Determination of the directions of gap nodes in exotic superconductors

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Abstract

The superconducting gap structure, especially the direction of the nodes, is an unresolved issue in most of unconventional superconductors. Recently it has been demonstrated that the thermal conductivity κ is a powerful tool for probing the nodal structure. Here measuring κ in $\boldsymbol{H}$ rotating within the basal plane, we discuss the nodal structure of the unconventional superconductors, 2D spin-triplet Sr_2RuO_4 , 2D heavy fermion $CeCoIn_5$, 2D organic κ-(BEDT-TTF)$_2$Cu(NCS)$_2$, and 3D borocarbide YNi_2B_2C.

Key words: unconventional superconductor, thermal conductivity, nodal structure

The unconventional superconductivity is characterized by the superconducting gap structure which has nodes along certain directions. Since the superconducting gap structure is closely related with the pairing symmetry, its determination is crucial for understanding the mechanism of superconductivity. The most definitive test for the nodal structure is the phase sensitive experiment, but this technique appears to be available only for high-T_c cuprates until now. As a result, the detailed structure, especially the direction of the nodes, is an unresolved issue in most of unconventional superconductors. Recently it has been demonstrated that the thermal conductivity κ is a powerful tool for probing the nodal structure. Here we have determined the nodal structure of several unconventional superconductors, in which the gap functions were shown to be anisotropic but the detailed gap structures were unknown, by measuring κ in $\boldsymbol{H}$ rotating within the basal planes.

The important advantage of choosing to measure the thermal conductivity is that it is a *directional* probe, sensitive to the relative orientation between the magnetic field and nodal directions of the order parameter [3–5]. This statement is based on the fact that the Doppler shift of the quasiparticle energy spectrum depends on the angle between the node and $\boldsymbol{H}$. For instance, when $\boldsymbol{H}$ is rotated within the basal plane, a clear fourfold oscillation of κ was reported in $YBa_2Cu_3O_{7-\delta}$ [6].

Figures 1(a)-(c) show the angular variation of the in-plane thermal conductivity κ_{xx} at T=0.4 K for Sr_2RuO_4, $CeCoIn_5$, and κ-(BEDT-TTF)$_2$Cu(NCS)$_2$, respectively, in which the thermal current $\boldsymbol{q}$ was applied within the 2D plane. In these measurements, $\boldsymbol{H}$ was rotated within the ab-plane and θ is the angle between $\boldsymbol{q}$ and $\boldsymbol{H}$. In this geometry, $\kappa_{xx}(H,\theta)$ can be decomposed into three terms with different symmetries; $\kappa(H,\theta) = \kappa_0(H) + \kappa_{2\theta}(H) + \kappa_{4\theta}(H)$, where κ_0 is θ-independent, $\kappa_{2\theta}(H) = C_{2\theta}(H)\cos 2\theta$ is a term with twofold symmetry, and $\kappa_{4\theta}(H) = C_{4\theta}(H)\cos 4\theta$ with fourfold symmetry with respect to the in-plane rotation. The term $\kappa_{2\theta}$, which has a minimum at $\boldsymbol{H}\perp\boldsymbol{q}$, appears as a result of the difference of the effective DOS for quasiparticles traveling parallel to the vortex and for those moving in the perpendicular direction. Figure 1(d) displays the out-of-plane thermal conductivity κ_{zz} of YNi_2B_2C at T=0.4 K, in which $\boldsymbol{q}$ is applied parallel to the c-axis and θ is the angle between $\boldsymbol{H}$ and [110]-axis. In this geometry, the twofold term is absent because $\boldsymbol{H}$ is always perpendicular to

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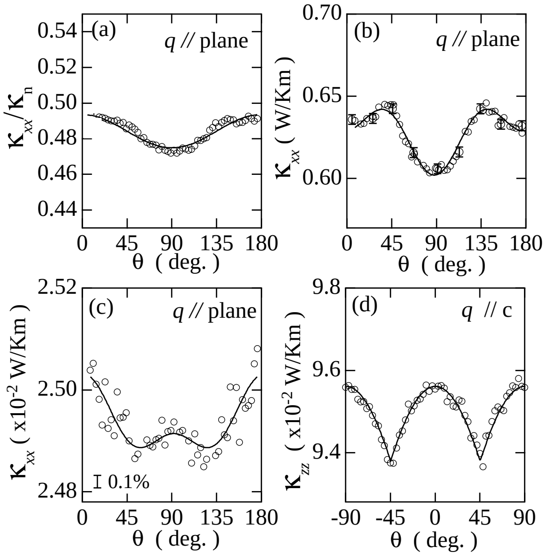

Fig. 1. The angular variation of the in-plane thermal conductivity κ_{xx} for (a) Sr_2RuO_4, (b) $CeCoIn_5$, and (c)κ-(BEDT-TTF)$_2$Cu(NCS)$_2$. $\theta = (\,\boldsymbol{q}, \boldsymbol{H})$. The angular variation of the out-of-plane thermal conductivity κ_{zz} of YNi_2B_2C is shown in (d). $\theta = (\,\boldsymbol{H}$, [110])

$\boldsymbol{q}$ while rotating $\boldsymbol{H}$.

Sr_2RuO_4 (T_c=1.4 K) is a spin-triplet superconductor with line node [7]. The amplitude of $|C_{4\theta}|/\kappa_n$ is less than 0.3% except in the vicinity of H_{c2}. As shown in Fig. 1(a), this value is less than 1/20 of the theoretical prediction in the presense of vertical node [3,4]. Therefore it is very unlikely that the observed four-fold symmetry is an indication of vertical line nodes.[8].

$CeCoIn_5$ is an ambient pressure superconductor (T_c=2.3 K) [9]. As shown in Fig. 1(b), a clear fourfold symmetry $\kappa_{4\theta}$ with a maximum at $\boldsymbol{H}\|$[110] and [1,-1,0] was observed. These results show that the symmetry of $CeCoIn_5$ most likely belongs to $d_{x^2-y^2}$, implying that the anisotropic antiferromagnetic fluctuation plays an important role for the superconductivity [10].

The superconducting order parameter of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ (T_c=10.4 K) is still controversial [11]. A clear fourfold oscillation was observed in Fig. 1(c), though the electron contribution occupies only 10% of the total thermal conductivity. Thus the superconducting gap symmetry of this material is d_{xy} [12]. This result shows that the simple antiferromagnetic fluctuation may not be relevant to the unconventional superconductivity[13].

Recent experimental studies reported a large anisotropic gap function of YNi_2B_2C (T_c=15.5 K). As shown in Fig. 1(d), the angular variation of κ_{zz} in $\boldsymbol{H}$ rotated within the *ab*-plane shows a peculiar fourfold oscillation with narrow cusps. These results provide the compelling evidence that the gap function has *point nodes* [5,14,15]. This unprecedented gap structure challenges the current view on the pairing mechanism of borocarbide superconductors.

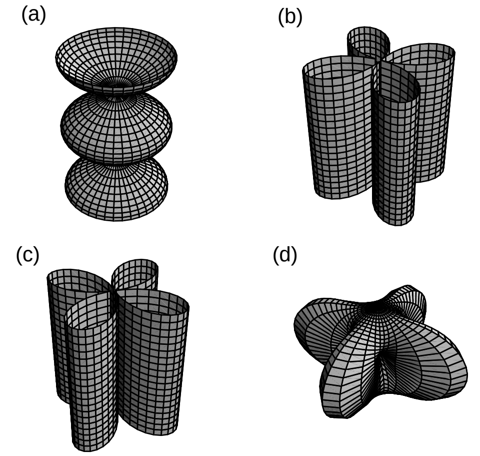

Fig. 2. Nodal structure of (a)Sr_2RuO_4, (b)$CeCoIn_5$, (c) κ-(BEDT-TTF)$_2$Cu(NCS)$_2$, and (d)YNi_2B_2C.

In summary, we have determined the gap function of the unconventional superconductors by the thermal conductivity. The gap functions are illustrated in Figs.2 (a)-(d).

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