I. INTRODUCTION

The occurrence of pressure-induced superconductivity (SC) in Ce-based heavy-fermion (HF) compounds has attracted a lot of attention in the field of condensed matter physics [1]. For most of such materials, SC appears in the vicinity of a magnetic quantum critical point (QCP) at \( p_c \), leading to the belief that spin fluctuations are responsible for the Cooper pairing [2]. On the other hand, Ce-valence fluctuations may also act as the pairing glue [3]. On the one hand, valence fluctuations may also act as the pairing glue [3] and the corresponding critical endpoint (CEP) at \( p_v \) can be deduced by resistivity scaling analysis [4]. It is noteworthy that the relative position between \( p_c \) and \( p_v \) may vary for different systems, probably depending on the hybridization strength \( (V) \) between Ce-4f and conduction electrons [3, 5]. For example, while \( p_c \) and \( p_v \) are well separated in CeCu$_2$Si$_2$ [6] and CeCu$_2$(Si$_1$-xGe$_x$)$_2$ [7], they are very close in CeAl$_2$Si$_2$ [5].

CeRhIn$_5$ belongs to the Ce-115 family, whose structure consists of alternating CeIn$_3$ and RhIn$_2$ layers stacked along the \( c \)-axis [9]. At ambient pressure, the compound is a prototypical heavy-fermion antiferromagnet with a Néel temperature \( T_N = 3.8 \) K, although a signature of SC was reported at \( \sim 90 \) mK [10]. Under pressure, the \( T_N \) of CeRhIn$_5$ passes through a maximum and disappears at \( \sim 2 \) GPa, above which the antiferromagnetic order is rapidly suppressed as confirmed by the NQR measurement [11]. Meanwhile, SC is observed over a broad pressure range with a maximum \( T_c \) of 2.3 K at \( p_c \approx 2.5 \) GPa [8]. Although experimental signatures for the existence of a QCP are found at \( p_c \), the nature of fluctuations remains under debate [12, 13]. In particular, de Haas-van Alphen (dHvA) measurements detect an abrupt change in the Fermi surface shape across \( p_c \) [14], yet the resi-
mated from the width of the Pb superconducting transition was less than 0.05 GPa. To determine better the absolute resistivity value, pressure-dependent resistivity at 292 K was extrapolated to $p = 0$. The obtained value was corrected by the one measured at ambient condition, yielding a normalization factor for the results under pressure. Thanks to this special care, the estimated error in the absolute resistivity value is within 2%.

III. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependencies of the magnetic resistivity $\rho^\text{mag} = \rho(\text{CeRhIn}_5) - \rho(\text{LaRhIn}_5)$ of CeRhIn$_5$ at pressures up to 5.63 GPa. The weak pressure variation of $\rho(\text{LaRhIn}_5)$ is taken into account following

![FIG. 1: (Color online) Logarithmic $T$-dependence of the magnetic resistivity of CeRhIn$_5$ along the (a) $a$- and (b) $c$-axis under pressures up to 5.63 GPa. The arrows and the dashed line are a guide to the eyes. The inset of (a) shows the $a$-axis data at $p = 0$. The resistivity maximum and bump are marked by $T^\text{mag}_1$ and $T_1$, respectively. The dashed line is a guide to the eyes. The inset of (b) shows the $c$-axis data at $p = 2.13$ GPa. The two dashed lines indicate the $-\ln T$ slope, and their intersection temperature is marked as $T_2$. The inset in between (a) and (b) shows the pressure dependencies of the $-\ln T$ slope below room temperature for both axes.](image)

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Ref. [13]. In general, the pressure evolution of $\rho^\text{mag}$ is reminiscent of that observed in other Ce-based Kondo lattice compounds. At $p = 0$, $\rho^{\text{mag}}_c$ exhibits a $-\ln T$ dependence below room temperature, reflecting incoherent Kondo scattering on excited crystal field (CF) levels [17]. Upon further cooling, a broad maximum is observed at $T_{\text{max}}$ and a small bump is discernable at a lower temperature $T_1$, which is defined empirically as $3/4$ of the temperature at which the second derivative of $\rho^\text{mag}$ reaches a maximum. With increasing pressure, $T_1$ decreases modestly and becomes no longer resolvable above 1.57 GPa, while $T_{\text{max}}$ first decreases then increases. In addition, a signature of magnetic ordering is observed below 1.78 GPa, while a superconducting transition occurs between 1.03 and 3.80 GPa.

As can be seen in Fig. 1(b), $\rho^{\text{mag}}_c$ behaves similarly to $\rho^{\text{mag}}_a$, except that the former displays two different $-\ln T$ dependencies above $T_{\text{max}}$. This new observation is likely due to the relatively small value of the first CF splitting energy in comparison with other Ce-based HF systems [18]. Extrapolations of these $-\ln T$ behaviors intersect at the temperature $T_2$ [inset of Fig. 1(b)], which increases with pressure. Nevertheless, the $-\ln T$ slope $k$ near room temperature for both axes grows by nearly the same factor of 3 up to 5.63 GPa, which signifies a strong enhancement of the Kondo coupling by pressure Ref. [17].

Figure 2 shows the anisotropy of the magnetic resistivity $\gamma_{\text{mag}} = \rho^{\text{mag}}_c / \rho^{\text{mag}}_a$ plotted as a function of temperature under pressures up to 5.63 GPa. At $p = 0$, $\gamma_{\text{mag}}$ decreases from $\sim 2.2$ to $< 1$ with decreasing temperature and shows an upturn below $T_N$. This upturn, whose origin remain unclear at present, was not observed in the previous study [19]. Under pressure, the evolution

![FIG. 2: (Color online) Temperature dependencies of the magnetic resistivity anisotropy under pressures up to 5.63 GPa. The inset shows a zoom of the data below 10 K at selected pressures. The dashed line is an extrapolation of the curve at $p \approx p_c$ to zero temperature.](image)

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of $\gamma_{\text{mag}}$ is very similar to that of Ref. [13], and exhibits qualitative difference at temperatures above and below $\sim 120$ K. For $T > 120$ K, $\gamma_{\text{mag}}$ is weakly temperature and pressure dependent, and hence is likely dominated by the crystalline anisotropy.

By contrast, below $\sim 120$ K, $\gamma_{\text{mag}}$ increases strongly with increasing pressure and decreasing temperature. Consequently, the temperature dependence of $\gamma_{\text{mag}}$ changes its curvature from downward to upward. At 2 K, the $\gamma_{\text{mag}}$ value grows by a factor of 3 throughout the investigated pressure range [inset of Fig.2]. This feature can likely be understood by taking into account the anisotropic hybridization between Ce-4f electrons and conduction electrons [21]. Following such an interpretation, the hybridization strength grows much faster with pressure along the c-axis than along the a-axis. Nevertheless, at $p = 2.57$ GPa, the $\gamma_{\text{mag}}$ value extrapolated to 0 K is very close to 1, pointing to isotropic magnetic scattering around $p_c$ [13].

We now turn the attention to the low-temperature resistivity. Specifically, the $\rho_a$ and $\rho_c$ data are fitted by the power law $\rho = \rho_0 + A T^n$ [21], where $\rho_0$ is the residual resistivity, A the coefficient, and $n$ the temperature exponent. As shown in Fig. 3, the resulting parameters display a similar pressure dependence along different axes. At $p \leq 1.57$ GPa, $n$ is as large as $\sim 5$, indicating dominant electron-magnon scattering due to the magnetic ordering. With increasing pressure above 1.57 GPa, since the magnetic ordering is rapidly suppressed, $n$ decreases steeply and $A$ increases accordingly. Around $p_c$, $n$ shows a minimum of $\sim 0.6$ while $A$ is enhanced by $\sim 3$ orders of magnitude. This non-Fermi liquid behavior is in good agreement with the previous results [13], pointing to the presence of quantum critical fluctuations. Although $\rho_0$ obtained from the fitting is negative and hence unphysical between 2.57 and 3.80 GPa, a value near $p_c$ can be estimated from Ref. [12], in which SC can be completely suppressed by applying high magnetic fields. When plotted in Fig. 3(c), this evidences an enhanced scattering around $p_c$, as expected [22]. At pressures above $\sim 4$ GPa, $n$ becomes not far from the Fermi liquid value $n = 2$. In this pressure range, the drop in $A$ by more than one order of magnitude up to 5.63 GPa is reminiscent of the case of CeCu$_2$Si$_2$ above $p_c$, and reflects a drastic enhancement of the 4f electron interactions [3].

![FIG. 3: (Color online) (a), (b) and (c) show the pressure dependencies of the coefficient A, temperature exponent $n$, and residual resistivity $\rho_0$, respectively, obtained by fitting with the power law $\rho(T) = \rho_0 + AT^n$ to the a- (closed symbol) and c- (open symbol) resistivity data at low temperature. Note that the high-field value at 2.57 GPa in panel (c) is taken from Ref. [12] and assumed to be isotropic.](image)

![FIG. 4: (Color online) (a) and (b) show the isothermal $\rho^*(p) = \rho(p) - \rho_0(p)$ for the a- and c-axis at selected temperatures, respectively. The vertical solid lines mark the initial pressure of the valence crossover. The solid circles denote the 50% drop compared to the maximum $\rho^*$ value, and the dashed lines are extrapolations of the circles to $p_c$. (c) Temperature dependencies of the slope $\chi$ for both axes (see text). The Curie-Weiss fitting yields $T_c \approx 18$ K and 0 K for the a- and c-axis, respectively. (d) Collapse of a-axis normalized data $\rho_{\text{norm}}$ when plotted against $h/\theta$, where $h = (p - p_{50\%})/p_{50\%}$ and $\theta = (T - T_c)/|T_c|$.](image)
respectively. At higher pressures, $\rho$ decreases. For $T_1$, this is due to the increasing influence of the spin disorder scattering. On the other hand, the depression of $T_{\text{max}}$ is ascribed to the rapid growing of the resistivity magnitude at $T_1$ as the Kondo temperature $T_K$ rises. In this pressure range, $T_{\text{max}}$ is primarily governed by the CF splitting $\Delta_{\text{CF}}$. But at pressures above $p_c$, since the resistivity contribution at $T_1$ starts to dominate, the $T_{\text{max}}$ line merges with that of $T_1$ and becomes an indication of $T_K$.

Strikingly, for both directions, the $T_N$ and COV lines terminate at almost the same point on the horizontal axis. In other words, the magnetic QCP at $p_c$ nearly coincides with the valence CEP at $p_v$, as already noted. Here we emphasize that the pressure evolution of $T_N$ is in excellent agreement with a previous study [12], although a wider superconducting window is observed in our case. Actually, we have also performed measurements of the $a$-axis resistivity under pressure on a crystal from Thompson’s group, and found identical results as those presented in this paper and notably $p_c \approx p_v$. Hence this coincidence appears to be an intrinsic property of CeRhIn$_5$.

The above results are summarized in the $p-T$ phase diagrams (PD) shown in Fig. 5. Overall, the PDs look very similar along the two crystallographic directions. The normal-state behavior, characterized by the $T_N$, $T_1$, $T_{\text{max}}$ and valence COV lines, is qualitatively similar to other Ce-based Kondo lattices [3]. At low pressure, as always observed, both $T_{\text{max}}$ and $T_1$ decreases. For $T_1$, this is due to the increasing influence of the spin disorder scattering. On the other hand, the depression of $T_{\text{max}}$ is ascribed to the rapid growing of the resistivity magnitude at $T_1$ as the Kondo temperature $T_K$ rises. In this pressure range, $T_{\text{max}}$ is primarily governed by the CF splitting $\Delta_{\text{CF}}$. But at pressures above $p_v$, since the resistivity contribution at $T_1$ starts to dominate, the $T_{\text{max}}$ line merges with that of $T_1$ and becomes an indication of $T_K$.

The existence of such a CEP can be further corroborated by a scaling analysis outlined in Ref. [4]. Following the procedure, we define $p_{50\%}$ as the pressure corresponding to 50% of the resistivity drop compared to the value at 1.78(2.32) GPa for the $a(c)$-axis data, and $\rho_{\text{norm}}$ as $\rho_{\text{norm}} = [\rho^* - \rho^*(p_{50\%})]/\rho^*(p_{50\%})$. As can be seen in Fig. 4(c), the slope $\chi = |d\rho_{\text{norm}}/dp|$ at $p_{50\%}$ increases with decreasing temperature, indicating that the $\rho_{\text{norm}}$ decrease is getting steeper on cooling. Assuming $\chi \propto (T - T_{\text{c}})^{-1}$, we obtain $T_{\text{c}} \approx -8$ K and 0 K for the $a$- and $c$-axis, respectively. The scaling analysis consists in plotting $\rho_{\text{norm}}$ against $h/\theta$, where $h = (p - p_{50\%})/p_{50\%}$ and $\theta = (T - T_{\text{c}})/|T_{\text{c}}|$ are the generalized distance from the CEP. It turns out that all the $a$-axis $\rho_{\text{norm}}$ isothermals below 12 K collapse on a single scaling curve [23]. This provides strong evidence for the existence of a CEP in the $p-T$ plane of CeRhIn$_5$. The fact that $T_{\text{c}}$ is slightly negative for the $a$-axis means that a crossover (COV) rather than a first-order transition occurs. In this respect, the temperature dependence of $p_{50\%}$ defines the valence COV line (see below), and its extrapolation to zero temperature yields $p_v(\approx p_{\text{c}}) = 2.6 \pm 0.2$ GPa for both cases. Notice that this $p_v$ is determined from the results at much higher temperature than $T_N$, yet it is nearly identical to $p_c$.

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![FIG. 5: (Color online) Pressure-temperature phase diagram of CeRhIn$_5$ along (a) $a$- and (b) $c$-axis, including the characteristic temperatures $T_1$, $T_2$ and $T_{\text{max}}$. For comparison, data from Ref. [12] are also included in (a).](image_url)

To gain more insight, we plot the low-temperature isothermal resistivity $\rho^*(p) = \rho(p) - \rho_0(p)$ at selected temperatures in Fig. 4(a) and (b). A maximum is observed around 1.78 and 2.32 GPa for the $a$- and $c$-axis, respectively. At higher pressures, $\rho^*$ decreases steeply without saturation, even in the paramagnetic state. This is also similar to that observed in CeCu$_2$Si$_2$ above 4 GPa, and, together with the rapid collapse of the $A$ coefficient shown above, provides strong evidence for the proximity to a valence CEP located at $(p_{\text{cr}}, T_{\text{cr}})$ in the $p-T$ plane of CeRhIn$_5$ [4].
explains the anomalous properties observed in CeRhIn$_5$ by the dHvA measurement, including the Fermi surface change and the cyclotron mass enhancement $^{14}$.

Another salient feature of Fig. 5 is that although $T_N$ and $T_c$ are isotropic, the COV line is sharper along the $a$-axis than along the $c$-axis. Naively, this is expected since the Ce-Ce distance is the shortest along the $a$-axis. Hence the nucleation of valence COV develops more rapidly in this direction. A better understanding of this issue may require further studies of the valence COV line by other probes such as NQR $^{24,26}$, as well as elaborated theoretical treatments in the future.

Finally, we present in Fig. 6 a comparison between in-plane $p-T$ diagrams of CeRhIn$_5$ and CeCu$_2$Si$_2$. Compared with the $T_1^{\text{max}}$ and $T_2^{\text{max}}$ lines of CeCu$_2$Si$_2$, the $T_1^{\text{max}}$ and $T_1$ lines of CeRhIn$_5$ are systematically lower, which is likely due to the smaller value of the first CF splitting energy $^{13}$. Nevertheless, in both cases, the two lines merge in the vicinity of $p_v$. At higher pressures, the $T_c$ and COV lines as a function of the distance from $p_v$ are nearly identical for these two compounds. This is quite remarkable considering their different crystal structures, and hence points to a common superconducting pairing mechanism. Note that, just below $p_v$, magnetic ordering is present in CeRhIn$_5$, but is absent in CeCu$_2$Si$_2$. It is thus tempting to speculate that, around the optimal pressure for superconductivity of CeRhIn$_5$, valence fluctuations play a more important role than spin fluctuations in the Cooper pairing, although both of them are expected to be present.

IV. CONCLUSION

In summary, we have studied the $a$- and $c$-axis resistivity of CeRhIn$_5$ under pressure up to 5.63 GPa. A careful data analysis enables us to add the valence crossover line and to locate the CEP at 2.6 GPa and slightly negative (zero) temperature in the $p-T$ plane. For the $a$-axis, a resistivity scaling is observed, and the updated phase diagram in the COV regime is very similar to that of CeCu$_2$Si$_2$. Our results provide first experimental evidence that the magnetic QCP and valence CEP coincide with each other in CeRhIn$_5$, which highlights the importance of Ce-4$f$ electron delocalization in understanding the pressure evolution of magnetism and superconductivity in this material.

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