

## Heat transport study of field-tuned quantum criticality in CeIrIn<sub>5</sub>

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The in-plane electrical resistivity,  $\rho$ , and thermal conductivity,  $\kappa$ , of the heavy-fermion superconductor CeIrIn<sub>5</sub> were measured down to 40 mK in magnetic fields up to 11 T applied along the  $c$  axis. For all fields above  $H_{c2} = 4$  T of filamentary superconductivity, we find that the ratio of heat and charge conductivities in the  $T \rightarrow 0$  limit obeys the Wiedemann-Franz law,  $\kappa/T = L_0/\rho$ , where  $L_0 = 2.45 \times 10^{-8} \text{ W } \Omega \text{ K}^{-2}$  is the Sommerfeld value of the Lorenz number. The temperature-dependent parts of both the electrical and thermal resistivity,  $w \equiv T/L_0\kappa$ , follow the functional dependence expected for the Fermi liquid theory of metals with  $\rho - \rho_0 = AT^2$ ,  $w - w_0 = BT^2$ , with  $\rho_0 = w_0$  and  $B \approx 2A$ . The coefficient  $B$  does not show a significant field dependence even upon approaching  $H_{c2} = 0.4$  T of the bulk superconducting state. The weak response to the magnetic field is in stark contrast with the behavior found in the closely related CeCoIn<sub>5</sub>, in which the field-tuned quantum critical point coincides with  $H_{c2}$ . The value of the electron-electron mass enhancement, as judged by the  $A$  and  $B$  coefficients, is about one order of magnitude reduced in CeIrIn<sub>5</sub> as compared to CeCoIn<sub>5</sub> (in spite of the fact that the zero field  $\gamma_0$  in CeIrIn<sub>5</sub> is twice as large as  $\gamma_0$  in CeCoIn<sub>5</sub>), which suggests that the material is significantly farther away from the magnetic quantum critical point at bulk  $H_{c2}$  and at all of the studied fields. A suppressed Kadowaki-Woods ratio in CeIrIn<sub>5</sub> compared to CeCoIn<sub>5</sub> suggests a notably more localized nature of  $f$  electrons in the compound.

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### I. INTRODUCTION

Ce-based heavy-fermion compounds  $\text{Ce}M\text{In}_5$  ( $M = \text{Co, Rh, Ir}$ ), known as the 115 family, show a variety of ground states at ambient pressure. CeIrIn<sub>5</sub> and CeCoIn<sub>5</sub> are bulk superconductors with the transition temperatures  $T_c = 0.4$  and 2.3 K, respectively [1,2]. Filamentary superconductivity is observed in CeIrIn<sub>5</sub> below  $T_{cf} \sim 1.2$  K [1]. CeRhIn<sub>5</sub>, an antiferromagnet with Néel temperature  $T_N = 3.8$  K, exhibits ambient pressure superconductivity at very low temperatures,  $T_c \approx 0.1$  K [3,4], and with the same value of  $T_c \approx 2.5$  K as CeCoIn<sub>5</sub> under pressure of 2 GPa [5].

Magnetic order can be induced in the superconducting members by Cd and Hg substitutions of In [6], so that phase diagrams with a rich interplay of magnetism, quantum critical points (QCPs) at  $T_N \rightarrow 0$  [7], and superconductivity are found as functions of pressure and composition (see Refs. [8,9] for reviews). Doping studies found that CeIrIn<sub>5</sub> [10–12], similar to CeCoIn<sub>5</sub> [6,13], also lies in the vicinity of the magnetic quantum critical point, and thus its superconductivity is most likely magnetically mediated. Our studies of thermal conductivity in both CeCoIn<sub>5</sub> [14] and CeIrIn<sub>5</sub> [15,16], though, found significant deviations from the simple  $d$ -wave scenario, supported by many experiments [17–20].

A magnetic field can also be used as the nonthermal tuning parameter for the quantum critical point, and in CeCoIn<sub>5</sub>, the field-tuned QCP coincides mysteriously with the superconducting upper critical field for magnetic-field orientations along both the  $c$  axis [21,22] and the  $ab$  plane [23]

of the tetragonal crystals. The existence of the QCP is reflected in anomalous temperature dependences of electrical resistivity [2,13,24] (closely following a T-linear dependence) and of the specific heat (showing logarithmic divergence), in band-dependent divergence of cyclotron effective masses [25,26] and directional violation of the Wiedemann-Franz law [24,27].

In CeRhIn<sub>5</sub>, field-induced magnetic order is found in the pressure range below  $p_{\text{max}} = 2.5$  GPa, corresponding to maximum superconducting  $T_c$  [28]. Interestingly, similar phenomenology of QCP coinciding with the first-order transition at  $H_{c2}$  is found in closely related heavy-fermion  $\text{Ce}_2\text{PdIn}_8$  [29], as well as in some other unconventional superconductors, including cuprates [30] and iron-based material  $\text{KFe}_2\text{As}_2$  [31].

Of great interest is the question of whether field-tuned quantum criticality can be found in CeIrIn<sub>5</sub>. The two materials, CeCoIn<sub>5</sub> and CeIrIn<sub>5</sub>, have identical Fermi surfaces [32,33] and show very similar normal state properties [33], so it is natural to expect similarity in response to magnetic field. Despite this apparent similarity, heat capacity measurements [34–36] do not indicate critical behavior near the bulk upper critical field, finding nearly temperature-independent  $C/T$  at the lowest temperatures. Instead, heat capacity, torque, and resistivity studies suggest that CeIrIn<sub>5</sub> shows a metamagnetic transition with a critical field of 25 T, far above superconducting  $H_{c2}$  [36–38]. These studies, though, reveal several unusual features. While the electronic term  $\gamma_0 \equiv C/T$  in heat capacity saturates at a constant value below  $T_{\text{FL}} \approx 0.8$  K in a magnetic field of 1 T and remains nearly constant with magnetic field  $H \parallel c$  in the range 1–17 T, with  $\gamma_0 \approx 0.7\text{--}0.8$  J/mol K<sup>2</sup> [35,36], deviations from this value at high fields start at progressively lower  $T_{\text{FL}}$  [36]. Another study suggested that the superconducting dome of CeIrIn<sub>5</sub> is located inside the dome of the precursor phase, similar to the pseudogap state in the high- $T_c$  cuprates [39,40], suppressed at a field of 6 T.

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We should keep in mind, though, that resistivity studies in  $\text{CeIrIn}_5$  cannot probe the region close to bulk  $H_{c2}$ , hidden inside the domain of filamentary superconductivity [1,41]. Subtraction of the Schottky anomaly in heat capacity measurements always leaves some uncertainty in the behavior at the lowest temperatures. To gain additional insight into the response of  $\text{CeIrIn}_5$  to application of a magnetic field, here we report the field evolution of the electronic transport properties of  $\text{CeIrIn}_5$  using simultaneous electrical resistivity and thermal conductivity measurements, with the latter enabling us to probe the range of filamentary superconductivity close to bulk  $H_{c2}$ . We find that the Wiedemann-Franz law is universally obeyed in the  $T \rightarrow 0$  limit for all fields where resistivity measurements are not affected by filamentary superconductivity, proving the true bulk nature of both electrical and heat transport. For all fields above bulk  $H_{c2}$ , we observe a Fermi-liquid (FL) temperature dependence of thermal resistivity,  $w - w_0 = BT^2$ , slightly decreasing with the field  $B$  coefficient and nearly field-independent  $T_{\text{FL}}$ . Notably smaller values of  $B$  in  $\text{CeIrIn}_5$  when compared to  $\text{CeCoIn}_5$ , as well as their very mild dependence on magnetic field, suggest that  $\text{CeIrIn}_5$  is significantly farther away from magnetic instability at  $H_{c2}$ , and the field-tuned criticality is significantly different in the two materials. We link this difference to the anomalously low value of the Kadowaki-Woods ratio of the  $T^2$  coefficient in electrical resistivity versus the  $\gamma$  coefficient of the specific heat. This suggests a more localized character of magnetism in  $\text{CeIrIn}_5$  than in  $\text{CeCoIn}_5$ .

## II. EXPERIMENT

Single crystals of  $\text{CeIrIn}_5$  were grown using the self-flux method [1]. As-grown crystals had a thin platelike shape, with large surfaces corresponding to the (001) basal plane of the tetragonal lattice. The two samples used in this study were from two different batches, but they revealed nearly identical results. Samples were cut into a rectangular shape with dimensions of  $\sim 4 \times 0.1 \times 0.045 \text{ mm}^3$  and  $\sim 2 \times 0.1 \times 0.01 \text{ mm}^3$ . Four contacts to the samples were made by soldering  $50 \mu\text{m}$  silver wires with indium solder, which resulted in a contact resistance typically  $\sim 1 \text{ m}\Omega$  at low temperature. The same contacts were used to measure electrical resistivity and thermal conductivity in a dilution refrigerator, thus essentially eliminating the uncertainty of the geometric factor determination. The thermal conductivity was measured using a standard four-probe steady-state method with two  $\text{RuO}_2$  chip thermometers calibrated *in situ* against a reference Ge thermometer. The electrical resistivity was measured using an LR700 ac resistance bridge, operating at a frequency of 16 Hz, by applying 0.1 mA excitation currents. To enable low-noise measurements of low resistance samples in identical conditions with thermal conductivity studies, measurements were performed in a separate dilution refrigerator run, during which the high-resistance wire coils of the thermal conductivity apparatus were temporary shorted with silver wires; see Ref. [24] for details.

The phonon contribution to thermal conductivity,  $\kappa_g$ , was determined from electrical resistivity and thermal conductivity measurements in heavily disordered samples of  $\text{Ce}_{1-x}\text{La}_x\text{IrIn}_5$  with  $x = 0.2$  and residual resistivity  $\sim 10 \mu\Omega \text{ cm}$ ; see

Ref. [42] for details. In these heavily disordered samples, the temperature-dependent inelastic scattering contribution to resistivity can be neglected, and the electronic contribution can be directly determined from the Wiedemann-Franz law as  $\kappa_e/T = L_0/\rho$ , which gives  $\kappa_g = \kappa - \kappa_e$ . This contribution represents a minor correction in the temperature range below 1 K, which is the focus of this study.

## III. RESULTS

In Fig. 1, we plot the temperature-dependent resistivity of  $\text{CeIrIn}_5$  measured in magnetic fields of 0, 3.15, 3.6, 4, 8, and 11 T applied along the tetragonal  $c$  axis (top-left panel). In zero field, the filamentary superconductivity is observed below  $T_{cf} = 1.2 \text{ K}$ , and the resistive transition is completely suppressed in a field of 4 T. The filamentary superconductivity

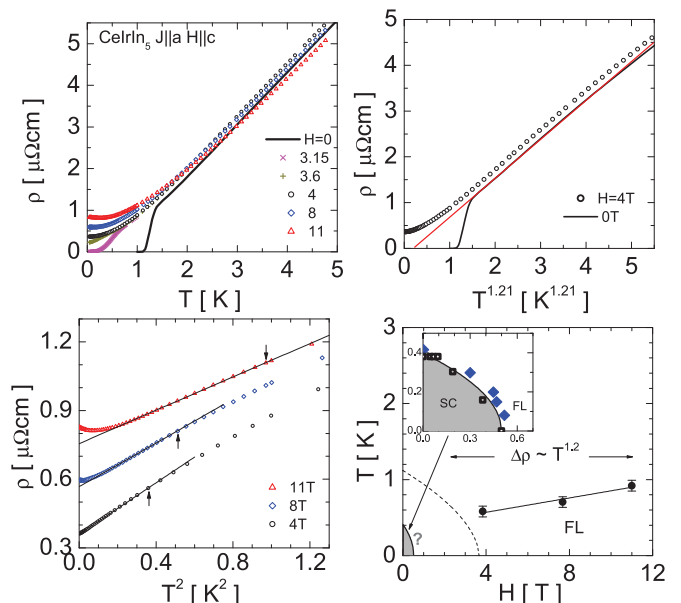


FIG. 1. Temperature-dependent in-plane electrical resistivity of  $\text{CeIrIn}_5$  measured in magnetic fields of 0, 3.15, 3.6, 4, 8, and 11 T applied along the tetragonal  $c$  axis (top-left panel). The filamentary superconductivity, observed in zero field below  $T_{cf} = 1.2 \text{ K}$ , is completely suppressed by  $H_{c2f} \approx 4 \text{ T}$ , revealing a saturating  $\rho(T)$  dependence on  $T \rightarrow 0$ . The top-right panel shows the data in zero field and in a field of 4 T plotted vs  $T^n$  with  $n = 1.21$ , best fit to the power-law function above the filamentary superconducting transition at  $T_{cf} = 1.2 \text{ K}$ . The bottom-left panel shows  $\rho(T)$  data plotted vs  $T^2$  for magnetic field  $H > H_{c2f}$ . Linear dependence, found at low temperatures for all fields, suggests the validity of the Fermi-liquid picture predicting  $\rho = \rho_0 + AT^2$ . Arrows indicate the high-temperature end of the interval where this linear dependence is obeyed, marking a characteristic temperature  $T_{\text{FL}}$ . Note the low values of  $T_{\text{FL}} \approx 0.7 - 1 \text{ K}$  for all fields and the slowly decreasing slope of the  $\rho(T^2)$  curves with magnetic field, suggesting a decreasing  $A$  coefficient (and thus effective mass) with increasing magnetic field. The bottom-right panel summarizes the phase diagram as found from resistivity, thermal conductivity (black squares) [15], and heat capacity (blue diamonds) [35] measurements. The dashed line in the main panel denotes the domain of filamentary superconductivity. We also show the field evolution of the Fermi-liquid properties as found from resistivity measurements (black dots) above  $H_{c2f}$ .

was shown to have the same angular dependence of  $H_{c2}$  as the bulk one [33,41], and it was suggested to originate from strain in the samples that was likely induced by the inclusion of a different phase [43]. A similar phenomenon is observed in  $\text{Sr}_2\text{RuO}_4$  in which superconductivity with higher  $T_c$  is induced by the inclusion of Ru metal [44] and in some other materials including chain  $\text{Nb}_2\text{Se}_3$  [45].

The  $\rho(T)$  dependences at temperatures above 1 K are very similar for all magnetic fields. They clearly deviate from the functional form expected in Fermi-liquid theory,  $\rho = \rho_0 + AT^2$ . The residual electrical resistivity,  $\rho_0$ , of the samples was determined from measurements down to 40 mK in a magnetic field of 4 T, which was sufficient to completely suppress filamentary superconductivity. It was about  $\sim 0.3 \mu\Omega \text{ cm}$ , showing the high purity of the samples. This value is notably lower than  $\sim 0.5 \mu\Omega \text{ cm}$  in previous studies by Nair *et al.* [39] and  $\sim 1.6 \mu\Omega \text{ cm}$  in a magnetic field of 12 T from Capan *et al.* [36]. The top-right panel shows the data in zero field and at 4 T plotted versus  $T^n$  with  $n = 1.21$ , which is the best fit to the power-law function for  $T_{cf} < T < 3.5$  K. This value is very close to the previously reported  $n = 1.27$  [10]. A similar power-law dependence with  $n = 1.21$  is found for fields up to 11 T, with the range of power-law dependence continuing down to  $T \approx 1$  K. At lower temperatures, all  $\rho(T)$  curves show clear signs of saturation when  $T$  tends to zero, and at the lowest temperatures they follow the expectations of Fermi-liquid behavior. This is illustrated in the bottom-left panel of Fig. 1, in which resistivity data are plotted versus  $T^2$ , linearizing the dependence with the slope proportional to the  $A$  coefficient. Slight upward deviations at the lowest temperatures for 8 and 11 T curves are similar to those observed in  $\text{CeCoIn}_5$  [22], and they are due to orbital magnetoresistance. For all magnetic fields  $H > H_{c2f}$ , the  $\rho(T^2)$  plots reveal a range of linear dependence at the lowest temperatures. Deviations from the  $T^2$  dependence at high temperatures mark a characteristic temperature  $T_{\text{FL}}$ , denoted by arrows. Note that  $T_{\text{FL}}$  has values in the range 0.7–1 K, with resistivity crossing over to  $T^n$  at slightly higher temperatures.  $T_{\text{FL}}$ , as determined from resistivity measurements, increases slightly with magnetic field, as shown in the phase diagram (bottom-right panel of Fig. 1). Due to a crossover character of deviations, definitions of  $T_{\text{FL}}$  have somewhat high errors, so it is difficult to make a reliable extrapolation of  $T_{\text{FL}}(H)$  toward bulk  $H_{c2} \approx 0.49$  T, determined from both thermal conductivity measurements [15,46] and heat capacity measurements [35]. The line in the bottom-right panel of Fig. 1 suggests extrapolation of  $T_{\text{FL}}$  to finite values in the  $H = 0$  limit, suggesting the nonexistence of the field-tuned quantum critical point at  $H_{c2}$  or even in zero field. However, significant error bars of the  $T_{\text{FL}}$  determination make this extrapolation from field 4 T unreliable toward bulk  $H_{c2}$ .

To gain additional insight into the magnetic-field-induced evolution of the normal state in  $\text{CeIrIn}_5$ , we performed thermal conductivity measurements. These measurements are not affected by filamentary superconductivity, and they can be performed in the very proximity of bulk  $H_{c2}$ . In Fig. 2, we show the thermal conductivity of  $\text{CeIrIn}_5$  measured in three magnetic fields: 0.52 T (slightly above the bulk  $H_{c2} = 0.49$  T), 4 T (above  $H_{c2f}$ ), and 10.7 T (far away from superconductivity). As can be seen from the 0.52 T curve, the  $\kappa/T$  versus  $T$  plot does not show any features upon entering the filamentary

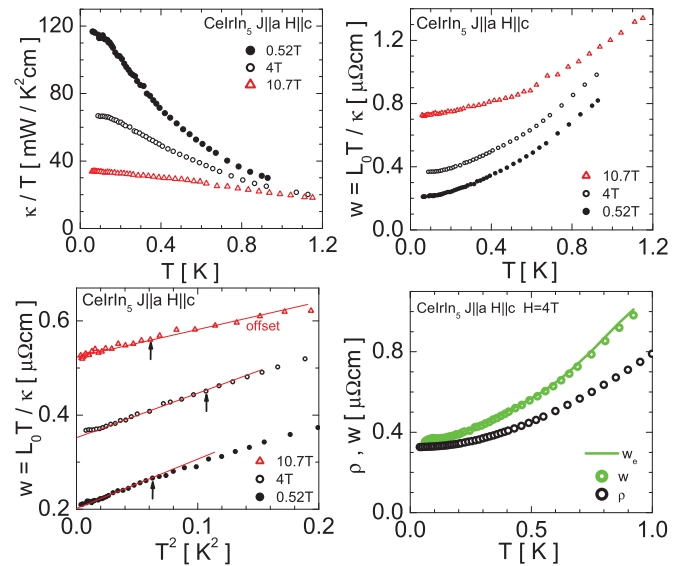


FIG. 2. Temperature-dependent in-plane thermal conductivity of  $\text{CeIrIn}_5$ , plotted as  $\kappa/T$  vs  $T$ , measured in magnetic fields of 0.52 T (slightly above bulk  $H_{c2} = 0.49$  T), 4 T, and 10.7 T applied along the tetragonal  $c$  axis (top-left panel). The filamentary superconductivity does not affect the thermal conductivity of the samples, but it leads to an extrinsic violation of the Wiedemann-Franz law. Upon complete suppression of filamentary superconductivity in a magnetic field 4 T, the thermal resistivity  $w \equiv L_0 T/\kappa$  closely matches electrical resistivity  $\rho$  in the  $T = 0$  limit, as shown in the bottom-right panel, clearly satisfying the Wiedemann-Franz law. Moreover, in the temperature range  $T < 1$  K, in which the phonon contribution is negligible, the thermal resistivity  $w_e$  follows the same Fermi-liquid temperature dependence  $w = w_0 + BT^2$ . This dependence is closely obeyed for all magnetic fields studied (bottom panels), even in the vicinity of bulk  $H_{c2}$ . Due to larger noise in the data, the determination of  $T_{\text{FL}}$  in  $w(T^2)$  plots is even less precise than that from the resistivity data (bottom-right panel).

zero-resistance state below approximately 1.0 K (not shown), leading to artificial violation of the Wiedemann-Franz law. As long as filamentary superconductivity is suppressed, thermal conductivity and electrical resistivity perfectly obey the Wiedemann-Franz law in the  $T \rightarrow 0$  limit, with  $\kappa/T\sigma = L_0$ , where electrical conductivity  $\sigma = 1/\rho$ , and  $L_0 = \frac{\pi^2}{3} \left(\frac{k_B}{e}\right)^2 = 2.45 \times 10^{-8} \text{ W } \Omega \text{ K}^{-2}$  is the Sommerfeld value of the Lorenz number, expected for fermionic systems. The validity of this ratio in the  $T \rightarrow 0$  limit can be seen by direct comparison of the temperature-dependent thermal analog of electrical resistivity,  $w \equiv L_0 T/\kappa$ , and resistivity (bottom-right panel in Fig. 2), which meet at  $T \rightarrow 0$ .  $\text{CeIrIn}_5$  is a good metal, and therefore the phonon contribution to thermal conductivity can be completely neglected in the temperature interval of interest,  $T < 1$  K. In Fig. 2 (bottom-right panel), we show this explicitly by subtracting the phonon contribution  $\kappa_g$ , as determined from measurements in disordered samples, from measured  $\kappa$  of pure  $\text{CeIrIn}_5$ . The resultant electronic part of thermal resistivity  $w_e$  is plotted in the bottom-right panel of Fig. 2 by a solid line. Close agreement is observed between  $w$  and  $w_e$  below 1 K, validating our conclusion about the negligible phonon correction.



## IV. DISCUSSION

### A. Temperature-dependent resistivity

As can be seen in the top panels of Fig. 1, the  $\rho(T)$  curves in CeIrIn<sub>5</sub> strongly deviate from expectations of the Fermi-liquid functional dependence above  $T \sim 1$  K, and they are well described by a  $\Delta\rho \propto T^n$  dependence with  $n = 1.21$ . Observation of a very strong  $\rho(T)$  dependence at such low temperatures [where phonon scattering becomes negligible but the strength of inelastic scattering,  $\Delta\rho_{\text{in}} = \rho(1 \text{ K}) - \rho(0) = 0.6 \mu\Omega \text{ cm}$ , is significantly larger than  $\rho(0) = 0.3 \mu\Omega \text{ cm}$ ] suggests strong magnetic scattering in the compound, similar to CeCoIn<sub>5</sub> [2,33]. The power-law non-Fermi-liquid temperature-dependent resistivity with similar exponents  $n$  is not unusual in the heavy-fermion systems close to quantum critical points. For example, similar values of the power-law exponents are found in CePd<sub>2</sub>Si<sub>2</sub> ( $n \sim 1.2$ ) [7]. The low exponent  $n = 1.21$  can be explained within spin fluctuation theory [47,48] for nearly antiferromagnetic metals in the framework of a spin-density-wave (SDW) scenario, though significantly lower  $\Delta\rho_{\text{in}}/\rho_0$  are usually expected in this case [48]. In the three-dimensional SDW scenario, the exponents are usually expected to be close to  $n = 1.5$  as found in three-dimensional (3D) CeIn<sub>3</sub> ( $n \sim 1.5$ ) [7]. For the case of two-dimensional magnetic fluctuations, the exponents are usually expected to be close to  $n = 1$  [49], as found in YbRh<sub>2</sub>Si<sub>2</sub> [50,51] and CeCu<sub>5.2</sub>Ag<sub>0.8</sub> ( $n \sim 1$ ) [52]. In CeCoIn<sub>5</sub>, the  $\rho(T)$  in zero field is close to  $T$ -linear above  $T_c$  [2], but it becomes  $n = 1.5$  at field-tuned QCP [27]. In this compound, the exponent  $n$  reveals significant anisotropy with  $n = 1$  in  $\rho_c(T)$  [24,53].

In CeIrIn<sub>5</sub>, the same power-law behavior of resistivity up to 3.5 K is found for all magnetic fields. This observation suggests that despite the magnetic character of scattering, dominant scattering is not tuned by a magnetic field. This is in stark contrast with CeCoIn<sub>5</sub>, which shows different power-law resistivity for low and high magnetic fields in the normal state [22,27].

### B. Field evolution of the effective mass

The temperature-dependent part of electronic thermal resistivity obeys the same functional dependence as electrical resistivity. However, because of the different Fermi surface integrals of heat and charge scatterings, the  $T^2$  coefficients  $A$  for resistivity and  $B$  for thermal resistivity are not the same. Typically, for Fermi surfaces without sharp corners, the two coefficient are different by a factor of about 2 [42]. In the left panel of Fig. 3, we plot the magnetic-field dependence of  $A$  and  $B$  coefficients of the  $T^2$  terms in the in-plane electrical (left axis) and thermal (right axis) resistivity of CeIrIn<sub>5</sub>. The  $A$  and  $B$  coefficients in CeIrIn<sub>5</sub> are indeed close to obeying the  $B = 2A$  relation, similar to CeCoIn<sub>5</sub> and most other cases [54–56]. The  $A$  and  $B$  coefficients in CeIrIn<sub>5</sub> closely follow each other as functions of magnetic fields, with  $B$  decreasing from approximately 1.2 to 0.8 upon increasing the field from 0.52 to 11 T. For reference, in the right panel we show similar data for CeCoIn<sub>5</sub> [27]. Note the tenfold difference in the scales for the two compounds. In sharp contrast to CeCoIn<sub>5</sub>, the  $A$  and  $B$  coefficients in CeIrIn<sub>5</sub> do not reveal any tendency for

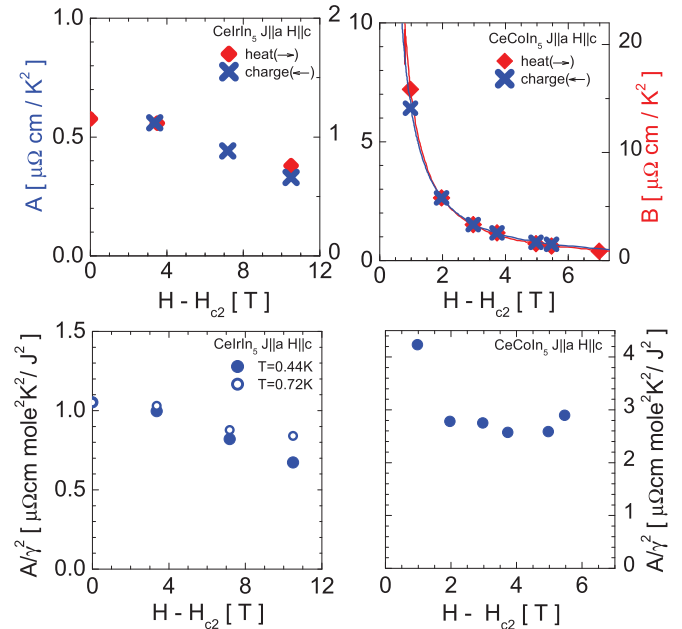


FIG. 3. Magnetic-field dependence of the  $T^2$  coefficients of the electrical resistivity,  $A$  (blue crosses, left axes), and of the thermal resistivity,  $B$  (red diamonds, right axes), for CeIrIn<sub>5</sub> (top-left panel) and CeCoIn<sub>5</sub> (top-right panel). The data are plotted vs  $H - H_{c2}$ , which is the distance to a quantum critical point in CeCoIn<sub>5</sub>. Note the tenfold difference of the  $A/B$  scales for the two cases. The field dependence  $B(H)$  in CeIrIn<sub>5</sub> suggests no divergence of the effective mass toward bulk  $H_{c2}$ . Significantly smaller values of  $A$  and  $B$  coefficients compared to those in CeCoIn<sub>5</sub> suggest that CeIrIn<sub>5</sub> is significantly farther away from the quantum critical point in the phase diagram. A decrease of the  $A$  and  $B$  coefficients with magnetic field suggests moving away from the QCP. The bottom panels show Kadowaki-Woods ratios,  $A/\gamma^2$ , calculated based on the measured  $A$  values and the literature values of the specific heat [36]. Note that the heat capacity data show a notable temperature dependence at 11 T, as reflected in the higher ratio value at 0.72 K.

divergence as functions of magnetic fields. The nearly tenfold difference in the  $A$  and  $B$  coefficients between CeCoIn<sub>5</sub> and CeIrIn<sub>5</sub> suggest a notable difference in the effective masses, reflecting close proximity to the quantum critical point in the case of CeCoIn<sub>5</sub> and a relatively large distance from it for CeIrIn<sub>5</sub>.

This very weak field dependence of the  $A$  and  $B$  coefficients in CeIrIn<sub>5</sub> is consistent with specific heat [34,36], finding a weak field dependence of the electronic specific-heat coefficient  $\gamma_0$ , and the dHvA experiments [57] and cyclotron effective mass,  $m^*$  (for a field between 6 and 17 T) at low temperature [36,57]. In CeCoIn<sub>5</sub>, the  $A$  coefficient changes from 7.5 to 0.5  $\mu\Omega \text{ cmK}^{-2}$  for fields  $\sim 6 - 16$  T [22], and a significant field dependence is found for effective masses of carriers, particularly strong for  $\beta$  and  $\alpha$  sheets of the Fermi surface [33].

In our study of field-tuned quantum criticality in CeCoIn<sub>5</sub> upon approaching from both inside the superconducting dome from below  $H_{c2}$  and outside the superconducting dome from above  $H_{c2}$  [46], we noticed that the heaviest electrons are strongly bound in the superconducting condensate. In this

case, the big difference in the strength of electron-electron renormalization between CeCoIn<sub>5</sub> and CeIrIn<sub>5</sub> can be directly linked to the fivefold difference in the value of the superconducting  $T_c$ . CeCoIn<sub>5</sub> and CeIrIn<sub>5</sub> have identical Fermi surfaces [32], yet interestingly they demonstrate very different electron renormalization and  $T_c$ .

Another interesting observation is that the transition at  $H_{c2}$  in CeIrIn<sub>5</sub> is second order [35], while in CeCoIn<sub>5</sub> it is first order. The first-order character of the transition is taken as arising from paramagnetic limiting of the upper critical field. We can speculate that orbital limiting of  $H_{c2}$  observed in CeIrIn<sub>5</sub> in configuration  $H \parallel c$  may be responsible for the lack of a coincident quantum critical point.

Summarizing, we do not find a field-tuned quantum critical point at bulk  $H_{c2}$  in CeIrIn<sub>5</sub>, nor do we see indications of its existence in all ranges of magnetic fields studied (up to 11 T). This is in sharp contrast to CeCoIn<sub>5</sub>, suggesting that CeIrIn<sub>5</sub> is significantly farther away from the QCP. This finds support in the tenfold difference of the Fermi liquid  $T^2$  coefficients between the two compounds.

### C. Kadowaki-Woods ratio

It is of interest to note that the very big difference in  $A$  and  $B$  coefficients between CeCoIn<sub>5</sub> and CeIrIn<sub>5</sub> is not expected based on previous specific-heat studies [34–36]. In zero field, both materials have similar  $\gamma = C/T$  values above  $T_c$ , somewhat higher in CeIrIn<sub>5</sub>. The big difference in  $A$  coefficients suggests that the Kadowaki-Woods ratio, defined as  $r_{KW} = A/\gamma^2$ , is anomalously low in CeIrIn<sub>5</sub>. Indeed, as shown in Fig. 3, near  $H_{c2}$  in CeIrIn<sub>5</sub> we find  $r_{KW} \sim 0.1a_0$  ( $a_0 = 10 \mu\Omega \text{ cm mol}^2 \text{ K}^2/\text{J}^2$ ), and the ratio does not show a significant field dependence. In CeCoIn<sub>5</sub>, for instance, this ratio is about  $0.52a_0$  at  $H_{c2} \sim 6$  T, which falls on the universal line for some other heavy fermions [22].

The Kadowaki-Woods ratio cancels out mass renormalization in electrical resistivity and heat capacity measurements and leads to scaling of  $A$  and  $\gamma^2$  proportional to level degeneracy of  $f$  electrons [58]. Ce ions in CeCoIn<sub>5</sub> and CeIrIn<sub>5</sub> are in the same crystal field environment, so it is natural to take the same value  $n = 2$ . While the  $r_{KW}$  for CeCoIn<sub>5</sub> has a value typical for heavy-fermion materials, it is anomalously low in CeIrIn<sub>5</sub>.

The anomalously low value of the Kadowaki-Woods ratio in CeIrIn<sub>5</sub> suggests that different groups of carriers are determining the electrical resistivity and the heat capacity of the samples. Two scenarios can be at play. In the first, conduction electrons are strongly disconnected from  $f$  electrons due to the localized character of the latter. In this case, similar values of heat capacity in CeCoIn<sub>5</sub> and CeIrIn<sub>5</sub> reflect a nearly identical  $f$ -electron contribution, but a significantly more localized character in CeIrIn<sub>5</sub>. In the second scenario, we need to assume a significant difference in the properties

of different groups of carriers on the multiband Fermi surface of the materials. This scenario would require the presence of light and mobile carriers dominating in the electrical transport and heavy carriers dominating the heat capacity.

One possible way to distinguish between these two scenarios is to study magnetoconductance. In the latter scenario, the magnetoconductance of CeIrIn<sub>5</sub> should be significantly larger than in CeCoIn<sub>5</sub>. Comparing the resistivity data for CeIrIn<sub>5</sub> in a magnetic field of 11 T in Fig. 1 (bottom-left panel) with similar data in CeCoIn<sub>5</sub> [22], we find that orbital magnetoconductance at the lowest temperatures is stronger in CeCoIn<sub>5</sub>, which is at odds with this scenario.

## V. CONCLUSIONS

In conclusion, temperature-dependent electrical resistivity and thermal conductivity measurements in CeIrIn<sub>5</sub> as functions of magnetic fields applied along the  $c$  axis revealed the validity of the Wiedemann-Franz law in the  $T \rightarrow 0$  limit as long as resistivity measurements are not affected by filamentary superconductivity. At temperatures above 1 K, the temperature-dependent resistivity is well represented by a power-law function  $\Delta\rho \propto T^n$ , with nearly field-independent  $n = 1.21$ . At the lowest temperatures, the temperature dependences of both electrical resistivity,  $\rho(T)$ , and thermal resistivity,  $\rho(T)$ , follow the expectations of the Landau Fermi-liquid theory with  $B \approx 2A$ , as expected for Fermi surfaces without sharp features in the angular Fermi velocity distributions. The coefficient  $B$  does not exhibit a significant field dependence even on approaching  $H_{c2} = 0.4$  T of the bulk superconducting state. The weak response to the magnetic field is in stark contrast with the behavior found in the closely related CeCoIn<sub>5</sub>, in which the field-tuned quantum critical point coincides with  $H_{c2}$ . The value of the electron-electron mass enhancement, as judged by the  $A$  and  $B$  coefficients, is about one order of magnitude reduced in CeIrIn<sub>5</sub> as compared to CeCoIn<sub>5</sub>, suggesting that the material is significantly farther away from the magnetic quantum critical point. The suppressed Kadowaki-Woods ratio in CeIrIn<sub>5</sub> compared to CeCoIn<sub>5</sub> suggests a notably more localized nature of  $f$  electrons in the compound.

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