange field due to the sensitivity of Andreev reflections to spin polarization, represented in the BTK-type models by a suppression in the Andreev term coefficient. Ref. 9 showed that, at low temperature, this sensitivity is independent of the strength of the barrier and the exchange potential can be evaluated directly from the ZBC since the ABS appear for all quasiparticle trajectories. As in the case of Ag/BSCCO junction, as seen in Fig. 2b, the ZBC variation with temperature conforms qualitatively to Ref. 9 curves for $d$-wave junctions with $\beta=0$, in opposition to the expectation for a junction like ours, exhibiting high amplitude Andreev peaks which rather suggest a nodal orientation (the fit curve actually imposes $\beta=45^\circ$). As in the case of Ag/BSCCO junction, this just apparently contradictory behavior can be explained by the ABS shift to finite energies, so that the low energy DOS, devoid of ABS contribution, is given mainly by single particle processes. As seen in Fig. 2,
the conductance of maximum ABS amplitude (spin up peak shifted at lower energy \(E < 0\)) behave as expected from the pure \(d\)-wave ZBC, with the distortions due to polarization. At lower temperature, due to polarization, the spin up distribution is enhanced in the detriment of the lowering spin down peak, so that the conductance of ABS at \(E > 0\) first increases and then decreases with decreasing temperature, opposite to the monotonically increasing \(E=\Delta_s\) conductance in the \(Ag/BSCO\) case. The special case of some spin-triplet pairing is also excluded since our junctions were highly transparent (small \(Z\)), so that the Andreev reflections are too strong to be suppressed by the exchange interaction responsible at higher \(Z\) for the lowering of ZBC with decreasing temperature, e.g. when the pairing is \(p_y\). Moreover, even if the split appears immediately under \(T_c\), as may be expected for the \(p\)-wave BTRS, the asymmetric effect of polarization on the ABS peaks proves that the splitting cannot be attributed to the BTRS state since this is spin independent.

### III. CONCLUSION

In this paper we report the results of tunneling measurements on two types of junctions, with and without an exchange potential. The ABS in the case of \(Ag/BSCO\) junctions is shifted at low temperature to finite energies, both positively and negatively, due to a BTRS state, so splitting occurs and the zero energy conductance decreases with lowering temperature as in the case of junctions with orientation unfavorable to Andreev reflections. However, when the conductance is measured at the position of the shifted ABS peaks, we observed the dependency proper to the zero energy behavior of pure \(d\)-wave junctions with orientation similar to our junction. In the case of \(Fe/Ag/BSCO\) junctions, the ABS are affected by the combined influence of the spin independent BTRS state and the spin dependent exchange interaction in the barrier. Consequently, the splitting is much larger than the s-wave gap, the spectrum show four peaks, and the spectrum is asymmetric due to the polarization of the ferromagnetic layer. Again, the conductance at zero energy decreases with decreasing temperature since the ABS are displaced to finite energies. The behavior predicted for zero energy conductance is identified at the new position of the spin up peak. However, the spin down peak still decreases with temperature due to the DOS imbalance induced by polarization in the iron layer. The polarization starts to affect the peaks at a transition temperature corresponding to a switch of the iron ultrathin film magnetization from in-plane to normal direction. While the ZBC temperature dependency match the theoretical curves for a \(p_y\)-wave junction, spectral features like the peak asymmetry exclude the possibility of a spin-triplet presence.

---

1. C.R. Hu, Phys. Rev. Lett. 72, 1526 (1994)
2. D.B Bailey, M. Sigrist, and R.B. Laughlin, Phys. Rev. B 55, 15239 (1997)
3. M. Fogelstrm, D.Rainer, and J.A.Sauls, Phys. Rev. Lett. 79, 281 (1997)
4. M. Covington, M. Aprili, E. Paraoanu, L. H. Greene, F. Xu, J. Zhu, and C. A. Mirkin, Phys. Rev. Lett. 79, 277 (1997)
5. S. Sinha and K.-W. Ng, Phys. Rev. Lett. 80, 1296 (1998)
6. X. Hao, J. S. Moodera, and R. Meservey, Phys. Rev. B 42, 8235, (1990)
7. A. Sawa, S. Kashiwaya, H.Obara, H. Yamasaki, M. Koyanagi, and Y. Tanaka, Physica B 284-288, 493 (2000)
8. K. Lee, S. Kim, B. Friedman, D. Cha, and I. Iguchid, Physica C 352, 135 (2001)
9. S. Kashiwaya, Y. Tanaka, N. Yoshida, M.R. Beasley, Phys. Rev. B 60, 3572 (1999)
10. T. Hirai, Y. Tanaka, N. Yoshida, Y. Asano, J. Inoue, and S. Kashiwaya, cond-mat/0210693
11. N. Stefanakis, Phys. Rev. B 64, 224 502 (2001)
12. M. Zareyan, W. Belzig, and Yu. V. Nazarov, Phys. Rev. B 65, 184 505 (2002)
13. Z. Faraii and M. Zareyan, cond-mat/0304336
14. M. Freamat and K.-W. Ng, cond-mat/0301081
15. W. Guo, L. P. Shi, and D. L. Lin, Phys. Rev. B 62, 14259, (2000) and references therein.