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TUNNELING CURRENT INTO THE VORTEX LATTICE STATES OF s- AND p-WAVE SUPERCONDUCTORS

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The tunneling current between the metallic tip of a scanning microscope and s-wave and p-wave superconductors in a quantizing magnetic field is investigated. The differential conductance is calculated both as a function of bias voltage at the centre of the vortex line and for varying position of the scanning tunneling microscope tip at a stable voltage.

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1. Introduction

The spatial variation of the gap functions which characterise various unconventional superconductors as well as the space modulation by strong external magnetic field have recently become the subject of increasing interest. The low temperature scanning tunneling microscopy (STM) experiments provide precise quasiparticle excitation spectra and provide an insight into the detailed variation of the superconducting gap function [1–11]. Thus, in our paper we have calculated the tunneling current between the STM tip and s-wave and equal spin isotropic p-wave superconductors in a quantizing magnetic field, hoping that this method may help to distinguish these superconducting phases in real systems.

2. Tunneling properties

Let us assume that the tunneling transport occurs along the vortex lines running along the direction of the magnetic field.

The tunneling current due to an applied voltage V at the position r on the surface of the superconductor is proportional to [10]:

$$I(r,V) \propto \int \mathrm{d}\omega A_{\mathrm{S}}(r,\omega)A_{\mathrm{N}}(r,\omega+V)[f(\omega)-f(\omega+V)],$$

where $f(\omega)$is the Fermi function, $A_{\mathrm{N}}(r,\omega)$ is a single-particle spectral function for the normal metal of the tip and $A_{\mathrm{S}}(r,\omega)$ is a single-particle spectral function for the superconductor (in the quasiparticle approximation)

$$A_{\mathrm{N}}(\boldsymbol{r},\omega)=2\pi\sum_{\boldsymbol{k}}\delta(\omega-E_{\boldsymbol{k}}),\qquad A_{\mathrm{S}}(\boldsymbol{r},\omega)=-\frac{1}{\pi}\lim_{\varepsilon\to 0}\mathrm{Im}G(\omega+\mathrm{i}\varepsilon,\boldsymbol{r}).$$

The spectral component of the Green function $G(\omega,\boldsymbol{r})$ is determined in a standard way from the equations of motion in the mean field approximation [10]. The Green function considered is expanded into the basis of single-electron Landau states.

In a sufficiently strong magnetic field, when a cut-off energy of the attractive interaction is lower than the cyclotron frequency, the Green function decomposition can be restricted to the n-th Landau level subspace. Then, the single-quasiparticle spectral function can be written in the following form [10]:

$$A_{\mathrm{S}}(\boldsymbol{r},\omega)=\sum_{\boldsymbol{k}}|\varphi_{n,\boldsymbol{k}}(\boldsymbol{r})|^2\left[u_{\boldsymbol{k}}^2\delta(\omega-E_{\boldsymbol{k}})+v_{\boldsymbol{k}}^2\delta(\omega+E_{\boldsymbol{k}})\right],$$

where

$$\varphi_{n,k}=\frac{1}{\sqrt{N_x}}\sum_{v}\exp(-\mathrm{i}vk_x a_x)\phi^{\mathrm{Lan}}_{n,k_y+v\pi/a_y},$$

$$\phi^{\mathrm{Lan}}_{n,k_y+v\pi/a_y}=\exp\left[\mathrm{i}\left(k_y+v\frac{2\pi}{a_y}\right)y\right]\phi^{\mathrm{osc}}_n\left[\frac{x}{l}-\left(k_y+v\frac{2\pi}{a_y}\right)l\right],$$

and

$$u_{\boldsymbol{k}}^2=\frac{1}{2}\left(1+\frac{\xi}{E_{\boldsymbol{k}}}\right),\quad v_k^2=\frac{1}{2}\left(1-\frac{\xi}{E_k}\right),\quad E_{\boldsymbol{k}}=\sqrt{\xi^2+|\Delta_k|^2},\quad \xi=\varepsilon_n-\mu,$$

$\varepsilon_n=\hbar\omega_{\mathrm{c}}(n+1/2)$ is the energy of the n-th Landau level, ω_{c} denotes the cyclotron frequency and μ is the chemical potential. The quasiparticle excitation spectra $E_{\boldsymbol{k}}$ in the s-wave and p-wave systems are calculated numerically from the appropriate set of self-consistent equations [10] and shown in Fig. 1. These spectra are qualitatively different. In s-wave systems the values of $E_{\boldsymbol{k}}$ are close to its maximum value in almost total $\boldsymbol{k}$-space and sharply fall down near the periodic dips only (Fig. 1a). In the p-wave systems the values of $E_{\boldsymbol{k}}$ are close to its minimum value and sharply rise up near the periodic heights (Fig. 1b). Thus for the s-wave pairing

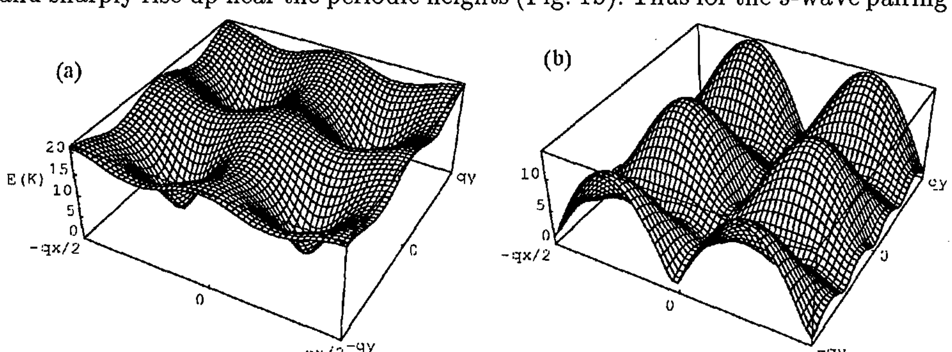

Fig. 1. Quasiparticle spectrum for an s-wave superconductor (a) and p-wave superconductor (b).

the quasiparticle density of states has a maximum near the top of the quasiparticle band (Fig. 2), while for the p-wave pairing near the bottom of the band (Fig. 2).

Finally the tunneling differential conductance $\mathrm{d}I/\mathrm{d}V$ for the transport along the k_z direction is proportional to

$$\sigma(r,V) = -\sum_{\boldsymbol{k}} |\varphi_{n,\boldsymbol{k}}(r)|^2 \left[u_{\boldsymbol{k}}^2 f'(E_{\boldsymbol{k}}+V) + v_{\boldsymbol{k}}^2 f'(E_{\boldsymbol{k}}-V)\right],$$

where f' is the derivative of the Fermi function.

Since at low temperatures f' behaves like the Dirac-type function, only one term in the above expression gives non-zero contribution to differential conductance for a given voltage V. If $V > 0$ this term is proportional to $v_{\boldsymbol{k}}^2$ while for $V < 0$ it is proportional to $u_{\boldsymbol{k}}^2$. Thus for a given voltage V, the contribution to differential conductance comes from quasiparticles with energies close to V or $-V$. Therefore, the asymmetry of conductance reveals when we change V into $-V$ (see Fig. 3).

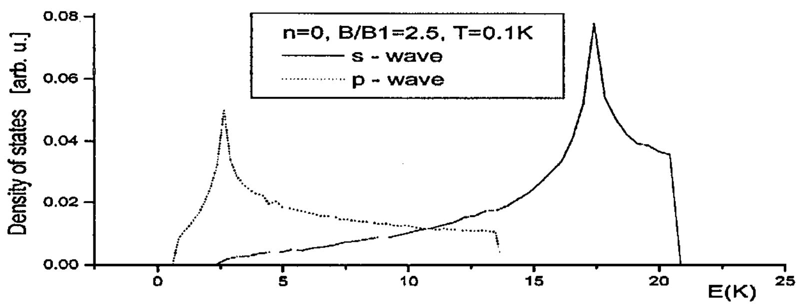

Fig. 2. Quasiparticle density of states as a function of energy for an s-wave superconductor (solid line) and p-wave superconductor (dotted line). The plots are calculated using the following parameters: $B/B_1 = 2.5$ ($n = 0$), $T = 0.1$ K.

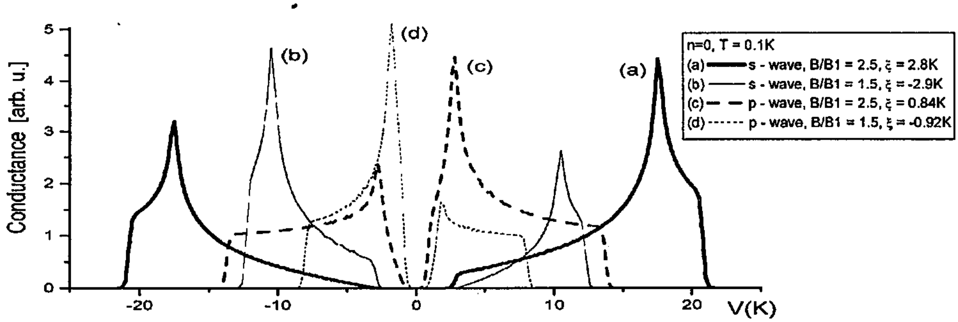

Fig. 3. The tunneling differential conductance $\sigma(r, V)$ calculated at the centre of a vortex of the s-wave superconductor (curves (a) and (b)) and p-wave superconductor (curves (c) and (d)) as a function of bias voltage. The curves are calculated for $T = 0.1$ K. The magnetic field values are: $B/B_1 = 2.5$ (a, c), $B/B_1 = 1.5$ (b, d). The self-consistently calculated ξ are as follows: (a) $\xi = 2.8$ K, (b) $\xi = -2.9$ K, (c) $\xi = 0.84$ K, (d) $\xi = -0.92$ K.

Another asymmetry of intensities of the differential conductance is determined by the sign and value of the energy interval $\xi = \varepsilon_n - \mu$ and thus reveals the quantum limit effect (see Fig. 3 and compare curves (a) and (b) as well as curves (c) and (d)). Fully symmetric intensities of the conductance $\sigma(+V) = \sigma(-V)$ appear in the case of $\xi = 0$.

A further characteristic feature of our results is an essential difference (especially seen in ultraquantum limit) in the shape of the curves depicting the tunneling conductance as a function of a bias voltage for s-wave and p-wave superconductors (see Fig. 3 and compare the curves (a) and (b) with (c) and (d)). The same qualitative difference between the shapes of the curves of the quasiparticle density of states for the s-wave and p-wave superconductors can also be observed (see Fig. 2).

3. Conclusions

The calculated conductance of a tunneling current between the STM tip and s-wave and p-wave superconductors in a quantizing magnetic field is angularly modulated and exhibits symmetry of the vortex lattice. The differential conductance is asymmetric with respect to sign of the applied bias voltage as well as to the interval of the energy between the last occupied Landau level (within which the Cooper pairs are formed) and the chemical potential. This asymmetry should be diametrically opposed for s-wave and p-wave superconductors in STM experiments. Moreover, there exists a qualitative difference in shape of the tunneling conductance between the s-wave and p-wave systems. Thus, we may suspect that STM experiments may help to distinguish the s-wave and p-wave phases in real systems.

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