Andreev bound states in rounded corners of $d$-wave superconductors

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Abstract

Andreev bound states at boundaries of $d$-wave superconductors are strongly influenced by the boundary geometry itself. In this work, the zero-energy spectral weight of the local quasiparticle density of states is presented for the case of wedge-shaped boundaries with rounded corners. Generally, both orientation of the $d$-wave and the specific local reflection properties of the rounded wedges determine, whether Andreev bound states exist or not. For the bisecting line of the wedge being parallel to the nodal direction of the $d$-wave gap function, strong zero-energy Andreev bound states are expected at the round part of the boundary.

Key words: unconventional superconductivity, Andreev bound states, boundary geometry

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1. Introduction

At straight boundaries of $d_{x^2−y^2}$-wave superconductors, an enhancement of the zero-energy spectral weight can be found in the local quasiparticle density of states [1,2,3]. This effect is due to Andreev bound states. And if the boundary is specular, their existence strongly depends on the orientation of the boundary with respect to the $d$-wave gap function. Experimentally, Andreev bound states can be observed as pronounced zero-bias conductance peaks in the tunneling spectrum [4,5]. Furthermore, locally resolved STM-measurements show a clear correlation between the tunneling spectra and the boundary geometry on the nano-scale [6].

In a recent work [7,8], a variety of $d$-wave superconductors with specular non-trivial boundary geometries has been examined within the framework of quasiclassical theory [9,10]. As a general result, apart from their orientational dependence, Andreev bound states are also strongly influenced by the shape of the boundary geometry on the length scale of the coherence length $\xi$: Since the boundary geometry determines, how incoming quasiparticles get reflected (and if they 'see' a sign change in the gap function), the local reflection behaviour of a non-trivial boundary geometry is the crucial factor for the existence of zero-energy Andreev bound states.

2. Wedges and Andreev bound states

Wedges with sharp corners have different reflection properties, depending on their opening angle. For opening angles $\alpha_n^+ = \pi/(2n)$ incoming and outgoing quasiparticle trajectories are always parallel, whereas for opening angles $\alpha_n^- = \pi/(2n−1)$ the direction of the outgoing trajectory is additionally mirrored at the bisecting line of the wedge. If the bisecting line of the wedge itself is kept parallel to the nodal direction of the $d$-wave gap function, this different reflection behaviour has amazing consequences on the quasiparticle spectra in the corners, at least theoretically: The zero-energy spectral
The boundary geometry of a rounded wedge is fixed by the opening angle $\alpha$ and the radius $r$ (left). The reflection properties of the wedge (1) and the round part of the boundary (2) may be completely different (right). Weight rapidly oscillates as a function of the opening angle, with maxima appearing at the angles $\alpha_n$ due to Andreev bound states. Minima are situated at the opening angles $\alpha_n^+,\alpha_n^-$, where zero-energy Andreev bound states do not exist [7,8].

3. Wedges with rounded corners

Wedges with rounded corners can be parametrized by an additional radius $r$ determining the rounding of the boundary geometry. However, the local reflection behaviour of the round part, which tends to mirror quasiparticle trajectories at the bisecting line of the wedge, may be different to that of the original wedge, cf. Fig. 1. Considering again the case, where the bisecting line of the wedge is parallel to the nodal direction of the $d$-wave, this new reflection type directly leads to zero-energy Andreev bound states close to the round part of the boundary geometry. A sharp right-angled wedge with opening angle $\alpha = \alpha_1^+$, for example, does not exhibit zero-energy Andreev bound states, but they are created by an additional rounding, as can be seen in Fig. 2, upper row.

Similarly, strong bound states exist at the rounded corner of a wedge with opening angle $\alpha = \pi/3 = \alpha_1^-$, which is presented in Fig. 2, lower row. In contrast to the right-angled wedge, however, considerable zero-energy Andreev bound states remain in the corner region when the rounding is decreased, because they get induced by the wedge-shaped boundary geometry itself. Although the reflection properties of both rounded corner and wedge enhance Andreev bound states separately, they are not identical (e.g. regarding the number of quasiparticle reflections). The competition between them may locally even lead to a destructive interference effect.

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