Universal heat conduction and nodal gap structure of the heavy-fermion superconductor $CeIrIn_5$

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The effect of impurity scattering on the thermal conductivity κ of the heavy-fermion superconductor $CeIrIn_5$ was studied for a current parallel $(J\|c)$ and perpendicular $(J\|a)$ to the tetragonal c axis. For $J\|a$, adding La impurities does not change the residual linear term κ_{0a}/T, showing that heat conduction in the basal plane is universal, compelling evidence that the superconducting gap vanishes along a symmetry-imposed line. By contrast, for $J\|c$, La impurities greatly enhance the residual linear term κ_{0c}/T. This is strong evidence that the line of nodes lies within the basal plane, a gap structure which is inconsistent with the d-wave symmetry proposed for the isostructural superconductor $CeCoIn_5$. Different symmetries in the two materials could explain why the phase diagram of this heavy-fermion family consists of two separate superconducting domes. We also compare our data on $CeIrIn_5$ to corresponding data on the heavy-fermion superconductor UPt_3, where no universal conduction is observed.

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I. INTRODUCTION

In certain symmetries, the energy gap of a superconductor vanishes along a line on the Fermi surface. For example, in the B_{1g} representation of the tetragonal D_{4h} point group, the $d_{x^2-y^2}$ state transforms as $k_x^2-k_y^2$ so that the line nodes are located where the $k_x=k_y$ and $k_x=-k_y$ planes intersect the Fermi surface.[1] A line node produces a density of states which grows linearly with energy at low energy. Universal heat conduction is a direct consequence of such a linear density of states, the result of a compensation between the growth in the zero-energy quasiparticle density of states and the decrease in the quasiparticle mean free path with increasing impurity scattering.[2,3] In the $T=0$ limit, the electronic thermal conductivity divided by temperature, κ/T, extrapolates to a finite residual linear term, κ_0/T, which is independent of impurity scattering and governed only by the quasiparticle velocities normal and tangential to the Fermi surface at the node.[2,3] Experimentally confirmed in cuprates[4,5] and ruthenates,[6] universal heat conduction has not yet been observed in a heavy-fermion superconductor,[7,8] even though in most cases a line node in the gap has been invoked to account for the properties of their superconducting state.

Here we report the observation of universal heat conduction in the heavy-fermion superconductor $CeIrIn_5$, for quasiparticle motion in the basal tetragonal plane but not normal to it, revealing the presence of a line of nodes in the gap function within the plane.

II. EXPERIMENTAL

Single crystals of $CeIrIn_5$ were grown by the self-flux method.[9] Two high-purity crystals were cut so that heat current flowed along the a axis and c axis, respectively. The residual resistivity of these pure samples was $\rho_{0a}=0.2$ $\mu\Omega$ cm and $\rho_{0c}=0.50$ $\mu\Omega$ cm, respectively. (The difference in ρ_0 values is due to mass tensor anisotropy.[10]) Another two single crystals were grown with a small amount of La impurities (approximately 0.1% of Ce) and cut along the same two directions with $\rho_{0a}=0.48$ $\mu\Omega$ cm and $\rho_{0c}=2.04$ $\mu\Omega$ cm, respectively. Addition of La lowered the bulk transition temperature T_c by roughly 10%, from 0.38 ± 0.01 K in the pure to 0.34 ± 0.01 K in the La-doped samples. Three additional c-axis samples were measured with $\rho_{0c}=0.81$, 1.18, and 1.65 $\mu\Omega$ cm. For all samples, ρ_0 was obtained by extrapolating the normal-state κ/T to $T=0$ and applying the Wiedemann-Franz law, as described in the caption of Fig. 1. The thermal conductivity was measured as described in Ref. 10. Note that the contribution of phonons to the thermal conductivity is entirely negligible below 1 K for all samples. In all samples, κ_N exhibits the temperature dependence characteristic of a Fermi liquid, $\kappa_N(T)/T=1/(a+bT^2)$ with $a=0.18(0.78)$ K^2 m/W and $b=0.32(0.95)$ m/W for 0.1% La-doped samples for $J\|a(J\|c)$; see Fig. 1. [For pure samples $a=0.085(0.196)$ K^2 m/W and $b=0.36(0.90)$ m/W.[10]] Note that the inelastic scattering coefficients (b) are independent of the residual resistivity, indicating that doping does not alter the normal-state properties significantly. The relative uncertainty in the absolute value of κ between different samples with the same current direction was removed by normalizing their electrical resistivity (measured using the same contacts) to a given value at room temperature, namely, $\rho_a(300\text{ K})=25.9$ $\mu\Omega$ cm and $\rho_c(300\text{ K})=52.7$ $\mu\Omega$ cm.

III. RESULTS

In Fig. 1, the thermal conductivity of the pure samples is compared to that of the La-doped samples, for a heat current parallel $(J\|c)$ and perpendicular $(J\|a)$ to the c axis of the tetragonal structure. Data for the pure samples were reported in a previous publication,[10] whose main finding was a pronounced a-c anisotropy, highlighted in Fig. 2. Indeed, while $\kappa_a(T)/T$ extrapolates to a sizable residual linear term, $\kappa_{0a}/T\approx20$ mW/K^2 cm, in quantitative agreement with

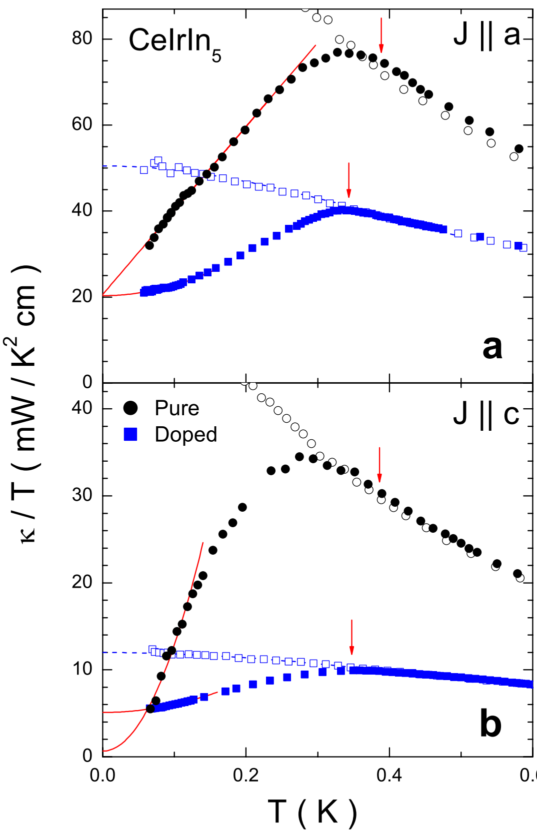

FIG. 1. (Color online) Thermal conductivity of $CeIrIn_5$ in the superconducting state ($H=0$; full symbols) and normal state ($H=0.5$ T$>H_{c2}=0.49$ T; open symbols) of pure (black circles) and La-doped ($Ce_{0.999}La_{0.001}IrIn_5$; blue squares) samples, plotted as κ/T vs T for a heat current parallel [$J\parallel c$; panel (b)] and perpendicular [$J\parallel a$; panel (a)] to the c axis of the tetragonal crystal structure. Red arrows show T_c. Solid red lines are an extrapolation of the low-temperature $H=0$ data to $T=0$, assuming a linear variation in κ/T for the pure $J\parallel a$ data and a T^2 variation for the other data. The blue dashed lines are Fermi-liquid fits to the normal-state data (Ref. 10), yielding an extrapolated residual linear term κ_{0N}/T from which we obtain the residual resistivity ρ_0, via the Wiedemann-Franz law $\kappa_{0N}/T=L_0/\rho_0$, where $L_0=2.45\times10^{-8}$ ΩW/K^2 (see Ref. 10). For $J\parallel a$, the residual linear term κ_0/T is large and independent of impurity content, showing heat conduction in the basal plane to be universal. By contrast, for $J\parallel c$, κ_0/T is negligible in the pure sample and grows to become sizable in the doped sample, showing heat conduction along the c axis to be nonuniversal.

theoretical expectation for a line node,[2,10,11] $\kappa_c(T)/T$ extrapolates to a negligible value.[10]

As seen in Fig. 1(a), κ_a/T in the pure sample is close to linear all the way from slightly below T_c down to the lowest measured temperature. La doping does not alter this dependence, except at very low temperature where it causes a T^2 behavior below 0.15 K. The development of this curvature at low temperature is theoretically expected for a line node, at temperatures below the impurity bandwidth γ.[2] The fact that no curvature is observed in the pure sample is consistent with the smaller γ in that sample. The two curves are seen to come together in the $T\to0$ limit, revealing that conduction in this direction is universal. We conclude that the superconducting gap of $CeIrIn_5$ definitely contains a line node. This is consistent with all other properties of this material, including the specific heat[12] ($C_e\sim T^2$) and the NMR relaxation rate[13] ($T_1^{-1}\sim T^3$).

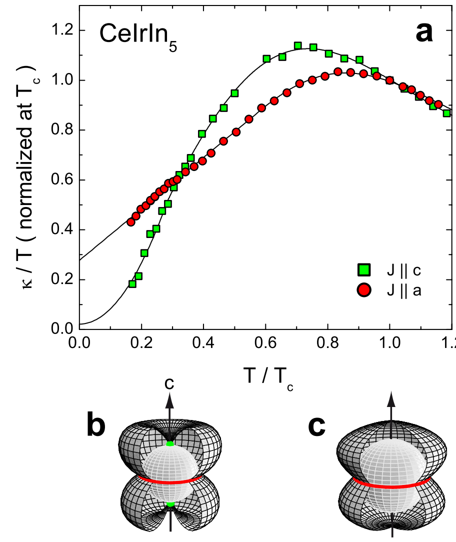

FIG. 2. (Color online) (a) Thermal conductivity of $CeIrIn_5$ as a function of temperature, normalized at $T_c=0.38$ K. Data from pure samples are shown for conduction parallel (green squares) and perpendicular (red circles) to the high-symmetry c axis. The low-temperature regime reveals a strong uniaxial anisotropy with $(\kappa_{0a}/T)/(\kappa_{0c}/T)\to\infty$ as $T\to0$, consistent with a line node in the basal plane. Lines are a guide to the eye. (b) Sketch of the hybrid gap, drawn on a single spherical Fermi surface for simplicity, which consists of a line node in the basal plane ($k_z=0$; red line) and two linear point nodes ($k_x=k_y=0$; green spots) along the c axis (black arrow). (c) Sketch of the polar gap, where $\Delta^2\sim\cos^2\theta$ with θ the polar angle away from the c axis, which only has a line node in the basal plane ($k_z=0$ or $\theta=\pi/2$; red line). (Adapted from Ref. 11.)

Let us now turn to the other current direction, along the c axis. In the pure sample, κ_c/T shows a downward curvature at low temperature such that a linear extrapolation to $T=0$ yields a negative residual linear term, implying that κ_c/T must acquire upward curvature below our lowest data point, as sketched by the red solid line in Fig. 1(b). La doping results in the unambiguous appearance of a sizable residual linear term κ_{0c}/T. This shows that heat conduction along the c axis is not universal.

In Fig. 3, the value of κ_0/T for several samples is plotted as a function of their residual resistivity ρ_0. While the large κ_0/T along the a axis is independent of ρ_0, κ_0/T along the c axis is proportional to ρ_0, vanishing in the limit of $\rho_0\to0$. This is precisely what is expected for a gap that has a line node in the basal plane. In D_{4h} symmetry, two states have such a line node: (1) the $k_z(k_x+ik_y)$ state in the even-parity E_g representation,[2,14] whose "hybrid gap"—drawn in Fig. 2(b)—also has linear point nodes along the c axis (i.e., point nodes at which the gap vanishes linearly with angle[2]); (2) the k_z state in the odd-parity A_{2u} representation (in weak spin-orbit coupling),[14] whose "polar gap"—drawn in Fig. 2(c)—has no other nodes. In both cases, κ_{0c}/T is predicted to grow as a function of γ, linearly for the hybrid gap, quadratically for the polar gap.[2,14] The dependence of γ on the normal-

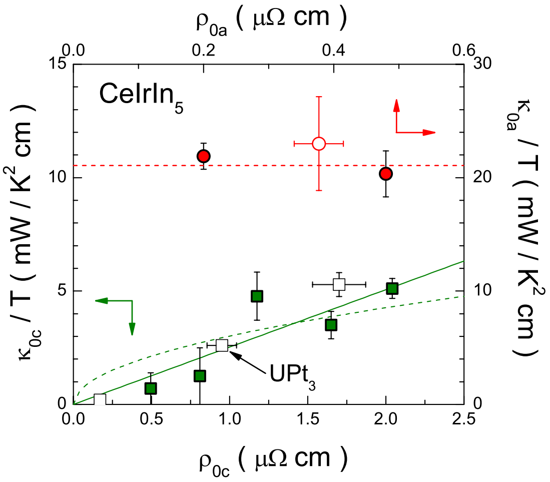

FIG. 3. (Color online) Residual linear term, κ_0/T, in the thermal conductivity of CeIrIn$_5$, as a function of the residual resistivity ρ_0, a measure of the impurity scattering rate Γ_0. The value of κ_0/T is obtained by extrapolating κ/T vs T data to T=0. The values of ρ_0 are obtained as described in Fig. 1. The error bars on κ_0/T and ρ_0 for our seven samples (those with full symbols) reflect the uncertainty in the extrapolation of κ/T and κ_N/T to T=0, respectively. The open red circle is the value of κ_{0a}/T quoted in Ref. 18 for an a-axis sample whose ρ_0 value we obtain as above by extrapolating the corresponding normal-state data (Ref. 18). To the error bar on κ_{0a}/T quoted in Ref. 18 (± 2 mW/K^2 cm), we have added a $\pm 10\%$ geometric-factor uncertainty on both κ_{0a}/T and ρ_0. The in-plane transport (red circles; top and right axes) shows κ_{0a}/T to be constant at ~ 21 mW/K^2 cm (horizontal red dashed line), independent of Γ_0: heat conduction in the plane is universal. By contrast, c-axis transport (green squares; bottom and left axes) is not universal with $\kappa_{0c}/T \to 0$ as $\rho_0 \to 0$. The solid green line is a linear fit to the c-axis data, the dependence expected for a polar gap in the strong-impurity-scattering limit, where $\kappa_{0c}/T \sim \rho_0$ (Ref. 14). The dashed green line is a fit to $\kappa_{0c}/T \sim (\rho_0)^{1/2}$, expected theoretically in the same limit for linear-point nodes along the c axis (Ref. 14). A comparison is made with the heavy-fermion superconductor UPt$_3$, using corresponding data from Ref. 7 (κ_{0c}/T; open squares). We have added a $\pm 10\%$ geometric-factor uncertainty on the UPt$_3$ data for both κ_{0c}/T and ρ_0.

state impurity scattering rate Γ_0 depends on the scattering phase shift; in the strong limit of resonant scattering ($\pi/2$ phase shift), $\gamma \sim (\Delta_0\Gamma_0)^{1/2}$.[2] Assuming that impurity scattering can be described by a single scattering rate Γ_0, we have $\Gamma_0 \sim \rho_0$, and in that limit $\kappa_{0c}/T \sim \gamma \sim (\rho_0)^{1/2}$ for a hybrid gap[2] and $\kappa_{0c}/T \sim \gamma^2 \sim \rho_0$ for a polar gap.[14] This would give a dependence of κ_{0c}/T on ρ_0 as indicated by the dashed and solid lines in Fig. 3, respectively. Within error bars, both dependencies are compatible with the data.

IV. DISCUSSION

A. Gap structure

The pronounced and qualitative uniaxial anisotropy revealed by heat transport in CeIrIn$_5$ is inconsistent with d-wave symmetry, whether it be the $d_{x^2-y^2}$ state of the B_{1g} representation (which transforms as $k_x^2-k_y^2$) or the d_{xy} state of the B_{2g} representation (which transforms as k_xk_y).[1,14] In such states, the gap would go to zero where the planes $k_x = \pm k_y$ (or k_x, k_y=0) cut the Fermi surface. The resulting "vertical" line nodes would make quasiparticle conduction along a and c fundamentally similar. It has been shown[15] that even within d-wave symmetry some uniaxial anisotropy can be generated by requiring that the c-axis dispersion of one Fermi surface sheet, the quasi-two-dimensional open cylinder,[16,17] be accidentally small along the nodal directions. However, this artificial constraint would not, in general, apply to or be effective on the other four or five sheets of the complex Fermi surface of CeIrIn$_5$.[16,17] By contrast, any order parameter in the D_{4h} point group that requires the superconducting gap to vanish in the k_z=0 plane by symmetry will automatically produce the qualitative anisotropy seen here,[2,14,15] for all Fermi-surface sheets, whatever their shape, dispersion, and location.

In a recent study of heat transport as a function of magnetic field direction in the basal plane, a tiny fourfold variation in κ vs field angle, of magnitude 1% of the normal-state conductivity, was interpreted as evidence for a d-wave gap.[18] The much larger uniaxial anisotropy discussed here, of magnitude 300% of the normal-state anisotropy at $T=T_c/6$, and increasing as $T \to 0$ (see Fig. 2), indicates that this fourfold variation does not reflect the dominant nodal structure. It could instead come from an in-plane anisotropy of the effective mass on whichever Fermi surface dominates the heat transport at a particular field. In a multiband superconductor such as CeIrIn$_5$, this dominance will shift with field from one Fermi-surface sheet to another if the gap is band dependent, as is dramatically the case in CeCoIn$_5$.[8] This could explain why the fourfold variation changes phase with field.[18] The fourfold variation with field angle could also be due to the presence of minima in the gap as a function of in-plane angle. Minima of this kind have been inferred from fourfold variations in the specific heat as a function of field angle in the pnictide superconductor FeSe$_{1-x}$Te$_x$,[19] where the gap does not contain nodes in the basal plane since κ_0/T=0.[20]

B. Comparison with UPt$_3$

It is instructive to compare our data on tetragonal CeIrIn$_5$ (with T_c=0.4 K) to similar data on hexagonal UPt$_3$,[7] another heavy-fermion superconductor (with T_c=0.44 K).[21] The presence of nodes in the gap of the latter compound has been inferred from the power-law temperature dependence of various physical properties.[21] Figure 4 compares the data for pure and doped CeIrIn$_5$ to that of pure and irradiated samples of UPt$_3$,[7] at low temperature. In CeIrIn$_5$, κ_a/T extrapolates to a finite value and remains unchanged with doping (it is universal). By contrast, κ_0/T in UPt$_3$ is negligibly small in both current directions, and it increases rapidly with irradiation (see also Fig. 3). The magnitude of the residual linear term expected from a line node may be estimated from the following expression:[2]

$$\frac{\kappa_0}{T} = \frac{1}{3}\gamma_N v_F^2 \frac{a\hbar}{2\mu\Delta_0}, \tag{1}$$

where γ_N is the linear term in the normal-state specific heat, v_F is the Fermi velocity, Δ_0 is the gap maximum, μ

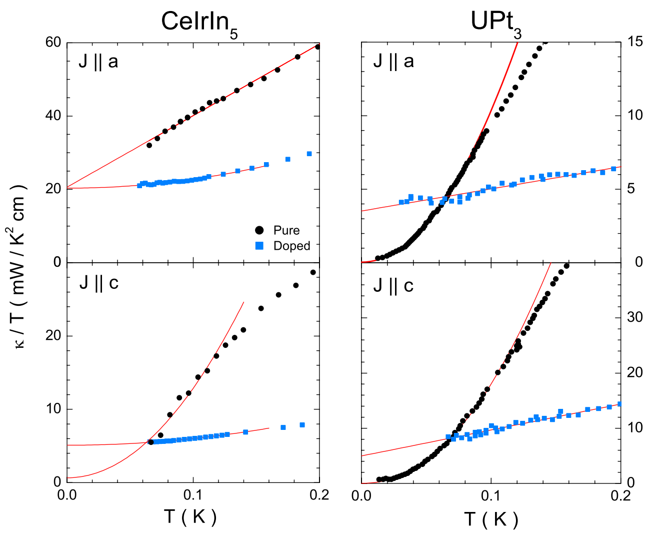

FIG. 4. (Color online) Comparison of low-temperature thermal conductivity in the heavy-fermion superconductors $CeIrIn_5$ (left panels) and UPt_3 (right panels; data from Ref. 7), for current directions parallel ($J \parallel c$; bottom panels) and perpendicular ($J \parallel a$; top panels) to the high-symmetry c axis of the tetragonal and hexagonal crystal structures, respectively. Data for pristine samples are shown as black circles; data for doped ($CeIrIn_5$) or irradiated (UPt_3) samples are shown as blue squares.

is the slope of the gap at the node, and a is a constant of order unity whose value depends on the particular gap structure. This expression works well for $CeIrIn_5$, giving a theoretical value of $\kappa_{0a}/T \simeq 0.2$ mW/K^2 cm.[10] Using the values of γ_N and v_F appropriate for UPt_3,[21] and assuming $\Delta_0 = 2.14 k_B T_c$ and $\mu = 2$, Eq. (1) gives a predicted value of $\kappa_{0b}/T \simeq 1.5$ mW/K^2 cm for UPt_3. The data of Ref. 7 go down as low as 16 mK and κ_b/T in a pure sample extrapolates to 0.2 mW/K^2 cm (and $\kappa_c/T \simeq 0$). This is at least one order of magnitude too small for a line node. Combined with the strong dependence of κ_0/T on scattering rate and the essentially isotropic nature of $\kappa(T)$, the thermal conductivity data on UPt_3 seem inconsistent with a line node in the basal plane. This leaves quite open the question of the gap structure in that material.

C. Comparison with $CeCoIn_5$

We now compare $CeIrIn_5$ with $CeCoIn_5$, whose critical temperature $T_c = 2.4$ K. In $CeCoIn_5$, a large residual linear term κ_0/T was found for transport in both directions.[8] With the addition of x La impurities per Ce atom, κ_0/T was seen to drop rapidly (for both directions), tracking the suppression of the normal-state conductivity $\kappa_N/T \sim 1/x \sim 1/\rho_0$.[8] This is in marked contrast to the behavior of the specific heat, which showed an increase in its residual linear term with doping,[8] as expected of a superconductor with a line of nodes in the gap. The difference was interpreted in terms of an extreme form of multiband superconductivity, whereby one sheet of the Fermi surface—of high mobility and light mass—has a gap of negligible magnitude.[8] (It was later shown that a tiny magnetic field is sufficient to suppress superconductivity on that sheet.[22]) In this context, it is difficult to ascertain the structure of the large gap from a measurement of the thermal conductivity. Nevertheless, a two-band model with a negligible gap on one Fermi surface and a line node on the other fits the data well with a universal in-plane conductivity from the line node of magnitude $\kappa_{0a}/T \approx 1.4$ mW/K^2 cm.[8] This value is 14 times smaller than in $CeIrIn_5$, but is nevertheless in rough agreement with theoretical expectation for a line node [Eq. (1)], since T_c (and so presumably the gap maximum Δ_0) is six times larger. (The remaining factor of 2 or so could come from a smaller Fermi velocity on the relevant band.)

The fact that the specific heat[23] and thermal conductivity[24] of $CeCoIn_5$ both exhibit a fourfold anisotropy as a function of magnetic field direction in the basal plane has been interpreted as evidence for d-wave symmetry,[25] as in the case of $CeIrIn_5$ discussed above. For the same reasons, it may be difficult to reliably discriminate between gap anisotropy and Fermi-surface anisotropy as the cause of the small fourfold variations detected in these studies, particularly in the presence of a strong band dependence of the gap. And again, as in the case of $FeSe_{1-x}Te_x$,[19] the fourfold variation in the specific heat may simply reflect the presence of minima in the gap of $CeCoIn_5$ as a function of in-plane angle and not nodes.

In the absence of further directional evidence, it is probably fair to say that the location of the line node in the gap structure of $CeCoIn_5$ is still an open question. Nevertheless, it is interesting to contemplate the possibility that the two $CeIrIn_5$ and $CeCoIn_5$ do have different gap structures, and hence different order parameter symmetries, as it would explain the fact that superconductivity in $CeIrIn_5$ appears to reside in a region of the generalized phase diagram of the CeMIn$_5$ family (where M=Ir, Co, or Rh) which is separate from the region where superconductivity in $CeCoIn_5$ and $CeRhIn_5$ resides.[26] In a scenario of magnetically mediated superconductivity, a different gap structure and pairing symmetry would come from a different momentum dependence of the magnetic fluctuations responsible for pairing.[27] The fact that superconductivity coexists with antiferromagnetism in $CeCoIn_5$ and $CeRhIn_5$ but not in $CeIrIn_5$ (Ref. 28) may be a manifestation of that difference.

V. CONCLUSION

In conclusion, we have found heat conduction in the heavy-fermion superconductor $CeIrIn_5$ to be universal in the basal plane but not along the c axis. This shows that the gap structure consists of a line of nodes in the basal plane, inconsistent with the d-wave symmetry proposed for $CeCoIn_5$. This suggests that there may be two distinct superconducting phases that form within the CeMIn$_5$ family of heavy-fermion metals.

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