Gap Structure and Anomalous Superconducting State of Quasi-2D Heavy-Fermion $CeCoIn_5$

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Abstract

To specify the direction of the nodes in the superconducting gap, we measured the thermal conductivity κ of quasi 2D heavy ferimon $CeCoIn_5$ in a magnetic field rotating within the 2D planes. A clear fourfold symmetry of κ which is characteristic of a superconducting gap with nodes along the $(\pm\pi, \pm\pi)$-directions is resolved. The thermal conductivity also reveals a first order phase transition at H_{c2}. The results indicate that the symmetry most likely belongs to $d_{x^2-y^2}$, implying that the anisotropic antiferromagnetic fluctuation is relevant to the superconductivity.

Key words: $CeCoIn_5$; $d_{x^2-y^2}$-wave symmetry; First order phase transition; Thermal conductivity

In the past two decades, unconventional superconductivity have been found in several heavy fermion (HF) systems, such as $CeCu_2Si_2$, UPt_3, UPd_2Al_3 *etc.* [1]. Unconventional superconductivity is characterized by the presence of gap nodes along a certain directions. Since the gap structure is intimately related to the pairing interaction, its determination is crucial for understanding the mechanism of the superconductivity. However, the detailed structure of the gap, especially the direction of the nodes, is unsolved issue in most unconventional superconductors.

Very recently, it has been reported that a quasi-2D heavy-fermion family $CeTIn_5$(T=Rh, Ir and Co) shows superconductivity [2,3]. Especially $CeIrIn_5$ and $CeCoIn_5$ are ambient superconductors with T_c=0.4 K and 2.3 K, respectively. Subsequent observations of the T-power low behavior in the specific heat, NMR relaxation rate, and thermal conductivity have identified $CeTIn_5$ as an unconventional superconductor with line nodes in the gap function[4,5]. However, the direction of the nodes remains unresolved because T-dependence of these quantities does not provide any directional informations.

Recently, it has been demonstrated that the thermal conductivity is powerful tool for probing the anisotropic gap structure[6–13]. An important advantage of the thermal conductivity is a *directional* probe, sensitive to the relative orientation among the heat flow, magnetic field and nodal direction of the gap function. In fact, a fourfold oscillation of thermal conductivity which originates from the gap structure with $d_{x^2-y^2}$ symmetry has been observed in $YBa_2Cu_3O_{7-\delta}$ [6]. In this work, we report the results of in-plane thermal conductivity κ of $CeCoIn_5$ in magnetic field rotating within the ab-plane and discuss the gap symmetry of $CeCoIn_5$.

First, we discuss T- and H-dependence of the thermal conductivity. As shown in Fig. 1 (a), κ increases steeply below T_c and shows a maximum around 1.7 K. This enhancement of κ is due to the suppression of the quasiparticle (QP) scattering rate below T_c, similar to high-T_c cuprates. Figure 1 (b) shows H dependence of κ for $H \perp ab$ plane. At all temperatures, κ decreases with H and the H-dependence becomes more gradual with decreasing T. The similar H-dependence is also observed in $H \parallel ab$-plane. Interestingly, κ jumps at H_{c2} at low temperatures (the inset of Fig.1(b)). Since the

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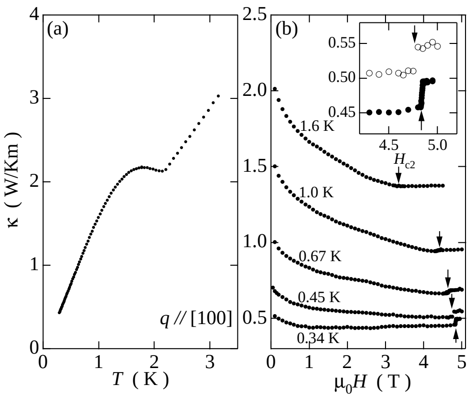

Fig. 1. Thermal conductivity as a function of (a) temperature and (b) magnetic field for $H \perp ab$-plane. The inset: H dependence of κ near H_{c2} at 0.35 K(●) and 0.45 K(○).

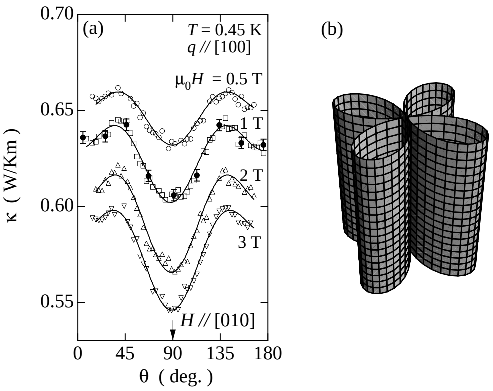

Fig. 2. (a) Angular variation $[\theta{=}(\boldsymbol{q},\boldsymbol{H})]$ of κ. The solid lines represent the result of the fitting by the function $\kappa = \kappa_0 + C_{2\theta}\cos 2\theta + C_{4\theta}\cos 4\theta$. The solid circles represent κ obtained under the field (1 T) cooling condition at every angle. (b) Superconducting gap function of $CeCoIn_5$.

jump of κ most likely originates from entropy jump, this result provides an evidence of the first order phase transition (FOPT). As far as we know that *this is the first material which exhibits a FOPT at* H_{c2}, though many theoretical studies have been made on this issue in the past several decades [14]. Thus, this material provides good opportunity to study this issue.

The understanding of the heat transport in the mixed state of unconventional superconductors has largely progressed in the past few years [11–13]. There, the most remarkable effect is the Doppler shift of the delocalized QP energy spectrum generated by the supercurrent flow around the each vortex. The Doppler shift gives rise to two effects: the enhancement of the QP density of states (DOS) at the Fermi level and Andreev scattering of the QPs. At high temperature, the latter effect is predominant and reduces κ, while at low temperature the former effect can exceed the latter effect and enhances κ with H. The decrease of $\kappa(H)$ as shown in Fig.1(b) indicates that Andreev scattering of QPs is the main origin of H-dependence of κ.

We now turn to the angular dependence of κ with respect to the angle θ between heat current $\boldsymbol{q}$ and the magnetic field $\boldsymbol{H}$ rotating within the 2D $CeIn_3$ plane (Fig.2(a)). The angular variation can be decomposed into three terms with different symmetries; $\kappa(\theta) = \kappa_0 + \kappa_{2\theta} + \kappa_{4\theta}$ where κ_0 is a θ-independent term, and $\kappa_{2\theta} = C_{2\theta}\cos 2\theta$ and $\kappa_{4\theta} = C_{4\theta}\cos 4\theta$ are two- and fourfold term with respect to the field rotation, respectively. The twofold term $\kappa_{2\theta}$ with a minimum at $H \perp q$ appears as a result of the different effective DOS between the QPs traveling parallel to the heat current and those moving in the perpendicular direction. On the other hand, the fourfold term $\kappa_{4\theta}$, which shows maximum along [110] and [1,-1,0] directions, suddenly grows below $T_c/2$ and its amplitude $C_{4\theta}/\kappa_n$ reaches about 2.7 % of the normal state thermal conductivity κ_n at 0.45 K. Here, we stress that the fourfold term originates from the QP structure inherent to the nodal structure because the other possible origins, such as the in-plane anisotropy of H_{c2} and tetragonal band structure are incompatible with these features of $\kappa_{4\theta}$. Moreover, as discussed before, the Andreev scattering effect is predominant in our T and H ranges. In this case, κ exhibits the maximum (minimum) value when $\boldsymbol{H}$ is directed to the nodal (antinodal) directions. Thus, the sign of $\kappa_{4\theta}$ indicates that the gap nodes exists along the $(\pm\pi, \pm\pi)$-directions. Together with the result of Knight shift[5], we are naturally lead to conclude that *$CeCoIn_5$ most likely belongs to $d_{x^2-y^2}$ symmetry* [8] (Fig.2(b)), implying that the anisotropic antiferromagnetic fluctuation is relevant to the superconductivity.

We thank K. Maki and I. Vekhter for stimulating discussions.

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