NODAL STRUCTURE OF UNCONVENTIONAL SUPERCONDUCTORS DETERMINED BY THERMAL CONDUCTIVITY*

Y. Matsuda and K. Izawa

Institute for Solid State Physics, University of Tokyo
Kashiwanoha 5-1-5, Kashiwa, Chiba 277-8581, Japan

(Received July 10, 2002)

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, spin-triplet Sr_2RuO_4, heavy fermion $CeCoIn_5$, organic κ-$(BEDT\text{-}TTF)_2Cu(NCS)_2$, and borocarbide YNi_2B_2C.

PACS numbers: 74.20.Rp, 74.25.Fy, 74.25.Jb, 74.70.Dd

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 [1]. As a result, the detailed structure, especially the direction of the nodes, is an unresolved issue in most of unconventional superconductors. The situation, therefore, strongly confronts us with the need for a powerful directional probe.

Recently it has been demonstrated that the thermal conductivity κ is a powerful tool for probing the nodal structure. The important property of the thermal conductivity is that it is a directional probe, sensitive to the orientation relative to the thermal flow, magnetic field and nodal directions. Here we have determined the nodal structure of several unconventional

* Presented at the International Conference on Strongly Correlated Electron Systems, (SCES 02), Cracow, Poland, July 10–13, 2002.

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 most remarkable effect on the thermal transport in anisotropic superconductors is the Doppler shift of the energy of a de-localized quasiparticles with momentum $\boldsymbol{p}$ ($\varepsilon(\boldsymbol{p}) \to \varepsilon(\boldsymbol{p}) - \boldsymbol{v}_s \cdot \boldsymbol{p}$) in the circulating supercurrent flow $\boldsymbol{v}_s$ [2, 3]. 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 [4–6]. This statement is based on the fact that the magnitude of the Doppler shift depends on the angle between the node and $\boldsymbol{H}$. For instance, when $\boldsymbol{H}$ is rotated within the basal plane in d-wave superconductors, the Doppler shift gives rise to the fourfold oscillation of the density of states (DOS), as reported in high-T_c cuprate $YBa_2Cu_3O_{7-\delta}$ [7].

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

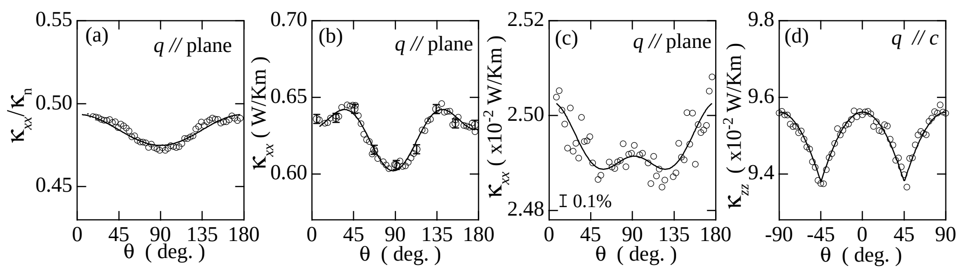

Fig. 1. The angular variation of the in-plane thermal conductivity κ_{xx} for Sr_2RuO_4 (a), $CeCoIn_5$ (b) and κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ (c). $\theta = (\boldsymbol{q}, H)$. The angular variation of the out-of-plane thermal conductivity κ_{zz} of YNi_2B_2C is shown in (d). $\theta = (\boldsymbol{H},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

A remarkable feature which characterizes Sr_2RuO_4 ($T_c = 1.4\,K$) is the spin-triplet pairing state with broken time reversal symmetry [8]. Recent experiments revealed the line node in the gap function. The amplitude of $|C_{4\theta}|/\kappa_n$ is less than 0.3% except in the vicinity of H_{c2}. These value is less than 1/20 of the theoretical prediction in the presence of vertical node [4,5]. Therefore, *it is very unlikely that the observed fourfold symmetry is an indication of vertical line nodes* [9]. These results lead us to conclude that the gap symmetry which is most consistent with the in-plane variation of thermal conductivity is $\boldsymbol{d}(\boldsymbol{k}) = \Delta_0 \hat{\boldsymbol{z}}(k_x + ik_y)(\cos ck_z + \alpha)$ (Fig. 2(a)).

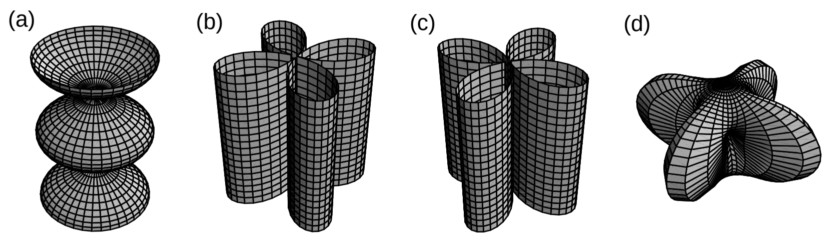

Fig. 2. Nodal structure of Sr_2RuO_4 (a), $CeCoIn_5$ (b), κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ (c) and YNi_2B_2C (d) determined by the thermal conductivity.

The family $CeTIn_5$ (T=Rh, Ir, and Co) are heavy fermion superconductors [10], which have been discovered very recently. Especially, $CeCoIn_5$ is an ambient pressure superconductor with transition temperature of 2.3 K. It is apparent in Fig. 2(b) that $\kappa_{4\theta}$ exhibits a maximum at $\boldsymbol{H}\|[110]$ and $[1,-1,0]$ at all temperatures. The sign of the present fourfold symmetry indicates the superconducting gap with nodes located along the $(\pm\pi,\pm\pi)$-directions, similar to high-T_c cuprates [11]. These results show that the symmetry of $CeCoIn_5$ most likely belongs to $d_{x^2-y^2}$ (Fig. 2(b)), implying that the anisotropic antiferromagnetic fluctuation plays an important role for the superconductivity.

Although the structure of the superconducting order parameter of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ ($T_c = 10.4\,K$) has been examined by several techniques, it is still controversial [12]. A clear fourfold oscillation can be seen 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} (Fig. 2(c)) [13]. This result shows that the simple antiferromagnetic fluctuation may not be relevant to the unconventional superconductivity in κ-(ET)$_2$Cu(NCS)$_2$ [14].

At an early stage, the gap symmetry of YNi_2B_2C ($T_c = 15.5$ K) was considered to be isotropic s-wave, mediated by conventional electron-phonon interactions, but recent experimental studies have reported a large anisotropic gap function. 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. The amplitude of this fourfold oscillation becomes very small when $\boldsymbol{H}$ is rotated conically around the *c*-axis with a tilt angle of 45°. These results provide the compelling evidence that the gap function of YNi_2B_2C has *point nodes*, which are located along the [100] and [010]-directions [15]. For point nodes, $\Delta(\boldsymbol{k}) = \frac{1}{2}\Delta_0\{1-\sin^4\theta\cos(4\phi)\}$ ($s+g$-wave) was proposed in Ref. [6, 16] (Fig. 2(d)). This unprecedented gap structure challenges the current view on the pairing mechanism and on the unusual superconducting properties of borocarbide superconductors.

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).

This work has been done in collaboration with H. Yamaguchi, K. Kamata, Y. Nakajima (ISSP, Tokyo), M. Nohara, H. Takagi (University of Tokyo), T. Sasaki (Tohoku University), H. Shishido, R. Settai and Y. Onuki (Osaka University), K. Maki (University of Southern California) and P. Thalmeier (Max Planck Institute).

REFERENCES

[1] C.C. Tsuei, J.R. Kirtley, *Rev. Mod. Phys.* **72**, 969 (2000).

[2] G.E. Volovik, *JETP Lett.* **58**, 469 (1993).

[3] C. Kübert, P.J. Hirschfeld, *Phys. Rev. Lett.* **80**, 4963 (1998); I. Vekhter, A. Houghton, *Phys. Rev. Lett.* **83**, 4626 (1999).

[4] K. Maki *et al.*, *Physica C* **341–348**, 1647 (2000); H. Won, K. Maki, `cond-mat/0004105`.

[5] I. Vekhter *et al.*, *Phys. Rev.* **B59**, R9023 (1999).

[6] K. Maki, P. Thalmeier, H. Won, *Phys. Rev.* **B65**, 140502 (2002).

[7] H. Aubin *et al.*, *Phys. Rev. Lett.* **78**, 2624 (1997).

[8] Y. Maeno, T.M. Rice, M. Sigrist, *Phys. Today* **54**, 42 (2001).

[9] K. Izawa *et al.*, *Phys. Rev. Lett.* **86**, 2653 (2001).

[10] H. Hegger *et al.*, *Phys Rev. Lett.* **84**, 4986 (2000).

[11] K. Izawa *et al.*, *Phys. Rev. Lett.* **87**, 057002 (2001).

[12] K. Kanoda, *Physica C* **282–287**, 299 (1997).

[13] K. Izawa *et al.*, *Phys. Rev. Lett.* **88**, 027002 (2002).

[14] K. Kuroki *et al.*, *Phys. Rev.* **B65**, 100516 (2002).

[15] K. Izawa *et al.*, *Phys. Rev. Lett.* **86**, 1327 (2001); K. Izawa *et al.*, *Phys. Rev. Lett.* **89**, 137006 (2002).

[16] P. Thalmeier, K. Maki, see Proceedings of SCES (2002).