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Tunnelling current in triplet superconductors with horizontal lines of nodes

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Abstract
We calculate the tunnelling conductance spectra of a normal-metal/insulator/triplet superconductor using the Blonder–Tinkham–Klapwijk (BTK) formulation. Possible states for the superconductor are considered with horizontal lines of nodes, breaking the time-reversal symmetry. These results would be useful to discriminate between pairing states in the superconductor Sr_2RuO_4 and also in UPt_3.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The recent discovery of superconductivity in Sr_2RuO_4 has attracted much theoretical and experimental interest [1]. Knight-shift measurements show no change when passing through the superconducting state, which is clear evidence for a spin triplet pairing state [2]. Muon spin rotation experiments show that the time-reversal symmetry is broken for the superconductor Sr_2RuO_4 [3]. The linear temperature dependence of the nuclear spin lattice relaxation rate $1/T_1$ of ^{101}Ru below 0.4 K [4] and specific heat measurements [5] are consistent with the presence of line nodes within the gap as in the high-T_c cuprate superconductors.

Knight-shift measurements show that the parity of the pairing function of UPt_3 is odd and a spin triplet pairing state is realized [6]. Muon spin rotation experiments show that the time-reversal symmetry is broken below T_{c2} for the superconductor UPt_3 [7]. The nuclear spin lattice relaxation rate $1/T_1$ and specific heat measurements are consistent with the presence of line nodes within the gap as in the high-T_c cuprate superconductors.

In tunnelling experiments involving singlet superconductors, both line nodes and time-reversal symmetry breaking can be detected from the V-like shape of the spectra and the splitting of the zero energy conductance peak (ZEP) at low temperatures respectively [8–11]. Electron tunnelling in Sr_2RuO_4 has been studied in [12–14] for spin triplet pairing states with vertical lines of nodes. Also, a Josephson effect test for the pairing symmetry of Sr_2RuO_4 has been proposed in reference [15]. Electron tunnelling in UPt_3 has been studied in [16].

In this paper, we discuss the tunnelling effect in a normal-metal/triplet superconductor with horizontal line nodes, taking into account three-dimensional effects. For the triplet superconductor Sr_2RuO_4 we shall assume three possible pairing states of a three-dimensional order parameter, having horizontal lines of nodes, which run parallel to the basal plane and break the time-reversal symmetry. The first two are the pairing states proposed by Hasegawa *et al* [17] having $A_{1g} \times E_u$ symmetry. The other is the f-wave pairing symmetry proposed by H Won and K Maki [18].

For the triplet superconductor UPt_3 we shall assume two possible pairing states of three-dimensional order parameters, having horizontal lines of nodes, which run parallel to the basal plane and break the time-reversal symmetry. These are the planar and bipolar pairing states proposed by Machida *et al* [19].

2. Theory for the tunnelling conductance

The interface has a δ-functional form perpendicular to the z-axis and is located at $z = 0$ as seen in figure 1(*a*) (*xy*-interface). Alternatively, we consider the situation where the interface

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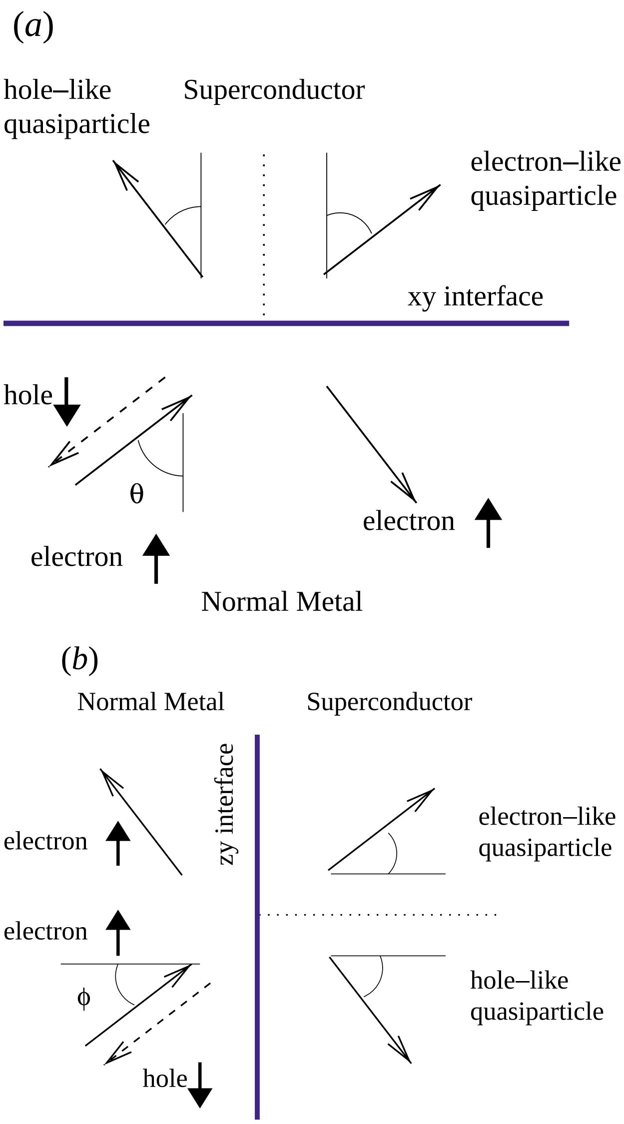

Figure 1. The figure illustrates the transmission and reflection processes of the quasiparticle at the interface of the junction with (*a*) *xy*-plane interface, (*b*) zy-plane interface.

is perpendicular to the *x*-axis and is located at $x = 0$ (zy-interface), see figure 1(*b*). We assume a semi-infinite double layer structure and a spherical Fermi surface. The motion of quasiparticles in inhomogeneous superconductors is described by the solution of the Bogoliubov-deGennes (BdG) equations. The effective pair potential is given by

$$\Delta_{\rho\rho'}(\boldsymbol{k},\boldsymbol{r}) = \Delta_{\rho\rho'}(\phi,\theta)\Theta(z)[\Theta(x)] \tag{1}$$

for the *xy*[zy]-interface, where $k_x, k_y, k_z = \cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta$. ϕ is the azimuthal angle in the *xy*-plane and θ is the polar angle. The quantities ρ, ρ' denote spin indices.

Suppose that an electron is injected from the normal metal with momentum k_x, k_y, k_z, and the interface is perpendicular to the z-axis. The electron (hole)-like quasiparticle will experience different pair potentials $\Delta_{\rho\rho'}(\phi,\theta)$ ($\Delta_{\rho\rho'}(\phi,\pi-\theta)$). When the interface is perpendicular to the *x*-axis, the electron (hole)-like quasiparticle will experience different pair potentials $\Delta_{\rho\rho'}(\phi,\theta)$ ($\Delta_{\rho\rho'}(\pi-\phi,\theta)$). The coefficients of the Andreev and normal reflection for the *xy*-interface are obtained by solving the BdG equations under the following boundary conditions:

$$\Psi(\boldsymbol{r})|_{z=0_-} = \Psi(\boldsymbol{r})|_{z=0_+} \tag{2}$$

$$\left.\frac{\mathrm{d}\Psi(\boldsymbol{r})}{\mathrm{d}z}\right|_{z=0_-} = \left.\frac{\mathrm{d}\Psi(\boldsymbol{r})}{\mathrm{d}z}\right|_{z=0_+} - \left.\frac{2mV}{\hbar^2}\Psi(\boldsymbol{r})\right|_{z=0_-} \tag{3}$$

while for the zy-interface the boundary conditions are

$$\Psi(\boldsymbol{r})|_{x=0_-} = \Psi(\boldsymbol{r})|_{x=0_+} \tag{4}$$

$$\left.\frac{\mathrm{d}\Psi(\boldsymbol{r})}{\mathrm{d}x}\right|_{x=0_-} = \left.\frac{\mathrm{d}\Psi(\boldsymbol{r})}{\mathrm{d}x}\right|_{x=0_+} - \left.\frac{2mV}{\hbar^2}\Psi(\boldsymbol{r})\right|_{x=0_-}. \tag{5}$$

Using the obtained coefficients, the tunnelling conductance for the *xy*-interface is calculated using the formula $\sigma(E) = \sigma_\uparrow(E) + \sigma_\downarrow(E)$, where the conductance for spin-up(-down) quasiparticle is given by the relation

$$\sigma_{\uparrow[\downarrow]}(E) = \frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \bar{\sigma}_{\uparrow[\downarrow]}(E,\phi,\theta)\sin\theta\cos\theta\,\mathrm{d}\phi\,\mathrm{d}\theta}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} 2\sigma_N\sin\theta\cos\theta\,\mathrm{d}\phi\,\mathrm{d}\theta} \tag{6}$$

where the normal-state conductance is given by

$$\sigma_N = \frac{\cos^2\theta}{\cos^2\theta + z_0^2}. \tag{7}$$

The corresponding formula for the tunnelling conductance for the zy-interface is

$$\sigma_{\uparrow[\downarrow]}(E) = \frac{\int_{-\pi/2}^{\pi/2}\int_0^{\frac{\pi}{2}} \bar{\sigma}_{\uparrow[\downarrow]}(E,\phi,\theta)\sin^2\theta\cos\phi\,\mathrm{d}\phi\,\mathrm{d}\theta}{\int_{-\pi/2}^{\pi/2}\int_0^{\frac{\pi}{2}} \sin^2\theta\cos\phi 2\sigma_N\,\mathrm{d}\phi\,\mathrm{d}\theta} \tag{8}$$

where the normal-state conductance is given by

$$\sigma_N = \frac{\cos^2\phi\sin^2\theta}{\cos^2\phi\sin^2\theta + z_0^2}. \tag{9}$$

The pairing potential is described by a 2×2 form

$$\hat{\Delta}_{\alpha,\beta}(\boldsymbol{k}) = \begin{pmatrix} -d_x(\boldsymbol{k}) + \mathrm{i}d_y(\boldsymbol{k}) & d_z(\boldsymbol{k}) \\ d_z(\boldsymbol{k}) & d_x(\boldsymbol{k}) + \mathrm{i}d_y(\boldsymbol{k}) \end{pmatrix} \tag{10}$$

in terms of the $d(\boldsymbol{k}) = (d_x(\boldsymbol{k}), d_y(\boldsymbol{k}), d_z(\boldsymbol{k}))$ vector.

For Sr_2RuO_4 the *d*-vector runs parallel to z-axis (i.e., $d(\boldsymbol{k}) = (0, 0, d_z(\boldsymbol{k}))$. The candidate pairing states are given by

(a) $d_z(\boldsymbol{k}) = (k_x + \mathrm{i}k_y)\cos(ck_z)$, with c being the lattice constant along the c-axis. This state has horizontal lines of nodes at $k_z = \pm\frac{\pi}{2c}$ and breaks the time-reversal symmetry.
(b) $d_z(\boldsymbol{k}) = \left(\sin\left(\frac{ak_x}{2}\right) + \mathrm{i}\sin\left(\frac{ak_y}{2}\right)\right)\cos\left(\frac{ck_z}{2}\right)$, with horizontal lines of nodes at $k_z = \pm\frac{\pi}{c}$.
(c) $d_z(\boldsymbol{k}) = (k_x + \mathrm{i}k_y)^2 k_z$, with horizontal lines of nodes at $k_z = 0$.

Then we will choose two candidate pairing states corresponding to the *B*-phase of UPt_3 (low temperature T and low field H): (a) The unitary planar state with $d(\boldsymbol{k}) = (\lambda_x(\boldsymbol{k}), \lambda_y(\boldsymbol{k}), 0)$ and (b) the non-unitary bipolar state with $d(\boldsymbol{k}) = (\lambda_x(\boldsymbol{k}), \mathrm{i}\lambda_y(\boldsymbol{k}), 0)$ where $\lambda_x(\boldsymbol{k}) = k_z\left(k_x^2 - k_y^2\right)$, $\lambda_y(\boldsymbol{k}) = k_z 2k_x k_y$.

According to the BTK formula, the conductance of the junction, $\bar{\sigma}_{\uparrow[\downarrow]}(E)$, for up(down) spin quasiparticles, is expressed in terms of the probability amplitudes $a_{\uparrow[\downarrow]}, b_{\uparrow[\downarrow]}$ as [8]

$$\bar{\sigma}_{\uparrow[\downarrow]}(E) = 1 + |a_{\uparrow[\downarrow]}|^2 - |b_{\uparrow[\downarrow]}|^2. \tag{11}$$

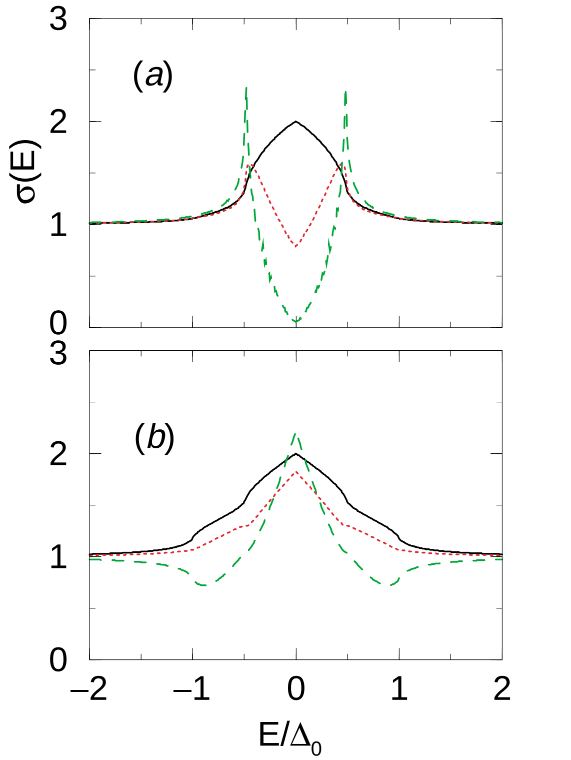

Figure 2. Normalized tunnelling conductance $\sigma(E)$ as a function of E/Δ_0 for $z_0 = 0$ (solid line), $z_0 = 0.5$ (dotted line), $z_0 = 2.5$ (dashed line), for the superconductor Sr_2RuO_4. In (*a*) the interface is perpendicular to the z-axis, and in (*b*) the interface is perpendicular to the x-axis. The pairing symmetry of the superconductor is $(k_x + ik_y)\cos(ck_z)$-wave.

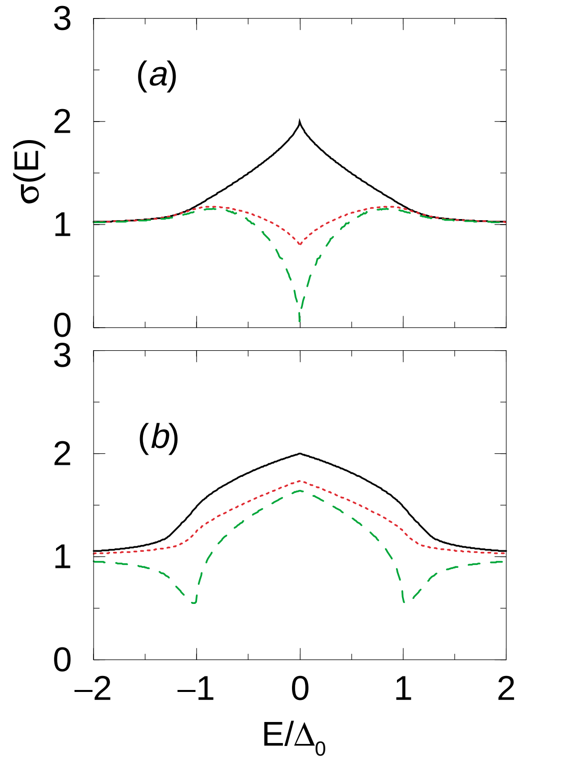

Figure 3. The same as in figure 2. The pairing symmetry of the superconductor is $(\sin(\frac{ak_x}{2}) + i\sin(\frac{ak_y}{2}))\cos(\frac{ck_z}{2})$-wave.

The Andreev and normal reflection amplitudes $a_{\uparrow[\downarrow]}$, $b_{\uparrow[\downarrow]}$ for the spin-up(-down) quasiparticles are obtained as

$$a_{\uparrow[\downarrow]} = \frac{4n_+}{4 + z_0^2 - z_0^2 n_+ n_- \phi_- \phi_+^*} \quad (12)$$

$$b_{\uparrow[\downarrow]} = \frac{-\left(2iz_0 + z_0^2\right) + \left(2iz_0 + z_0^2\right) n_+ n_- \phi_- \phi_+^*}{4 + z_0^2 - z_0^2 n_+ n_- \phi_- \phi_+^*} \quad (13)$$

where $z_0 = \frac{mV}{\hbar^2 k_s}$. The BCS coherence factors are given by

$$u_\pm^2 = [1 + \sqrt{E^2 - |\Delta_\pm|^2}/E]/2 \quad (14)$$

$$v_\pm^2 = [1 - \sqrt{E^2 - |\Delta_\pm|^2}/E]/2 \quad (15)$$

and $n_\pm = v_\pm/u_\pm$. The internal phase coming from the energy gap is given by $\phi_\pm = [\Delta_\pm/|\Delta_\pm|]$, where Δ_+ (Δ_-) is the pair potential experienced by the transmitted electron-like (hole-like) quasiparticle.

3. Sr_2RuO_4

In figures 2–4 we plot the tunnelling conductance $\sigma(E)$ as a function of E/Δ_0 for various values of z_0, for the xy-interface (*a*) and zy-interface (*b*), for the superconductor Sr_2RuO_4. The pairing symmetry of the superconductor is $(k_x + ik_y)\cos(ck_z)$-wave in figure 2, $\left(\sin\left(\frac{ak_x}{2}\right) + i\sin\left(\frac{ak_y}{2}\right)\right)\cos\left(\frac{ck_z}{2}\right)$-wave in figure 3 and $(k_x + ik_y)^2 k_z$-wave in figure 4.

The conductance peak is formed in the electron tunnelling for the xy-interface and zy-interface when the transmitted quasiparticles experience a different sign of the pair potential on the Fermi surface (FS). Also the line shape of the spectra is sensitive to the presence or absence of nodes of the pair potential on the Fermi surface.

For the $(k_x + ik_y)\cos(ck_z)$-wave case, for the xy-interface, the scattering process changes the electron momentum from $(\phi, \pi - \theta)$ to (ϕ, θ) on the FS. However, this process conserves the sign of the pair potential for $0 < \phi < 2\pi$. As a result, no peak exists in the conductance spectra, as seen in figure 2(*a*) for $z_0 = 2.5$. Also the nodes of the pair potential at $k_z = \pm\pi/2c$ intersect the FS along the z-axis and a V-like gap opens in the tunnelling spectra as in the case of the *d*-wave superconductor. On the other hand for the zy-interface the transmitted quasiparticles experience a different sign of the pair potential for (ϕ, θ) and $(\pi - \phi, \theta)$ only at discrete ϕ-values that explain the residual values of the conductance within the energy gap seen in figure 2(*b*). Recent measurements of the thermal conductivity for the superconductor Sr_2RuO_4 in magnetic field, rotating within the planes, demonstrated that the gap function is $(k_x + ik_y)(\cos(ck_z) + a_0)$ [20].

The spectra is sensitive to the amount of mixing between the nodal and the nodeless component which is determined by the value of a_0. If $|a_0| < 1$ the horizontal lines of nodes still exist but at different positions along the k_z axis. Therefore, we expect the tunnelling spectra to be qualitatively similar to that for the pairing state $(k_x + ik_y)\cos(ck_z)$.

For the $\left(\sin\left(\frac{ak_x}{2}\right) + i\sin\left(\frac{ak_y}{2}\right)\right)\cos\left(\frac{ck_z}{2}\right)$-wave case, and for the xy-interface, the scattering process in the momentum space connects points of the FS with the same sign as in the $(k_x + ik_y)\cos(ck_z)$-wave case. This means that the pair potential does not change sign and no ZEP is formed as seen in

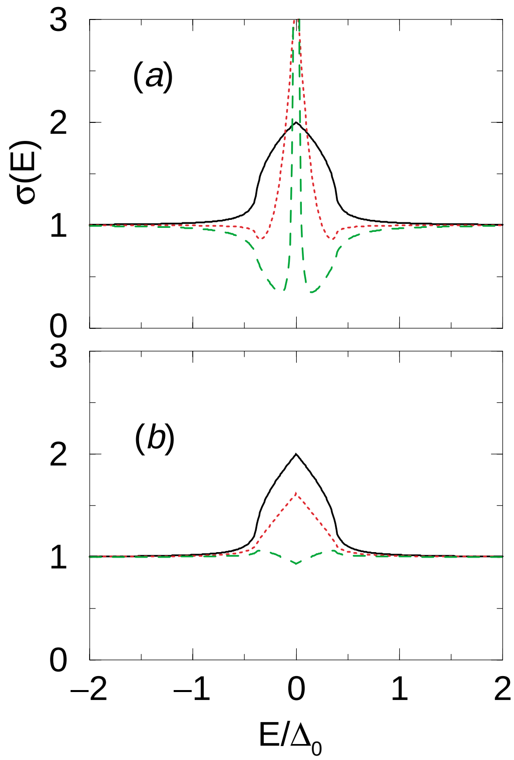

Figure 4. The same as in figure 2. The pairing symmetry of the superconductor is $(k_x + \mathrm{i}k_y)^2 k_z$-wave.

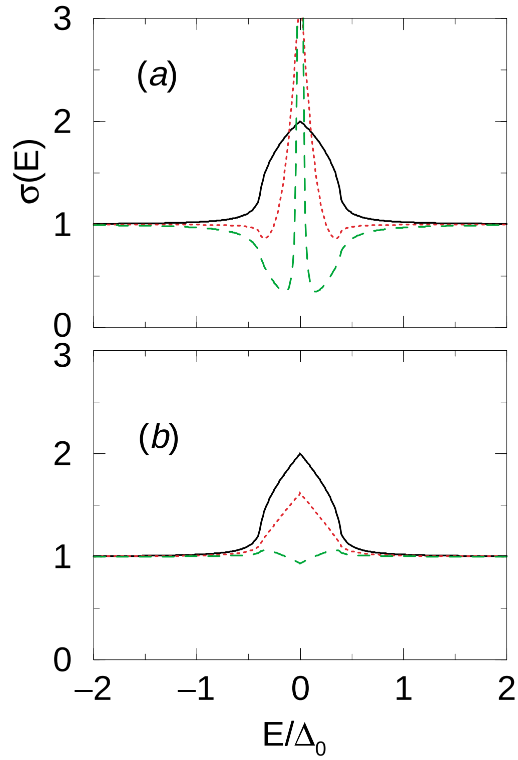

Figure 5. Normalized tunnelling conductance $\sigma(E)$ as a function of E/Δ_0 for $z_0 = 0$ (solid line), $z_0 = 0.5$ (dotted line), $z_0 = 2.5$ (dashed line), for the superconductor UPt_3. The pairing symmetry of the superconductor is planar.

figure 3(*a*). However, the pair potential intersects the spherical FS at the poles, i.e., at $k_z = \pm\pi/c$, forming point-like nodes. This explains the logarithmic singularity at $E = 0$ at the spectra. The tunnelling spectra for the zy-interface are enhanced due to the bound states that are formed at discrete values of the quasiparticle angle ϕ as seen in figure 3(*b*).

The situation is opposite in the $(k_x + \mathrm{i}k_y)^2 k_z$-wave case where the scattering process for *xy*-interface connects points of the FS, i.e., $(\phi, \pi - \theta)$ and (ϕ, θ), with the opposite signs. As a consequence the ZEP is formed, for $0 < \phi < 2\pi$ as seen in figure 4(*a*). Also in this case, the node of the pair potential at $k_z = 0$ intersects the FS and the spectra have a V-shaped form as in the $(k_x + \mathrm{i}k_y)\cos(ck_z)$-wave case. For the zy-interface, the order parameter has the same ϕ-dependence as in the $(k_x + \mathrm{i}k_y)\cos(ck_z)$-wave, and the tunnelling spectra for the zy-interface are similar.

The conclusion is that the tunnelling at the *xy*-interface can be used to distinguish the pairing states with horizontal lines of nodes on the FS. The numerical results presented here are in agreement with recent analytical calculation for the case of the low transparency barrier and triplet pairing states with horizontal lines of nodes [21]. Also only one electron band for Sr_2RuO_4 contributes to superconductivity. However, it has been proposed recently that the γ band is nodeless while α and β bands have horizontal lines of nodes [22]. In this case, all three bands contribute to the pairing state and the actual shape of the spectra depends on the amount of contribution of different bands.

In this paragraph, a comparison is made between the pairing states examined here and the corresponding states without the k_z-dependence. For the $k_x + \mathrm{i}k_y$-wave case, for the *xy*-interface, the gap has a U-shaped structure due to the absence of sign change of the order parameter along the z-axis. For the zy-interface, the difference is more pronounced at $z_0 = 0$ where $\sigma(E)$ is constant within the gap for the $k_x + \mathrm{i}k_y$-wave case, while it possesses a Λ-shaped structure for the $(k_x + \mathrm{i}k_y)\cos(ck_z)$-wave.

For the $\sin\left(\frac{ak_x}{2}\right) + \mathrm{i}\sin\left(\frac{ak_y}{2}\right)$-wave, and *xy*-interface, the spectra is expected to have the U-shaped line shape, while for the zy-interface the spectra should have residual values due to the presence of bound states. However, a detailed calculation is needed to account for the actual shape of the spectra.

4. UPt_3

In figures 5 and 6 we plot the tunnelling conductance $\sigma(E)$ as a function of E/Δ_0 for various values of z_0, for the *xy*-interface (*a*) and zy-interface (*b*), for the superconductor UPt_3. The pairing symmetry of the superconductor is the unitary planar in figure 5 and the non-unitary bipolar in figure 6.

The conductance peak is formed in the electron tunnelling for the *xy*-interface and zy-interface when the transmitted quasiparticles experience a different sign of the pair potential on the Fermi surface (FS). Also the line shape of the spectra is sensitive to the presence or absence of nodes of the pair potential on the FS.

For the planar case for the *xy*-interface, the scattering process changes the electron momentum from $(\phi, \pi - \theta)$ to (ϕ, θ) on the FS. This process changes the sign of the pair potential for $0 < \phi < 2\pi$. As a result, a peak exists in the

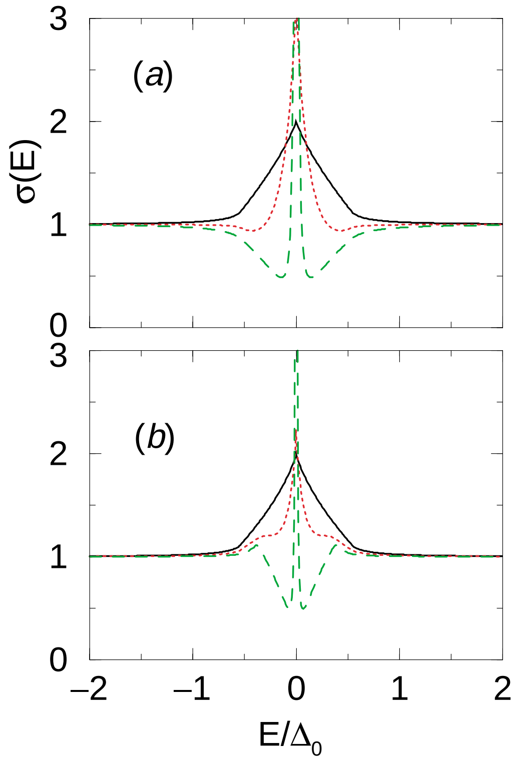

Figure 6. The same as in figure 5. The pairing symmetry of the superconductor is bipolar.

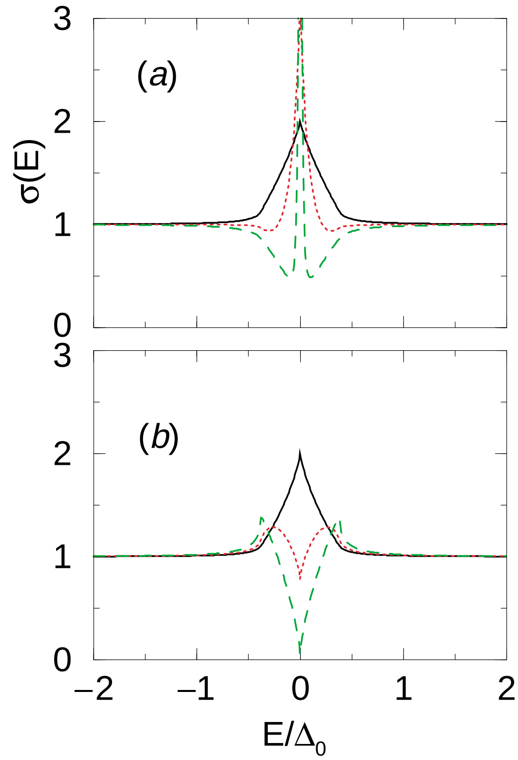

Figure 7. The same as in figure 5. The pairing symmetry describes the A phase of UPt_3 where the secondary component of the order parameter vanishes.

conductance spectra as seen in figure 5(*a*) for $z_0 = 2.5$. Also the nodes of the pair potential at $k_z = 0$ intersect the FS along the z-axis and a V-like gap opens in the tunnelling spectra as in the case of the *d*-wave superconductor. On the other hand for the zy-interface, the transmitted quasiparticles experience a different sign of the pair potential for (ϕ, θ) and $(\pi - \phi, \theta)$ only at discrete ϕ-values that explain the residual values of the conductance within the energy gap seen in figure 5(*b*).

For the bipolar case, and for the *xy*-interface, the scattering process in the momentum space connects points of the FS with a different sign as in the planar-wave case. This means that the pair potential changes sign and a ZEP is formed as seen in figure 6(*a*). The tunnelling spectra for the zy-interface are enhanced due to the sign change caused by the scattering (ϕ, θ) to $(\pi - \phi, \theta)$ as seen in figure 6(*b*).

The conclusion is that the tunnelling at the zy-interface can be used to distinguish the pairing states with horizontal lines of nodes on the FS.

In this paragraph, we analyse the pairing state corresponding to the A phase (high T, low H) of UPt_3, where the secondary order parameter vanishes. The resulting order parameter does not break the time-reversal symmetry. For the *xy*-interface, the spectra has a ZEP due to the sign change of the order parameter along the z-axis as seen in figure 7(*a*). Also the line shape of the spectra is V-like because the nodes of the pair potential at $k_z = 0$ intersect the FS. For the zy-interface, the scattering process from (ϕ, θ) to $(\pi - \phi, \theta)$ does not change the sign of the pair potential and no ZEP occurs as seen in figure 7(*b*). However, the line nodes which run parallel to k_z intersect the FS and the spectra are V-shaped.

5. Experimental relevance

In this section, a comparison of the existing tunnelling experiments on Sr_2RuO_4 and UPt_3 is done. The tunnelling experiments that have been performed on cleaved *c*-axis junctions of Ru-embedded Sr_2RuO_4 show a bell-shaped spectrum with a sharp peak at zero bias for the 1.4-T phase and a sharp ZEP for the 3-K phase [23]. The spectra for the 1.4-K phase are similar to the board ZEP observed in Ru-free Sr_2RuO_4 via point contact spectroscopy [24], although their experiments actually measure the tunnelling resistance. This type of spectra for the 1.4-K phase are consistent with nodeless Eu pairing state where the broadening of the ZEP is due to the presence of Andreev bound states. The sharp peak seen in the 3-K phase is an indication of a pairing state with horizontal lines of nodes. It has been suggested that a phase transition occurs where the 3-K phase with line node transforms to a nodeless Eu state close to the bulk T_c [25]. In the experiments of Mao *et al* [23] the tunnelling direction is along the *c*-axis. However, the experimentalists believe that the Andreev reflection takes place in the in-plane direction due to the Ru inclusions. Then the pairing state that fits well with the experimental data for the zy-interface is $d_z(\boldsymbol{k}) = (k_x + \mathrm{i}k_y)\cos(ck_z)$ as seen in figure 2(*b*), rather than $d_z(\boldsymbol{k}) = \left(\sin\left(\frac{ak_x}{2}\right) + \mathrm{i}\sin\left(\frac{ak_y}{2}\right)\right)\cos\left(\frac{ck_z}{2}\right)$ and $d_z(\boldsymbol{k}) = (k_x + \mathrm{i}k_y)^2 k_z$, as seen in figures 3(*b*) and 4(*b*). On the other hand if the Andreev reflection occurs in the *c*-axis direction then the pairing state which fits more precisely with the experimental data is $d_z(\boldsymbol{k}) = (k_x + \mathrm{i}k_y)^2 k_z$ which shows a clear ZEP for the *xy*-interface, for the low transparency barrier as seen in figure 4(*a*).

Point contact spectroscopy for heavy fermion superconductors UPt_3 has been performed where distinct minima in the differential resistance versus voltage have been observed for current flow parallel to the *c*-axis, and only very weak structures—if at all—have been observed for current flow within the basal plane [26]. Their observation is consistent with the calculated tunnelling conductance for the unitary planar state seen in figures 5(*a*) and (*b*), for the tunnelling conductance along the *c*-axis and *a*-axis respectively. Moreover measurements of the differential conductivity of UBe_{13}–Au contacts, where the UBe_{13} is in polycrystalline form, reveal the existence of low-energy Andreev surface bound states, which are identified by the presence of ZEP and are consistent with an order parameter with nontrivial symmetry of the energy gap [27].

6. Conclusions

We calculated the tunnelling conductance in normal-metal/insulator/triplet superconductor with horizontal lines of nodes, junction using the BTK formalism. We assumed possible pairing potentials for the superconductor that break the time-reversal symmetry. For the Sr_2RuO_4 the tunnelling at the *xy*-interface can be used to distinguish the pairing states with horizontal lines of nodes from the ZEP that is formed when the pair potential changes its sign on the FS during the scattering process. Also for the *xy*-interface, the line shape of the spectra is V-like due to the presence of nodes of the pair potential along the z-axis at the FS, while for the zy-interface the tunnelling conductance has residual values due to the formation of bound states at discrete values of the angle ϕ.

For the UPt_3, for the tunnelling along the z-axis, a ZEP is formed for the pairing states we examined, while the spectra along the x-axis have residual values or develop a ZEP depending on the details of the pairing state. In each case, the observation of a ZEP in the tunnelling experiments is consistent with an order parameter with non-trivial symmetry of the energy gap.

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