

Tunneling Spectra for Quasi-One-Dimensional Organic Superconductors

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The tunneling conductance spectra of a normal metal/insulator/quasi-one-dimensional superconductor is calculated using the Blonder-Tinkham-Klapwijk formulation. The pairing symmetry of the superconductor is assumed to be p or d, and f-wave. It is found that there is a well-defined zero-bias peak in electron tunneling along the direction parallel to the chains or normal to these when the transmitted quasiparticles feel different sign of the pair potential. The actual line shape of the spectra is sensitive to the nodes of the pair potential on the Fermi surface.

KEY WORDS: tunneling spectra; organic superconductors; Andreev reflection; zero energy peak.

1. INTRODUCTION

Almost 20 years after the discovery of the organic superconductors [1], the problem of determination of their pairing state has not yet found a definite solution. The critical magnetic field H_{c2} exceeds the Pauli paramagnetic limit and indicates that the pairing symmetry is triplet [2]. The Knight shift does not change between the normal and superconducting states and it is a signature for triplet pairing state [3]. However the absence of Hebel-Slichter peak and the power-law decay of $1/T_1$ below T_c [4] is an indication of the presence of nodes of the pair potential on the Fermi surface.

The scattering theory [5,6] can be used to distinguish the symmetry of the pair potential. In d-wave superconductors, the pair potential changes sign under a 90° rotation. And so under appropriate orientation of the a axis of the ab plane of d-wave superconductor the transmitted quasiparticles feel different sign of the pair potential. This results in the formation of bound states within the energy gap, which are detected as zero-energy peaks (ZEP) in the conductance spectra [7–10].

The scattering theory has also been used for the determination of the pairing symmetry in (TMTSF)₂X [11]. However their calculation is restricted to the presence or absence of ZEP at the surface, which can not distinguish the p from the f-wave case. In a more realistic calculation, Tanuma *et al.* [12] used the extended Hubbard model on a quasi-one-dimensional lattice at quarter-filling to study the quasiparticle states near the surface of a quasi-one-dimensional organic superconductor, where the pairing symmetry can actually be distinguished from the overall line shape of the surface density of states (SDOS) and the presence or absence of ZEP.

In this paper, we extend the BTK formula to calculate the tunneling conductance in a normal metal/insulator/quasi-one-dimensional organic superconductor, where the structure of the Fermi surface is taken into account. The pairing symmetry of the superconductor is assumed to be triplet p, singlet d, d_{xy} , and triplet f-wave. In particular, we find that the ZEP appears in the electron tunneling along the a or b axis, when the transmitted quasiparticles experience different sign of the pair potential. Also, the line shape of the spectra is sensitive to the presence or absence of nodes of the pair potential on the Fermi surface. The present calculation is useful for (TMTSF)₂PF₆, although this salt needs pressure to show superconductivity and is not very suitable for

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(TMTSF)₂ClO₄, which is the only material exhibiting superconductivity in the Bechgaard salts at ambient pressure, but its unit cell is doubled due to anion ordering [13]. Tunneling spectroscopy on the quasi-two-dimensional organic superconductor κ -(BEDT-TTF)₂Cu(NCS)₂ has also been performed using scanning tunneling microscopy [14]. In this compound, the conducting Cu(NCS)₂ layers run parallel to the *bc* plane, along the *a* axis, and the in-plane tunneling data strongly suggest d-wave pairing state. These features can be used to distinguish the pairing symmetry in quasi-one-dimensional organic superconductor.

2. THE MODEL FOR THE NS INTERFACE

The motion of quasiparticles in inhomogeneous superconductors is described by the four-component Bogoliubov de Gennes (BdG) equations. The BdG equations are decoupled into two sets of (two-component) equations, one for the spin-up electron, spin-down hole quasiparticle wave functions ($u_\uparrow(\mathbf{r}), v_\downarrow(\mathbf{r})$) and the other for ($u_\downarrow(\mathbf{r}), v_\uparrow(\mathbf{r})$). The BdG equation for spin index $s(\bar{s}) = \uparrow(\downarrow)$ or $s(\bar{s}) = \downarrow(\uparrow)$ read [8]

$$\begin{aligned} (\mathcal{H}_e(\mathbf{r}) - s\mu_B H)u_s(\mathbf{r}) + \int d\mathbf{r}' \Delta_{s\bar{s}}(\mathbf{s}, \mathbf{x})v_{\bar{s}}(\mathbf{r}') \\ = E_s u_s(\mathbf{r}), \\ \int d\mathbf{r}' \Delta_{s\bar{s}}^*(\mathbf{s}, \mathbf{x})u_s(\mathbf{r}') - (\mathcal{H}_e^*(\mathbf{r}) - s\mu_B H)v_{\bar{s}}(\mathbf{r}) \\ = E_s v_{\bar{s}}(\mathbf{r}). \end{aligned} \quad (1)$$

The single-particle Hamiltonian is given by $\mathcal{H}_e(\mathbf{r}) = -\hbar^2 \nabla^2 / 2m_e + V(\mathbf{r}) - E_F$, where H is the external magnetic field, and E_s is the energy measured from the Fermi energy E_F . For a given spin projection s , the magnetic field shifts the energy by $-s\mu_B H$. $\Delta_{s\bar{s}}(\mathbf{s}, \mathbf{x})$ is the pair potential, after a transformation from the position coordinates \mathbf{r}, \mathbf{r}' to the center of mass coordinate $\mathbf{x} = (\mathbf{r} + \mathbf{r}')/2$ and the relative vector $\mathbf{s} = \mathbf{r} - \mathbf{r}'$. After Fourier transformation the pair potential depends on the relative wave vector \mathbf{k} and \mathbf{x} . In the weak coupling limit \mathbf{k} is fixed on the Fermi surface ($|\mathbf{k}| = k_F$), and only its direction is variable. After applying the quasiclassical approximation [8], i.e.

$$\begin{pmatrix} \bar{u}_s(\mathbf{r}) \\ \bar{v}_{\bar{s}}(\mathbf{r}) \end{pmatrix} = e^{-i\mathbf{k}\cdot\mathbf{r}} \begin{pmatrix} u_s(\mathbf{r}) \\ v_{\bar{s}}(\mathbf{r}) \end{pmatrix}, \quad (2)$$

so that the fast-oscillating part of the wave function is divided out, the BdG equations are reduced to the

Andreev equations [6]

$$\begin{aligned} E_s \bar{u}_s(\mathbf{r}) &= -i v_F \mathbf{k} \cdot \nabla \bar{u}_s(\mathbf{r}) + \Delta_{s\bar{s}}(\mathbf{k}, \mathbf{r}) \bar{v}_{\bar{s}}(\mathbf{r}), \\ E_s \bar{v}_{\bar{s}}(\mathbf{r}) &= -i v_F \mathbf{k} \cdot \nabla \bar{v}_{\bar{s}}(\mathbf{r}) + \Delta_{s\bar{s}}^*(\mathbf{k}, \mathbf{r}) \bar{u}_s(\mathbf{r}), \end{aligned} \quad (3)$$

where the quantities $\bar{u}_s(\mathbf{r})$ and $\bar{v}_{\bar{s}}(\mathbf{r})$ are electronlike and holelike quasiparticles with spin index s , and \bar{s} respectively, and v_F is the Fermi velocity. We consider the normal metal/insulator/superconductor junction shown in Fig. 1. The electron momentum parallel to the interface $k_{||}$ is conserved. For the interface seen in Fig. 1a, the insulator is modeled by a delta function located at $x = 0$, of the form $V \delta(x)$. The temperature is fixed at 0 K. We take the pair potential as a step function, i.e. $\Delta_{s\bar{s}}(k_{||}, \mathbf{r}) = \Theta(x) \Delta_{s\bar{s}}(k_{||})$. For the geometry

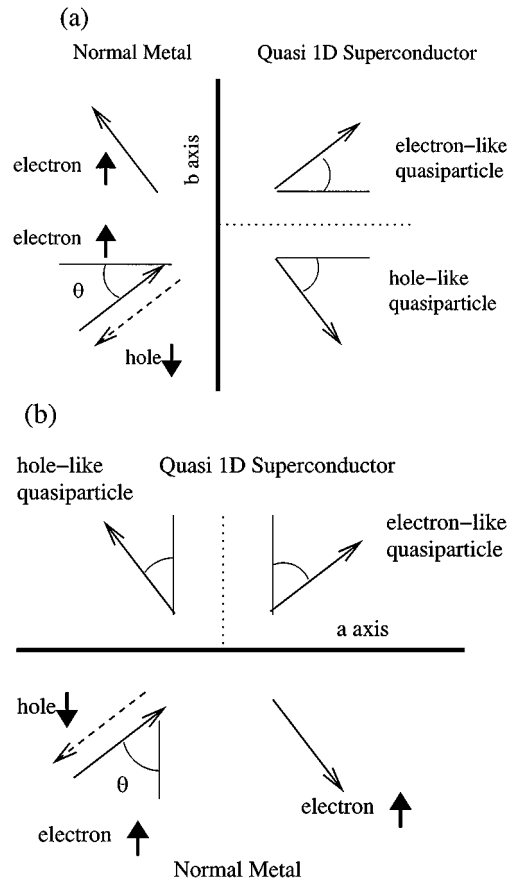


Fig. 1. The geometry of the normal metal/insulator/quasi-one-superconductor interface. The arrows illustrate the transmission and reflection processes at the interface. (a) The insulator (vertical line) is normal to the *a* axis. (b) The insulator (horizontal line) is normal to the *b* axis.

shown in Fig. 1, Eqs. (3) take the form

$$\begin{aligned} E_s \bar{u}_s(x) &= -i v_F k_{F_x} \frac{d}{dx} \bar{u}_s(x) + \Delta_{s\bar{s}}(k_{||}) \bar{v}_{\bar{s}}(x), \\ E_s \bar{v}_{\bar{s}}(x) &= -i v_F k_{F_x} \frac{d}{dx} \bar{v}_{\bar{s}}(x) + \Delta_{s\bar{s}}^*(k_{||}) \bar{u}_s(x). \end{aligned} \quad (4)$$

When a beam of electrons is incident from the normal metal to the insulator, with momentum k , the general solution of Eqs. (4) is the two-component wave function $\Psi_I = (u_{\uparrow[\downarrow]}, v_{\downarrow[\uparrow]})$, which for $x < 0$ is written as

$$\begin{aligned} \Psi_I &= \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{i x k_{F_x}} + a_{\uparrow[\downarrow]} \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{i x k_{F_x}} \\ &+ b_{\uparrow[\downarrow]} \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-i x k_{F_x}}, \end{aligned} \quad (5)$$

where $a_{\uparrow[\downarrow]}$, $b_{\uparrow[\downarrow]}$ are the amplitudes for Andreev and normal reflection for spin-up (down) quasiparticles, k_{F_x} is the x -component of the Fermi wave vector $k_F = \sqrt{\frac{2mE_F}{\hbar^2}}$. The wave vector of quasiparticles in the normal metal, and the wave vector of the electron-like, holelike quasiparticles in the superconductor are set equal. Since the translational symmetry holds in the y axis direction, the momenta parallel to the interface is conserved. Using the matching conditions of the wave function at $x = 0$, $\Psi_I(0) = \Psi_{II}(0)$, and $\Psi'_I(0) - \Psi'_{II}(0) = (2mV/\hbar^2)\Psi_I(0)$, the Andreev and normal reflection amplitudes $a_{\uparrow[\downarrow]}$, $b_{\uparrow[\downarrow]}$ for the spin-up (down) quasiparticles are obtained as

$$a_{\uparrow[\downarrow]} = \frac{4n_+}{4 + z_{\uparrow[\downarrow]}^2 - z_{\uparrow[\downarrow]}^2 n_+ n_- \phi_- \phi_+^*}, \quad (6)$$

$$b_{\uparrow[\downarrow]} = \frac{-(2i z_{\uparrow[\downarrow]} + z_{\uparrow[\downarrow]}^2) + (2i z_{\uparrow[\downarrow]} + z_{\uparrow[\downarrow]}^2) n_+ n_- \phi_- \phi_+^*}{4 + z_{\uparrow[\downarrow]}^2 - z_{\uparrow[\downarrow]}^2 n_+ n_- \phi_- \phi_+^*}, \quad (7)$$

where $z_0 = \frac{mV}{\hbar^2 k_s}$, $z_{\uparrow[\downarrow]} = \frac{2z_0}{k_{F_x}}$. The BCS coherence factors are given by

$$u_{\pm}^2 = [1 + \sqrt{E^2 - |\Delta_{\pm}|^2}/E]/2, \quad (8)$$

$$v_{\pm}^2 = [1 + \sqrt{E^2 - |\Delta_{\pm}|^2}/E]/2, \quad (9)$$

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 electronlike (holelike) quasiparticle.

According to the BTK formula, the conductance of the junction $\bar{\sigma}_{\uparrow[\downarrow]}(E_s, k_{||})$ for spin-up (down) quasiparticles is expressed in terms of the probability amplitudes $a_{\uparrow[\downarrow]}$, $b_{\uparrow[\downarrow]}$ as [5]

$$\bar{\sigma}_{\uparrow[\downarrow]}(E_s, k_{||}) = 1 + |a_{\uparrow[\downarrow]}|^2 - |b_{\uparrow[\downarrow]}|^2. \quad (10)$$

The tunneling conductance normalized by that in the normal state is given by

$$\sigma(E) = \sigma_{\uparrow}(E_{\uparrow}) + \sigma_{\downarrow}(E_{\downarrow}), \quad (11)$$

$$\sigma_{\uparrow[\downarrow]}(E_s) = \frac{1}{R_N} \int_{-k_{||}^{\max}}^{k_{||}^{\max}} dk_{||} [\bar{\sigma}_{\uparrow[\downarrow]}(E_s, k_{||})], \quad (12)$$

where

$$R_N = \int_{-k_{||}^{\max}}^{k_{||}^{\max}} dk_{||} [\sigma_{N\uparrow}(k_{||}) + \sigma_{N\downarrow}(k_{||})], \quad (13)$$

$$\sigma_{N\uparrow[\downarrow]}(k_{||}) = \frac{4\lambda_1}{4 + z_{\uparrow[\downarrow]}^2}. \quad (14)$$

3. PAIRING STATES AND FERMI SURFACE LINE SHAPE

For the spin triplet pairing state the Cooper pairs have spin 1 degree of freedom. The gap function is a 2×2 symmetric matrix that in the spin space can be written as

$$\hat{\Delta}(\mathbf{k}) = i\sigma_y(\mathbf{d} \cdot \hat{\boldsymbol{\sigma}}), \quad (15)$$

where $\hat{\boldsymbol{\sigma}}$ denotes the Pauli matrices and \mathbf{d} is a vector that defines the axis along which the Cooper pairs have zero spin projection. In the following we will take $\mathbf{d} \parallel \hat{\mathbf{a}}$, i.e. parallel to the chains. In that case $\Delta_{\uparrow\uparrow} = \Delta_{\downarrow\downarrow} = 0$, while $\Delta_{\uparrow\downarrow} = \Delta_{\downarrow\uparrow} = \Delta(k_{||})$.

The Fermi surface (FS) consists of two branches and is open in the k_y direction, as shown in Fig. 2.

We consider the following pairing cases

(a) In case of p_x -wave, p_y -wave superconductor

$$\Delta_{p_x} = \Delta_0 \sin(2k_x a), \quad \Delta_{p_y} = \Delta_0 \sin(k_y a). \quad (16)$$

Δ_{p_x} changes its sign along the FS in the k_x direction while the Δ_{p_y} changes its sign along the FS in the k_y direction as seen in Fig. 2a,d.

(b) In case of d_x -wave, d_y -wave superconductor

$$\Delta_{d_x} = \Delta_0 \cos(2k_x a), \quad \Delta_{d_y} = \Delta_0 \cos(k_y a) \quad (17)$$

Δ_{d_x} changes its sign along the FS in the k_x direction while the Δ_{d_y} changes its sign along the FS in the k_y direction as seen in Fig. 2b,e.

(c) In case of f_x -wave, f_y -wave superconductor

$$\Delta_{f_x} = \Delta_0 \sin(4k_x a), \quad \Delta_{f_y} = \Delta_0 \sin(2k_y a) \quad (18)$$

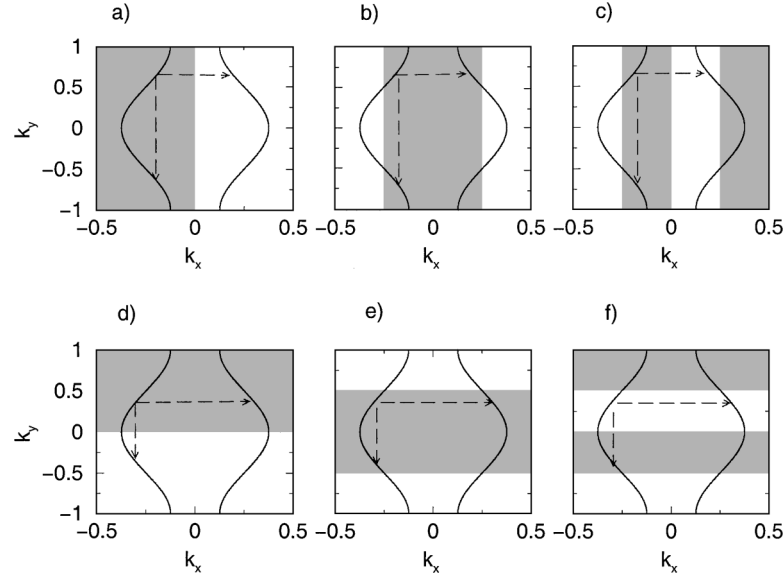


Fig. 2. The shape of the Fermi surface (solid line) for the pair potentials (a) p_x -wave, (b) d_x -wave, (c) f_x -wave, (d) p_y -wave, (e) d_y -wave, and (f) f_y -wave. Inside the shaded (white) region the pair potential is negative (positive). k_x, k_y are in units of π/a ; a is the crystal lattice spacing. The horizontal (vertical) arrow indicates the change in the momentum in the electron tunneling along the a (b) axis.

- Δ_{f_x} changes its sign along the FS in the k_x direction while the Δ_{f_y} changes its sign along the FS in the k_y direction as seen in Fig. 2c,f.
- (d) In case of d_{xy} -wave, $d_{x^2-y^2}$ -wave superconductor

$$\Delta_{d_{xy}} = \Delta_0 \sin(2k_x a) \times \sin(k_y a),$$

$$\Delta_{d_{x^2-y^2}} = \Delta_0 (\cos(2k_x a) - \cos(k_y a)), \quad (19)$$

$\Delta_{d_{xy}}, \Delta_{d_{x^2-y^2}}$ changes sign along the FS as seen in Fig. 3a,b.

4. TUNNELING CONDUCTANCE CHARACTERISTICS

In Figs. 4–7 we plot the tunneling conductance $\sigma(E)$ as a function of E/Δ_0 for various values of z_0 , for different orientations normal to the a or b axis. The pairing symmetry of the superconductor is p_x -wave, p_y -wave, in Fig. 4; d_x -wave, d_y -wave, in Fig. 5; f_x -wave, f_y -wave, in Fig. 6; d_{xy} -wave, $d_{x^2-y^2}$ -wave, in Fig. 7.

The conductance peak is formed in the electron tunneling along the a or b axis, when the transmitted quasiparticles experience different sign of the pair potential. 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 p_x -wave case when the a axis of the crystal is at right angle to the interface, the horizontal line in Fig. 2a representing the scattering process connects points of the FS with opposite sign of the pair potential for $-\pi/a < k_y < \pi/a$. As a result a peak exists in the conductance spectra, at $E = 0$ as seen in Fig. 4a for $z_0 = 2.5$. The height of the ZEP is proportional to the range of k_y for which sign change occurs and it is expected to have its maximum value when the a axis of the crystal is normal to the interface, since for this orientation the transmitted quasiparticles feel different sign of the pair potential for all $-\pi/a < k_y < \pi/a$. On the other hand, when the a axis is along the interface then the vertical line in Fig. 2a connects points of the FS with the same sign of the pair potential for $-\pi/2a < k_x < \pi/2a$, i.e. there is no k_x for which, the transmitted quasiparticles feel the sign change of the pair potential, and no ZEP is formed as seen in Fig. 4b. For the p_x -wave case the nodes of the pair potential do not intersect the FS and the line shape of the spectra is U-like as in the case of the s-wave superconductor.

The situation is opposite in the p_y -wave case where the scattering process for the surface orientation normal to the a (b) axis, described by the horizontal (vertical) line in Fig. 2d connects points of the FS with the same (opposite) sign. As a consequence, for the surface orientation normal to the

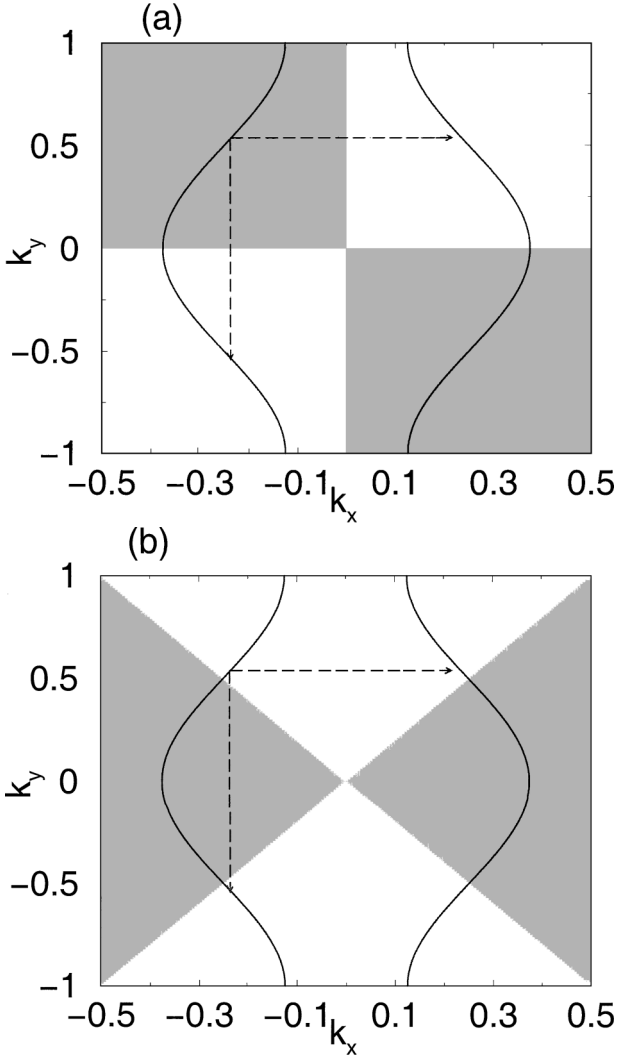


Fig. 3. The shape of the Fermi surface (solid line) for the pair potentials (a) d_{xy} -wave and (b) $d_{x^2-y^2}$ -wave. Inside the shaded (white) region the pair potential is negative (positive). k_x, k_y are in units of π/a , where a is the crystal lattice spacing. The horizontal (vertical) arrow indicates the change in the momentum in the electron tunneling along the a (b) axis.

a axis, there is no k_y for which the transmitted quasiparticles feel the sign change of the order parameter, and no ZEP is formed, as seen in Fig. 4c, while for the interface along the a axis the transmitted quasiparticles feel the different sign of the pair potential, for all $-\pi/2a < k_x < \pi/2a$, and a ZEP exists as seen in Fig. 4d. For the p_y -wave case the nodes of the pair potential intersect the FS and the spectra has a V-shaped form as in the case of d-wave superconductors.

For the d-wave case, and for tunneling along the a or b axis, the scattering process, described by the

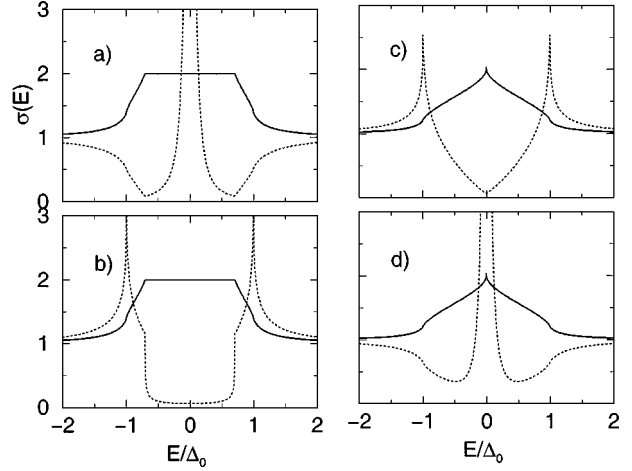


Fig. 4. Normalized tunneling conductance $\sigma(E)$ as a function of E/Δ_0 for $z_0 = 0$ (solid line), $z_0 = 2.5$ (dotted line), for different orientations; (a) and (c) for surface orientation normal to a axis, and (b) and (d) for surface orientation normal to b axis. The pairing symmetry of the superconductor is p_x in (a) and (b), and p_y in (c) and (d).

horizontal or vertical line in Fig. 2b, e connects points of the FS with the same sign in all cases. This means that the pair potential does not change sign and no ZEP is formed as seen in Fig. 5. Also due to the presence of nodes of the pair potential along the FS, the line shape of the spectra is V-like.

For the f-wave case, although the pair potential has a different structure, the lines in Fig. 2c, f connect points of FS with the same sign change of the pair potential as in the p-wave case. As a result the tunneling

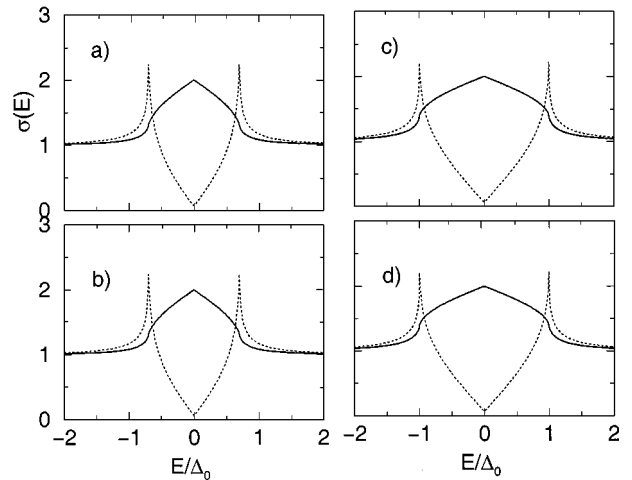


Fig. 5. The same as in Fig. 4. The pairing symmetry of the superconductor is d-wave.

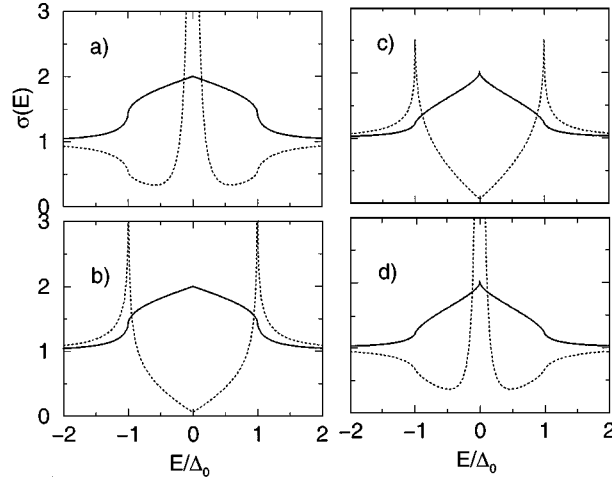


Fig. 6. The same as in Fig. 4. The pairing symmetry of the superconductor is f-wave.

spectra shows ZEP as in the p-wave case, due to the sign change of the transmitted quasiparticles. However in all cases in the f-wave case the pair potential intersects the FS and nodes are formed. As a consequence the line shape of the spectra is V-like, as seen in Fig. 6, unlike the p_x -wave case where the pair potential is nodeless and the tunneling spectra has a U-shaped form. The conclusion is that the line shape of the spectra can be used to distinguish the p_x from the f-wave pairing state. Our results are comparable with that of Tanuma *et al.* [12] although their calculation was based on a different model, i.e. the extended

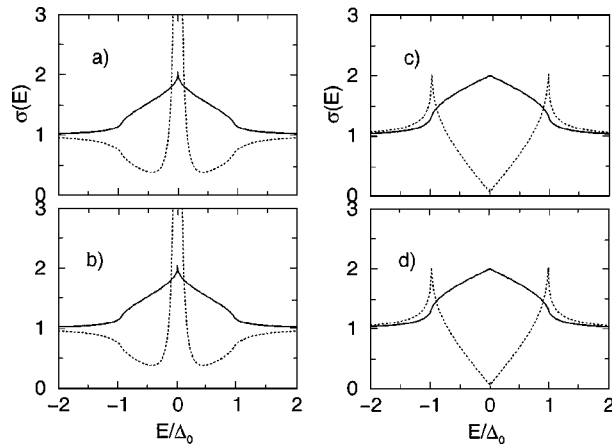


Fig. 7. Normalized tunneling conductance $\sigma(E)$ as a function of E/Δ_0 for $z_0 = 0$ (solid line), $z_0 = 2.5$ (dotted line), for different orientations; (a) and (c) for surface orientation normal to a axis, and (b) and (d) for surface orientation normal to b axis. The pairing symmetry of the superconductor is d_{xy} -wave in (a) and (b), and $d_{x^2-y^2}$ -wave in (c) and (d).

Table I. Presence (Yes) or Absence (No) of a Zero-Bias Conductance Peak in Electron Tunneling Along the a and b Axes for Different Symmetries of the Pair Potential and Also the Overall Line Shape of the Tunneling Spectra

Symmetry	a axis ZEP	b axis ZEP	Line shape
p_x	Yes	No	U
p_y	No	Yes	V
d_x	No	No	V
d_y	No	No	V
f_x	Yes	No	V
f_y	No	Yes	V
d_{xy}	Yes	Yes	V
$d_{x^2-y^2}$	No	No	V

Hubbard model on a quasi-one-dimensional lattice at quarter-filling.

For the d_{xy} -wave ($d_{x^2-y^2}$ -wave) case, and for tunneling along the a (b) axis, the scattering process, described with the horizontal or vertical line in Figs. 3a,b connects points of the FS with different (the same) sign. This means that the pair potential felt by the transmitted quasiparticles changes (conserves) sign during the scattering process and a ZEP (no ZEP) is formed at $E = 0$ for the d_{xy} -wave ($d_{x^2-y^2}$ -wave) case as seen in Fig. 7. Also due to the presence of nodes of the pair potential along the FS, the line shape of the spectra is V-like. In addition the tunneling spectra for the d_{xy} -wave, for tunneling direction along the a or b axis, is equivalent to the tunneling spectra for $d_{x^2-y^2}$ -wave with surface orientation tilted by $\pi/4$, i.e. along the nodal direction.

In the metallic limit ($z_0 = 0$), $\sigma(E)$ has the same form for each pairing potential independently from the orientation.

In Table I we summarize the results concerning the presence or absence of ZEP, and also the overall line shape of the tunneling spectra for various pairing potentials.

5. BOUND STATE ENERGIES

These features are explained if we calculate the energy of the midgap state, which is given for large z_0 by the value in which the denominator of Eqs. (6) and (7) vanishes. The equation giving the energy peak level is written as [10]

$$\phi_- \phi_+^* n_+ n_- |_{E=E_p} = 1.0 \quad (20)$$

In the p_x -wave case, for surface orientation normal to a axis, this equation has the solution $E = 0$, for $-\pi/a < k_y < \pi/a$; since $n_+ n_- |_{E=0} = -1$. Also, the

transmitted quasiparticles feel a different sign of the pair potential, i.e. $\phi_- \phi_+^*|_{E=0} = -1$. When a midgap state exists, the tunneling conductance $\bar{\sigma}_s(E, k_y)$ is equal to 2 and the peak in $\sigma(E)$ seen in Fig. 4a is due to the normal state conductance R_N in Eq. (12), which depends inversely on the z_0^2 for large z_0 . For surface orientation normal to b axis the range of k_x for which Eq. (20) has solutions collapses to zero, and no bound states are formed. Then $\sigma(E)$ approaches zero as $1/z_0^2$ and there is no conductance peak. In the p_y -wave case for surface orientation normal to a axis Eq. (20) has no solutions because $\phi_- \phi_+^*|_{E=0} = 1$, while for surface orientation normal to b axis a bound state is formed for all k_x in the interval $-\pi/2a < k_x < \pi/2a$. For the d-wave case and for tunneling along the a or b axis of the crystal, the condition $\phi_- \phi_+^*|_{E=0} = -1$ is not satisfied and no bound states are formed. For the f-wave case that condition is the same as in the p-wave case, and hence the ZEP is formed as in the p-wave pairing state. For the d_{xy} -wave ($d_{x^2-y^2}$ -wave) case the condition $\phi_- \phi_+^*|_{E=0} = -1$ is true (false) for tunneling along the a and b axis and hence the ZEP (no ZEP) is formed for both tunneling directions.

6. MAGNETIC FIELD EFFECT

In this section, we describe the effect of the external magnetic field H in the direction parallel to the chains, in the spectra. The effect of the magnetic field depends on the spin of the quasiparticles. The tunneling conductance is given by

$$\sigma(E) = \sigma_\uparrow(E - \mu_B H) + \sigma_\downarrow(E - \mu_B H). \quad (21)$$

In Fig. 8, the tunneling conductance $\sigma(E)$ is plotted for fixed magnetic field $\mu_B H/\Delta_0 = 0.2$ and barrier strength $z_0 = 2.5$. The pairing symmetry of the superconductor is p, d, f, and d_{xy} respectively.

The magnetic field splits symmetrically the tunneling spectrum, which is a linear superposition of the spectra for spin-up (down) quasiparticles. The amplitude of the splitting depends linearly on the magnetic field H . For the case of $\mu_B H/\Delta_0 = 0.2$ seen in Fig. 8 the spin-up (down) part of the spectra partially overlap while for larger values of the magnetic field the spin-up and spin-down branches are well separated. In the latter case the right (left) branch of the spectra originates from spin-up (down) quasiparticle spectra $\sigma_{q\uparrow}(E - \mu_B H)$ ($\sigma_{q\downarrow}(E + \mu_B H)$).

The condition for the formation of bound states is slightly modified under the presence of magnetic

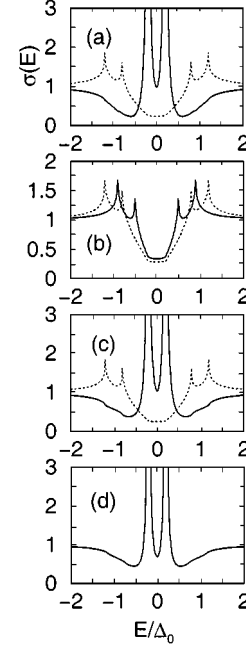


Fig. 8. Tunneling conductance $\sigma(E)$ in the presence of a magnetic field $\mu_B H/\Delta_0 = 0.2$ parallel to the a axis of the crystal, as a function of the energy E/Δ_0 , for surface orientation normal to a axis. The strength of the barrier is $z = 2.5$. The pairing symmetry of the superconductor is (a) p_x -wave (p_y -wave), solid (dotted) line, (b) d_x -wave (d_y -wave), solid (dotted) line, (c) f_x -wave (f_y -wave), solid (dotted) line, and (d) d_{xy} -wave.

field to $E - \mu_B H = 0$, for the spin-up region, and $E + \mu_B H = 0$, for the spin-down, from the corresponding $E = 0$ in the absence of any field. So that the multiplication of the bound states and the presence of magnetic field results into the appearance of double peak in the conductance spectra.

7. CONCLUSIONS

We calculated the tunneling conductance in normal metal/insulator/quasi-one-dimensional superconductor, using the BTK formalism. We showed that the ZEP appears in the electron tunneling along the a or b axis, when the transmitted quasiparticles experience different sign of the pair potential. Also, the line shape of the spectra is sensitive to the presence or absence of nodes of the pair potential on the Fermi surface, and results in a U-shaped structure for the p_x -wave case and a V-shaped one for the d-wave and f-wave cases.

The ZEP are due to the formation of bound states within the gap. The calculation of the conductance $\bar{\sigma}_s(E, k_y)$ for which bound state occurs shows

an enhancement at the bound state energy. The effect of the magnetic field in the direction parallel to the chains is to split linearly the ZEP.

Throughout this paper, the spatial variation of the order parameter near the surface that depends on the boundary orientation is ignored for simplicity. However, since the features presented here are intrinsic which are generated by the existence of surface bound states, the essential results do not change qualitatively. Also, we assumed perfectly flat interfaces in the clean limit, so that any impurity scattering and the effect of the surface roughness are ignored.

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