How to determine pairing symmetry of quasi-1D organic superconductors through magnetotunneling spectroscopy

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Abstract

Application of magnetic fields is proposed to be a good way of discriminating anisotropic p-, d-, and f-wave pairing symmetries from tunneling spectra in a model quasi-1D superconductor $(\mathrm{TMTSF})_2X$. The shape of the Fermi surface affects sensitively which affect the shape of the gap along with the presence/absence of the Andreev bound states, where the magnetic field further probes the gap function through the Doppler shift. Thus the magnetotunneling spectroscopy is promising in distinguishing the pairing symmetry in $(\mathrm{TMTSF})_2X$.

Key words: Tunneling spectroscopy; pairing symmetry; Andreev bound states; Doppler shift

1. Introduction

Pairing symmetry of Bechaard salts $(\mathrm{TMTSF})_2X$, a prominent organic superconductor, remains to be controversial. There are strong experimental evidences for spin-triplet superconductivity [1,2], so the orbital part should be either p or f-wave.

Now, it is known that Andreev bound states (ABS), which arise at surfaces when the injected and reflected quasiparticles feel different sign of the pair potential, is sensitive to the pairing symmetry in anisotropic superconductors [3]. The formation of ABS is reflected as a zero-bias conductance peak (ZBCP) in tunneling conductance [3], which can be employed as a possible probe to distinguish the pairing symmetry candidates.

Recently, it has been pointed out that the pairing symmetry in $(\mathrm{TMTSF})_2X$ can be distinguished from the presence (for p and f-waves) or absence (d-wave) of the ABS [4]. Subsequently we have pointed out [9] that p and f can still be distinguished by looking at the shape of the gap in the surface density of states in which the zero-energy peak (ZEP) resides. In these studies, the Fermi surface has been assumed to be symmetric with respect to the k_b axis. However, in the actual $(\mathrm{TMTSF})_2X$, a warping of the Fermi surface exists due to transfers across the chains in different directions as well as the triclinic structure of the lattice, which makes it difficult to determine the pairing symmetry solely from tunneling spectroscopy.

In the present study, we propose an *in situ* way of probing the symmetry from the tunneling spectroscopy is to apply a magnetic field ($\perp$ ab-plane). In the presence of a magnetic field, screening current affects the ABS spectrum (which is called the Doppler shift), and the ZBCP can split due to this [6]. We find here that ZBCP indeed splits into two for d-wave, while it does not for p and f. The way in which the Doppler shift occurs reflects the shape of the Fermi surface, so the magnetotunneling spectrum provides a unique way of determining the pairing symmetry.

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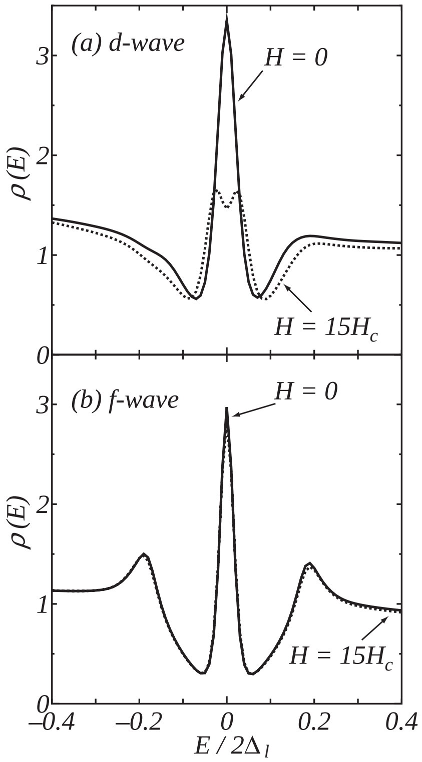

Fig. 1. Magnetic field dependence of the surface density of states normal to a axis for $t' = -0.08t_a$; (a) d-wave, (b) f-wave.

2. Method and Results

In $(\mathrm{TMTSF})_2X$ there are three (singlet d-, triplet p- and f-wave) possible pairing symmetries, where three of the present authors have recently proposed that f-wave is plausible [7]. While this was studied with a microsopic model, we can introduce an extended Hubbard model that incorporates the effective attractive interactions V in calculating the tunneling spectrum. We take here an anisotropic triangular lattice to take into account the effect of both the diagonal hopping t' and the triclinic structure in the actual materials. The sample edge is assumed to be $\perp$ a axis.

If we apply a magnetic field parallel to the c-axis, we can take the vector potential to be $\boldsymbol{A} = (0, H\lambda, 0)$ [6] since the penetration depth in $(\mathrm{TMTSF})_2X$ is much greater than the coherence length. We have performed a mean-field approximation to solve the Bogoliubov-de Gennes equation for the surface with the method developed in the previous works [9]. Then the site dependent pair potentials, $\Delta_{ij}^{\sigma\sigma'} = \sum_q^{0,x,y,z} \mathrm{i} d_{ij}^q (\hat{\sigma}_q \cdot \hat{\sigma}_y)_{\sigma\sigma'}$, are determined self-consistently with $d_{ij}^q = \frac{V}{2}\sum_{\sigma,\sigma'}(\hat{\sigma}_q \cdot \hat{\sigma}_y)^\dagger_{\sigma'\sigma}\langle c_{i\sigma}c_{j\sigma'}\rangle$ for each pairing symmetry (in this paper, d and f). From this the normalized surface density of states is numerically calculated.

Let us show the magnetic field dependence of the surface density of states for d and f-waves for $t' = -0.08t_a$. The magnitude of the applied magnetic field here is $H < 30H_c$, where $30H_c$ roughly corresponds to $H_{c2}^c(\sim 0.1$ T), i.e., the upper critical field parallel to c-axis, of $(\mathrm{TMTSF})_2\mathrm{PF}_6$ [1]. For d-wave, the ZEP is mainly formed by the quasiparticles having momentum near $k_b = \pi/2$, where the b component of the Fermi velocity $v_{\mathrm{F}b}(k_a)$ and $v_{\mathrm{F}b}(-k_a)$ have the same sign. Namely, the magnetic field gives in this case the injected and reflected quasiparticles additional phase shifts with the same sign, which degrades the constructive interference for the formation of ZEP. By contrast, for f-waves, quasiparticles with $k_b = 0$ mainly contribute to the formation of the Andreev bound states. For $k_b = 0$, $v_{\mathrm{F}b}(k_a)$ and $v_{\mathrm{F}b}(-k_a)$ have opposite signs regardless of the value of t'. In such a case, the magnetic field gives the injected and reflected quasiparticles additional phase shifts with opposite signs, which almost cancel out when added, so that the formation of ZEP is barely affected [8].

In summary, we have shown that we can distinguish d and f-waves through the appearance/disappearance of ZEP splitting in the presence of a magnetic field. [9]

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