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# Pinning down the pairing symmetry of heavy-fermion compound CeIrIn<sub>5</sub>

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## Abstract.

From the thermal transport measurements in rotating magnetic fields  $\mathbf{H}$ , we pinned down the superconducting gap structure of CeIrIn<sub>5</sub>. Clear fourfold oscillation was observed when  $\mathbf{H}$  is rotated within the  $ab$ -plane, while no discernible oscillation was observed within the  $bc$ -plane. In sharp contrast to previous reports, our results are most consistent with  $d_{x^2-y^2}$  symmetry, implying that the superconductivity of CeIrIn<sub>5</sub> is mediated by antiferromagnetic spin fluctuations as well as that of CeRhIn<sub>5</sub> and CeCoIn<sub>5</sub>.

## 1. Introduction

The relationship between the magnetism and unconventional superconductivity, whereby the gap function  $\Delta(\mathbf{k})$  has nodes on the Fermi surface where  $\Delta(\mathbf{k}) = 0$ , in heavy-fermion (HF) compounds continues to be a central focus of investigations into strongly correlated electron systems. Many analyses have focused on the superconductivity mediated by magnetic fluctuations, often in proximity to a quantum critical point (QCP), where magnetic ordering temperature is driven to zero by an external parameter such as pressure and chemical substitution. Indeed, unconventional superconductivity appears in the vicinity of an antiferromagnetic (AF) QCP in most Ce-based HF compounds [1, 2, 3] as well as high- $T_c$  and organic materials.

Notable counter examples have been recently reported in two Ce compounds, prototypical heavy-fermion CeCu<sub>2</sub>Si<sub>2</sub> and CeIrIn<sub>5</sub>, where two distinct domes of different HF superconducting (SC) phases appear as a function of pressure or chemical substitution. In CeCu<sub>2</sub>Si<sub>2</sub>, one SC dome appears at low pressure around the AF QCP, and the second dome emerges at high pressure distant from the QCP [4]. The superconductivity in the low pressure dome is consistent with the magnetically mediated pairing, while Cooper pairing glued by the Ce-valence fluctuations was proposed for the high pressure region without discernible AF fluctuations [4, 5].

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By analogy with CeCu<sub>2</sub>Si<sub>2</sub>, CeIrIn<sub>5</sub> in the second dome was suggested to be a strong candidate for the Ce-valence fluctuation mediated superconductor [5]. Identification of the SC gap structure is of primary importance, because it is intimately related to the pairing symmetry. Several measurements revealed that the superconductivity of CeIrIn<sub>5</sub> is unconventional, having line nodes in the gap. Recently, the gap function of CeIrIn<sub>5</sub> was suggested to be of hybrid type,  $k_z(k_x + ik_y)$ , with  $E_g$  symmetry [7] similar to UPt<sub>3</sub> [8]. This is in sharp contrast to the  $d_{x^2-y^2}$  gap in CeCoIn<sub>5</sub> (and most likely in CeRhIn<sub>5</sub> under pressure) [9].

Here, to shed light on the pairing mechanism of CeIrIn<sub>5</sub>, we measured the thermal conductivity in magnetic field  $\mathbf{H}$  rotated relative to the crystal axes, which is established as a powerful method for determining the gap structure. In nodal superconductors, the heat transport is governed by delocalized near-nodal quasiparticles (QPs). Applied magnetic field  $\mathbf{H}$  creates a circulating supercurrent flow  $\mathbf{v}_s(\mathbf{r})$  associated with vortices. The Doppler shift of the energy of QP with momentum  $\mathbf{p}$ ,  $E(\mathbf{p}) \rightarrow E(\mathbf{p}) - \mathbf{v}_s \cdot \mathbf{p}$ , is important near the nodes, where the local energy gap is small ( $\Delta(\mathbf{p}) < |\mathbf{v}_s \cdot \mathbf{p}|$ ). Consequently, the density of states (DOS) sensitively depends on the angle between  $\mathbf{H}$  and nodal directions [10]. Clear twofold or fourfold oscillations of thermal conductivity and heat capacity due to nodes have been observed in several materials [9] when  $\mathbf{H}$  is rotated relative to the crystal axes. The results provide strong evidence for  $d_{x^2-y^2}$  gap symmetry, which put a constraint on the pairing mechanism in CeIrIn<sub>5</sub> [11].

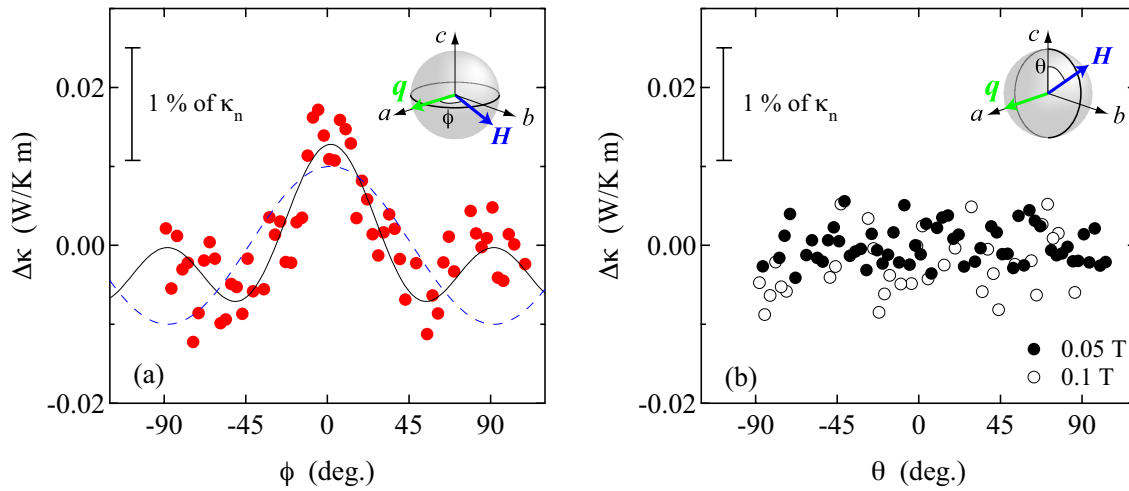
## 2. Experimental

Single crystals were grown by the self-flux method. The bulk transition temperature is 0.4 K, and upper critical fields parallel to the  $ab$ -plane and the  $c$  axis,  $H_{c2}^{ab}$  and  $H_{c2}^c$ , are 1.0 T and 0.5 T at  $T = 0$  K, respectively. We measured the thermal conductivity  $\kappa$  along the tetragonal  $a$  axis (heat current  $\mathbf{q} \parallel a$ ) on the sample with a rectangular shape ( $2.8 \times 0.45 \times 0.10$  mm<sup>3</sup>). To apply  $\mathbf{H}$  with high accuracy (misalignment of less than 0.05°) relative to the crystal axes, we used a system with two SC magnets generating  $\mathbf{H}$  in two mutually orthogonal directions and dilution refrigerator equipped on a mechanical rotating stage at the top of the Dewar.

## 3. Results and Discussions

Figures 1(a) and (b) show the angular variation of thermal conductivity at 0.2 K ( $k_B T / \Delta \sim 0.2$ ) when  $\mathbf{H}$  is rotated within the 2D  $ab$ -plane at  $|\mathbf{H}| = 0.1$  T ( $H/H_{c2}^{ab}(T) \simeq 0.14$ ) and within the  $bc$ -plane at  $|\mathbf{H}| = 0.05$  T ( $H/H_{c2}^c(T) \simeq 0.14$ ) and at  $|\mathbf{H}| = 0.1$  T ( $H/H_{c2}^{ab}(T) \simeq 0.14$ ), respectively. Here  $\phi = (\mathbf{H}, a)$  and  $\theta = (\mathbf{H}, c)$  are the polar and azimuthal angles, respectively. For  $\mathbf{H} \parallel ab$ -plane,  $\kappa(\phi)$  exhibits a distinct oscillation as a function of  $\phi$ , which is characterized by peaks at  $\phi = 0^\circ$  and  $\pm 90^\circ$  and minima at around  $\pm 45^\circ$ . As shown by the solid line,  $\kappa(\phi)$  can be decomposed into three terms,  $\kappa(\phi) = \kappa_0 + \kappa_{2\phi} + \kappa_{4\phi}$ , where  $\kappa_{2\phi} = C_{2\phi} \cos 2\phi$  and  $\kappa_{4\phi} = C_{4\phi} \cos 4\phi$  have the twofold and fourfold symmetry with respect to  $\phi$ , respectively. We note that, as shown by the dashed line,  $\kappa(\phi)$  with minima at  $\pm 45^\circ$  and peaks at  $\pm 90^\circ$  cannot be fitted only by  $\kappa_{2\phi}$ -term, indicating the presence of the fourfold term. In sharp contrast to  $\mathbf{H}$  rotated within the  $ab$ -plane, no oscillation is observed when  $\mathbf{H}$  is rotated within the  $bc$ -plane; the amplitude of the oscillation is less than 0.2 % (0.3 %) of the normal state thermal conductivity  $\kappa_n$  for  $|\mathbf{H}| = 0.05$  T (0.1 T) if it exists. The  $\kappa_{2\phi}$ -term arises from the difference in effective DOS between QPs which transport parallel and perpendicular to the vortices. Since for  $\mathbf{H}$  within the  $bc$ -plane the field is always normal to  $\mathbf{q}$ ,  $\kappa_{2\phi}$ -term is absent for this geometry.

We address the origin of the fourfold oscillation. Figures 2(a) and (b) display  $\kappa_{4\phi}$  normalized by  $\kappa_n$  at 0.2 K below  $H_{c2}^{ab}(T)$  ( $\simeq 0.7$  T). In the normal state above  $H_{c2}^{ab}$ , no discernible oscillation was observed (not shown). At 0.69 T, just below  $H_{c2}^{ab}(T)$ ,  $\kappa_{4\phi}$  exhibits a minimum at  $\phi = 0^\circ$  ( $C_{4\phi} < 0$ ). At  $H = 0.5$  T, fourfold oscillation vanishes. Further decrease of  $H$  leads to the appearance of distinct fourfold oscillation with a maximum at  $\phi = 0^\circ$  ( $C_{4\phi} > 0$ ) at  $H = 0.1$  and 0.25 T. Figure 3(a) shows the  $H$ -dependence of  $C_{4\phi}/\kappa_n$ . Fourfold oscillation can originate



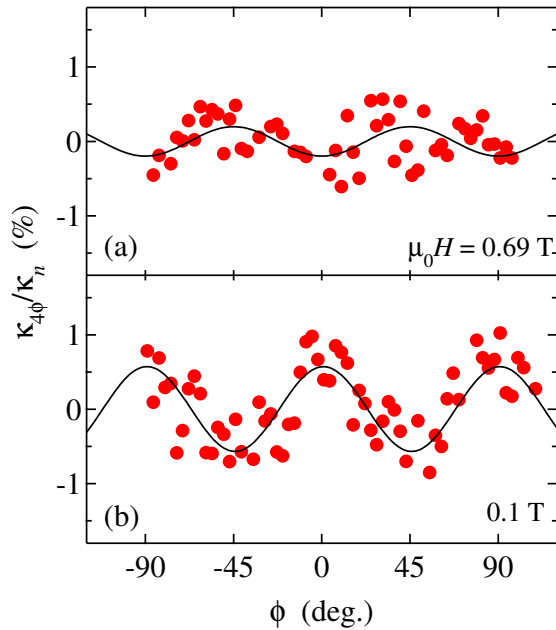
**Figure 1.** Angular variation of the thermal conductivity,  $\Delta\kappa(\phi)$ , at  $T = 0.2$  K with rotated  $\mathbf{H}$  (b) within the basal  $ab$ -plane as a function of azimuthal angle  $\phi$  for  $|\mathbf{H}| = 0.10$  T and (a) within the  $bc$ -plane as a function of polar angle  $\theta$  for  $|\mathbf{H}| = 0.05$  T (filled circles) and 0.10 T (open circles). The thermal current  $\mathbf{q}$  is applied parallel to the  $a$  axis. The dashed line shows the twofold variation  $\cos 2\phi$ . The solid line is a fit assuming the presence of fourfold variation.

from (i) the nodal structure and (ii) in-plane anisotropy of the Fermi surface and  $H_{c2}^{ab}$ . It should be stressed that the sign of  $C_{4\phi}$  just below  $H_{c2}^{ab}$  is the same as that expected from the in-plane anisotropy of  $H_{c2}^{ab}$  ( $H_{c2} \parallel (100) > H_{c2} \parallel (110)$ ) [12], whereas it is opposite to that at low fields. This immediately indicates that the origin of the fourfold symmetry at low fields is not due to the anisotropy of the Fermi surface or  $H_{c2}^{ab}$ . Rough estimation of the amplitude of the fourfold term in layered  $d$ -wave superconductors yields  $C_{4\phi}/\kappa_n \sim 2\%$ , which is of the same order as the data. The distinct fourfold oscillation within the  $ab$ -plane, together with the absence of the oscillation within the  $bc$ -plane, definitely indicates the vertical line nodes perpendicular to the  $ab$ -plane, and excludes a horizontal line of nodes at least in the dominant heavy electron bands, which is completely at odds with the hybrid gap function with horizontal node proposed in Ref. [7].

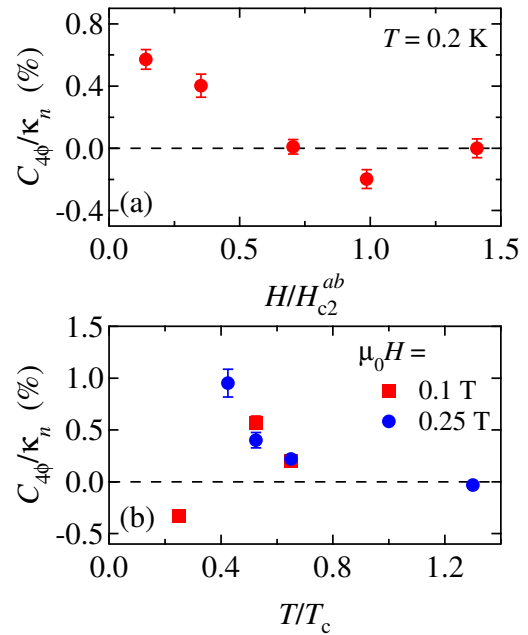
Thus, the SC symmetry of CeIrIn<sub>5</sub> is narrowed down to either  $d_{x^2-y^2}$  or  $d_{xy}$ . Further identification relies on the evolution of the oscillations with temperature and field. In the low- $T$ , low- $H$  limit, the Doppler shifted DOS shows a maximum (minimum) when  $\mathbf{H}$  is along the antinodal (nodal) directions. However, according to recent microscopic calculations, the pattern is inverted at higher  $T, H$  due to vortex scattering, and the fourfold components of the specific heat and that of the thermal conductivity have similar behavior across the phase diagram [13]. In Fig. 3(b), we plot  $C_{4\phi}/\kappa_n$  as a function of temperature. At  $H=0.1$  T, the sign change indeed occurs at  $T/T_c \simeq 0.25$ , which is compatible with theoretical expectation. Therefore, it is natural to consider that the SC symmetry of CeIrIn<sub>5</sub> is  $d_{x^2-y^2}$ , same as CeCoIn<sub>5</sub>, implying the superconductivity is most likely to be mediated by the AF fluctuations.

#### 4. Conclusions

In conclusion, the measurements of the thermal conductivity under rotated magnetic fields provide strong evidence that the superconducting gap of CeIrIn<sub>5</sub> at ambient pressure has vertical line nodes and is of  $d_{x^2-y^2}$  symmetry. This indicates that two distinct domes of heavy-fermion superconducting phases possess the same superconducting symmetry, in which antiferromagnetic fluctuations appear to play an important role. The determined gap symmetry in CeIrIn<sub>5</sub> which is



**Figure 2.**  $\kappa_{4\phi}/\kappa_n$  at  $T = 0.2$  K at (a)  $|\mathbf{H}| = 0.69$  T ( $\sim H_{c2}^{ab}(T) = 0.7$  T) and (b) 0.1 T. The solid lines represent the fit by  $C_{4\phi} \cos 4\phi$ .



**Figure 3.** (a)  $C_{4\phi}/\kappa_n$  at  $T = 0.2$  K as a function of  $H/H_{c2}^{ab}$ . (b)  $C_{4\phi}/\kappa_n$  at  $H = 0.1$  and 0.25 T as a function of  $T/T_c$ .

located in the second superconducting phase further restricts theories of the pairing mechanism.

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