Magneto-transport properties governed by the antiferromagnetic fluctuations in heavy fermion superconductor CeIrIn$_5$

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In quasi-two dimensional Ce(Ir,Rh)In$_5$ system, it has been suggested that the phase diagram contains two distinct domes with different heavy fermion superconducting states. We here report the systematic pressure dependence of the electron transport properties in the normal state of CeRh$_{0.3}$Ir$_{0.7}$In$_5$ and CeIrIn$_5$, which locates in first and second superconducting dome, respectively. We observed non-Fermi liquid behavior at low temperatures in both compounds, including non-quadratic $T$–dependence of the resistivity, large enhancement of the Hall coefficient, and the violation of the Kohler’s rule in the magnetoresistance. We show that the cotangent of Hall angle $\cot \Theta_H$ varies as $T^2$, and the magnetoresistivity is quite well scaled by the Hall angle as $\Delta \rho_{xx}/\rho_{xx} \propto \tan^2 \Theta_H$. The observed transport anomalies are common features of CeMIn$_5$ ($M=$Co, Rh, and Ir) and high-$T_c$ cuprates, suggesting that the anomalous transport properties observed in CeIrIn$_5$ are mainly governed by the antiferromagnetic spin fluctuations, not by the Ce-valence fluctuations which has been proposed to be the possible origin for the second superconducting dome.

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I. INTRODUCTION

The resent discoveries of heavy fermion compounds CeMIn$_5$ ($M=$Rh, Co, and Ir) give a unique opportunity to elucidate the interplay between the magnetism and the superconductivity. The ground state of these compounds can be tuned by pressure and chemical doping. CeCoIn$_5$ and CeIrIn$_5$ are superconductors with the transition temperature $T_c = 2.3$ K and 0.4 K at ambient pressure, respectively. On the other hand, CeRhIn$_5$ is an antiferromagnet with $T_N = 3.8$ K at ambient pressure and shows superconductivity under pressure.

In CeCoIn$_5$ and CeRhIn$_5$, the thermodynamic and transport properties in the normal state exhibit a striking deviation from conventional Fermi liquid behavior, which is commonly observed in the systems in the vicinity of the antiferromagnetic (AF) quantum critical point (QCP). Then it is widely believed that the superconductivity in CeRhIn$_5$ and CeCoIn$_5$ is closely related to the AF fluctuations.

Recently, it has been suggested that CeIrIn$_5$ should be distinguished from CeCoIn$_5$ and CeRhIn$_5$, although all three compounds share similar quasi-two dimensional (2D) band structure. Figure 1 depicts the schematic temperature – $x$ ($T$-$x$) phase diagram of CeRh$_{1-x}$Ir$_x$In$_5$ and temperature – pressure ($T$-$P$) phase diagram of CeIrIn$_5$. In this system the Rh substitution for Ir increases the $c/a$ ratio, acting as a negative chemical pressure that increases AF correlations. In CeRh$_{1-x}$Ir$_x$In$_5$, the ground state continuously evolves from AF metal ($x < 0.5$) to superconductivity ($x > 0.5$). $T_c$ shows a maximum at $x \sim 0.7$ and exhibits a cusp-like minimum at $x \sim 0.9$, forming a first dome (SC1). The superconductivity nature in SC1, which occurs in the proximity to AF QCP, should be essentially the same as CeCo(In$_{1-x}$Cd$_x$)$_5$ and CeRhIn$_5$. The strong AF fluctuations associated with the AF QCP nearby are observed in SC1. In CeIrIn$_5$ ($x = 1$), $T_c$ increases with pressure and exhibits a maximum ($T_c = 1$ K) at $P \sim 3$ GPa, forming a second dome (SC2). The AF fluctuations in SC2 far from the AF QCP are strongly suppressed, compared with those in SC1. Moreover, it has been reported that the nature of the crossover behavior from non-Fermi to Fermi liquid in strong magnetic fields for CeIrIn$_5$ is very different from that for CeCoIn$_5$ and CeRhIn$_5$.

From the analogy to CeCu$_2$(Si$_{1-x}$Ge$_x$)$_2$ with two distinct superconducting domes, a possibility that the Ce-valence fluctuations play an important role for the normal and superconducting properties in CeIrIn$_5$ has been pointed out. For instance, it has been suggested that while the superconductivity in SC1 is magnetically mediated, the superconductivity in SC2 may be mediated by the Ce-valence fluctuations. Thus the major outstanding question is whether the Ce-valence fluctuations play an important role for the physical properties of CeIrIn$_5$ in SC2 phase. Our previous studies indicate that the transport coefficients, including resistivity, Hall effect, and magnetoresistance, can be powerful tools to probe the AF spin fluctuations. In this paper, we report the systematic pressure study of the transport properties for CeRh$_{0.2}$Ir$_{0.8}$In$_5$ and CeIrIn$_5$, which locates in SC1 and SC2 phase, respectively. We provide several pieces of evidence that all the anomalous transport properties observed in CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ originate from the AF spin fluctuations irrespective of which supercon-
FIG. 1: Schematic $T$-$x$ phase diagram for CeRh$_{1-x}$Ir$_x$In$_5$ and $T$-$P$ phase diagram for CeIrIn$_5$.\textsuperscript{2,10,11}

The high quality single crystals of CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ were grown by the self-flux method. We performed all measurements on samples with a typical dimension of $\sim 1.0 \times 2.0 \times 0.1$ mm$^3$ in the transverse geometry for $H \parallel c$ and the current $J \parallel a$. The Hall effect and transverse magnetoresistance were measured simultaneously. We obtained Hall resistivity from the transverse resistance by subtracting the positive and negative magnetic field data. Hydrostatic pressure up to 2.41 GPa were generated in a piston-cylinder type high pressure cell with oil as a transmitting fluid (Daphne 7373 : petroleum ether = 1 : 1). The pressure inside the cell was determined by the superconducting transition temperature of Pb.

III. RESULTS

A. Resistivity

Figures 2(a) and (b) show the temperature dependence of the resistivity $\rho_{xx}$ in zero field at several pressures for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$, respectively. The overall feature of the temperature dependence for both compounds is typical in Ce-based heavy fermion compounds. On cooling from room temperature, $\rho_{xx}$ first decreases and then increases due to dominant Kondo scattering. At lower temperatures, $\rho_{xx}$ exhibits a metallic behavior after showing a broad maximum at around the temperature $T_{coh}$, shown by arrows. $T_{coh}$ corresponds to the Fermi temperature of $f$ electrons and the system becomes coherent below $T_{coh}$. $T_{coh}$ increases with pressure. The insets of Figs. 2(a) and (b) show the low temperature data of $\rho_{xx}$ for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$, respectively. The resistivities of CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ are markedly different from the $T^2$-behavior expected in Fermi liquid metals. At ambient pressure, $\rho_{xx}$ varies as

$$\rho_{xx} \sim T^\alpha$$

with $\alpha \sim 1$ for CeIrIn$_5$ and $\sim 0.7$ for CeRh$_{0.2}$Ir$_{0.8}$In$_5$. $\alpha$ increases with pressure for both systems and reaches $\sim 1.4$ at 2.4 GPa for CeIrIn$_5$ and $\sim 1.3$ at 2.19 GPa.

FIG. 2: (a) Temperature dependence of resistivity for CeIrIn$_5$ at 0, 0.56, 0.98, 1.59, and 2.41 GPa. (b) Temperature dependence of resistivity for CeRh$_{0.2}$Ir$_{0.8}$In$_5$ at 0, 0.49, 1.11, 1.50, and 2.19 GPa. Insets are expanded views at low temperatures. Downarrows drawn in main panels indicate $T_{coh}$ at ambient pressure, where the resistivity shows a broad maximum. Open circles shown in the insets indicate the resistivity at $T_m$ where $R_H$ shows a minimum. For detail, see the text in §.4.
for CeRh$_{0.2}$Ir$_{0.8}$In$_5$, indicating that the Fermi liquid behavior is recovering by applying pressure. We note that these $\alpha$-value is close to that reported in Ref. 24. These temperature and pressure dependence of resistivities for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ are very similar to those of CeCoIn$_5$ and CeRhIn$_5$.22,23

B. Hall effect

Figures 3 depict the Hall resistivity $\rho_{xy}$ as a function of magnetic field at ambient pressure for CeIrIn$_5$. The sign of $\rho_{xy}$ is negative. At low temperatures, $\rho_{xy}$ deviates from the $H$-linear dependence. Similar behavior is observed in CeRh$_{0.2}$Ir$_{0.8}$In$_5$. Figures 4 (a) and (b) show the temperature dependence of the Hall coefficient $R_H$ in zero field limit defined as $R_H \equiv \lim_{H \to 0} \frac{d\rho_{xy}}{dH}$ at several pressures for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$, respectively. For comparison, $R_H$ of LaIrIn$_5$, which has no f-electron and has similar band structure to CeIrIn$_5$, is plotted in the same figure. For LaIrIn$_5$, $R_H$ shows a shallow minimum at around 20 K and becomes nearly T-independent at low temperatures. The carrier number estimated from $R_H \sim 3 \times 10^{-10} \text{m}^3/\text{C}$ for LaIrIn$_5$ at low temperatures corresponds to nearly three electrons per unit cell, which is consistent with the number expected from the band structure, indicating $R_H \simeq 1/ne$ where $n$ is the carrier number.

The Hall effect in CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ is distinctly different from that in LaIrIn$_5$. The temperature dependence of $R_H$ for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ is closely correlated with the resistivity. The down-arrow in Figs. 3 (a) and (b) indicates $T_{coh}$ at ambient pressure determined by the resistivity peak in Figs. 2(a) and (b), respectively. In the high temperature regime above $T_{coh}$, $R_H$ for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ shows weak T-dependence. Well above $T_{coh}$, $R_H$ for both compounds well coincides with $R_H$ of LaIrIn$_5$, indicating $R_H \simeq 1/ne$. Below $T_{coh}$, $R_H$ for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ decreases rapidly with decreasing $T$. At lower temperatures, $R_H$ increases after showing minimum at $T_m$ indicated by up-arrows in Figs. 3 (a) and (b). With increasing pressure, $T_m$ increases and the enhancement of $|R_H|$ at low temperature regime is reduced for CeIrIn$_5$.

The insets of Figs. 4 (a) and (b) show the temperature dependence of $R_H$ at $\mu_0H=0$, 1, and 5 T at ambient pressure for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$, respectively. $R_H$ is defined by a field derivative of $\rho_{xy}$, $R_H \equiv d\rho_{xy}/dH$. The magnitude of $R_H$ below $T_{coh}$ is strongly suppressed by
FIG. 5: $|\cot \Theta_H|$ as a function of $(T/T_{coh})^2$ for CeIrIn$_5$ at 0 (●), 0.56 (○), 0.98 (■), 1.59 (∇), and 2.41 GPa (▲).

We here comment on the effect of the skew scattering. Usually, $R_H$ in heavy fermion compounds can be written by the sum of the ordinary Hall part $R^n_H$ due to Lorentz force and the anomalous Hall part $R^\n_H$ due to skew scattering:

$$R_H = R^n_H + R^\n_H. \quad (2)$$

The magnitude of $R^n_H$ is often much larger than that of $R^\n_H$ except for $T \ll T_{coh}$ and $T \gg T_{coh}$. In most Ce-based heavy fermion systems, $R^n_H$ is positive in sign and shows a strong $T$-dependence, which is scaled by $\chi \rho_{xx}$ (Ref.25) or $\chi$. At around $T_{coh}$, $R^n_H$ shows a broad maximum and its amplitude becomes much larger than $1/n_e$. It is obvious that $R_H$ of CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ are very different from that expected from the skew scattering. In fact, the sign of $R_H$ is negative in the whole temperature regime. Moreover, $R_H$ is close to $1/n_e$ at $T \sim T_{coh}$. A slight increase of $R_H$ observed at $T \gtrsim T_{coh}$ in the low pressure regime appears to come from small but finite contribution of the skew scattering. Thus the skew scattering contribution is small in CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ and the normal part of Hall effect is dominant. We also note that skew scattering is negligibly small in CeRhIn$_5$ and CeCoIn$_5$.21,22,23

The Hall effect in CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ below $T_{coh}$, particularly the enhancement of $|R_H|$ from $1/n_e$, is distinctly different from that expected in the conventional metals. Such an enhancement has also been reported in CeCoIn$_5$ and CeRhIn$_5$, and high-$T_c$ cuprates. There, it has been shown that the Hall problem can be simplified when analyzed in terms of Hall angle $\Theta_H = \tan^{-1} \frac{\rho_{xx}}{\rho_{zz}}$: $\cot \Theta_H$ well obeys a $T^2$-dependence,

$$\cot \Theta_H = AT^2 + B, \quad (3)$$

where $A$ and $B$ are constants.27,28,29 We here examine $\cot \Theta_H$ for CeIrIn$_5$. Figure 6 depicts $\cot \Theta_H$ as a function of $T^2$ for CeIrIn$_5$. In the all pressure regime, $\cot \Theta_H$ well obeys a $T^2$-dependence, except for the low temperature regime, exhibiting a striking similarity with CeCoIn$_5$ and CeRhIn$_5$, and high-$T_c$ cuprates.

C. Magnetoresistance

Figures 6(a) and (b) show the magnetoresistance $\Delta \rho_{xx}/\rho_{xx}(0) \equiv (\rho_{xx}(H) - \rho_{xx}(0))/\rho_{xx}(0)$ of CeIrIn$_5$ at ambient pressure and at $P = 2.41$ GPa, respectively. The magnetoresistance varies as $\Delta \rho_{xx}/\rho_{xx}(0) \propto H^2$ at very low field ($\mu_0 H < 0.2$ T). At ambient pressure, the magnetoresistance decreases with $H$ at high fields below 5 K. This phenomena has also been observed in CeCoIn$_5$ at ambient pressure21,22 and is attributed to the spin-flop scattering.

We here discuss the magnetoresistance in the conventional and unconventional metals. In conventional metals, the magnetoresistance due to orbital motion of carriers obeys the Kohler’s rule,

$$\frac{\Delta \rho_{xx}(H)}{\rho_{xx}(0)} = F \left( \frac{\mu_0 H}{\rho_{xx}(0)} \right), \quad (4)$$

where $F(x)$ is a function which depends on the details of electronic structure.30 It has been shown that the magnetoresistance in LaRhIn$_5$ with similar electronic structure but with weak electronic correlation well obeys the Kohler’s rule.21,22 We first test the validity of the Kohler’s rule in the magnetoresistance of CeIrIn$_5$. Figures 6(a)

FIG. 6: Magnetoresistance of CeIrIn$_5$ as a function of $H$ at (a) 0 GPa and (b) 2.41 GPa.
and (b) depict \( \Delta \rho_{xx}(\mu_0 H/\rho_{xx}(0)) \) for CeIrIn\(_5\) at (a)0GPa, and (b)2.41GPa. Modified Kohler’s plot \( \Delta \rho_{xx}(\mu_0 H/\rho_{xx}(0)) \) as a function of \( \tan^2 \Theta_H \) for CeIrIn\(_5\) at (c)0GPa and (d)2.41GPa.

and (b) depict \( \Delta \rho_{xx}/\rho_{xx}(0) \) of CeIrIn\(_5\) as a function of \( \mu_0 H/\rho_{xx}(0) \) at 0 and 2.41 GPa, respectively. The data never collapse into the same curve, indicating a violation of the Kohler’s rule.

A striking violation of the Kohler’s rule has been reported in CeCoIn\(_5\) and CeRhIn\(_5\), and high-\( T_c \) cuprates. It has been shown instead that in these systems the magnetoresistance is well scaled by \( \tan^2 \Theta_H \) (modified Kohler’s rule), where \( \Theta_H \equiv \tan^{-1}(\rho_{xy}/\rho_{xx}) \) is the Hall angle.\(^\text{21,23,31}\)

\[
\frac{\Delta \rho_{xx}}{\rho_{xx}(0)} \propto \tan^2 \Theta_H. \tag{5}
\]

We then examine the validity of the modified Kohler’s rule for CeIrIn\(_5\). In Figs. 7(c) and (d), the same data of magnetoresistance are plotted as a function of \( \tan^2 \Theta_H \). For both cases, the data collapse into the same curve for three orders of magnitude, indicating that the magnetoresistance well obeys modified Kohler’s rule. The deviation from the modified Kohler’s rule is observed at low temperature and high field region, possibly due to the spin-flop scattering.

### IV. DISCUSSION

Summarizing the salient features in the transport properties of CeIrIn\(_5\) below \( T_{coh} \), which corresponds to the Fermi temperature of \( f \) electrons,

(i) The dc-resistivity shows non-quadratic dependence, \( \rho_{xx} \propto T^\alpha \) with \( \alpha \) close to unity at ambient pressure.

(ii) \( |R_H| \) increases with decreasing temperature and reaches a value much larger than \( |1/ne| \) well below \( T_{coh} \). The Hall angle varies as \( \cot \Theta_H \propto T^2 \).

(iii) Magnetoresistance displays \( T_\text{-} \) and \( H_\text{-} \) dependence that strongly violates the Kohler’s rule, \( \Delta \rho_{xx}(H)/\rho_{xx}(0) \neq F(\mu_0 H/\rho_{xx}(0)) \). Magnetoresistance well obeys the modified Kohler’s rule that indicates a scaling by the the Hall angle, \( \Delta \rho_{xx}/\rho_{xx} \propto \tan^2 \Theta_H \).

It should be emphasized that all of these features bear striking resemblance to those observed in CeCoIn\(_5\), CeRhIn\(_5\), and high-\( T_c \) cuprates. Therefore, it is natural to consider that the transport properties commonly observed in CeIrIn\(_5\) originate from the same mechanism.

Our previous studies have shown that the anomalous features in the transport phenomena (i)–(iii) can be accounted for in terms of the recent theory in which the anisotropic inelastic scattering due to AF spin fluctuations are taken into account. In the presence of strong AF fluctuations, the transport scattering rate strongly depends on the position of the Fermi surface. Then the hot spots, at which the electron scattering rate is strongly enhanced by the AF fluctuations, appear at the positions where the AF Brilouin zone intersects with the Fermi surface. The presence of the hot spots has been confirmed in high-\( T_c \) cuprates and CeIn\(_3\).\(^\text{32}\) Since the hot spot area does not contribute to the electron transport, it reduces the effective carrier density, which results in the enhancement of \( |R_H| \) from \( |1/ne| \). In such a situation, various transport properties are determined by \( \tau_{cold} \), where \( \tau_{cold} \) is the scattering time of the cold spots on the Fermi surface, at which the electrons are less scattered. Moreover, it has been shown that the transport properties are modified by the backflow accompanied with the anisotropic inelastic scattering.\(^\text{33,34,35,36}\)

According to Refs.\(^\text{33,34,35,36}\), the transport properties under magnetic fields are governed by the AF correlation length \( \xi_{AF} \) in the presence of backflow effect. Zero-field diagonal conductivity \( \sigma_{xx}(0) \), Hall conductivity \( \sigma_{xy} \) and magnetoconductivity \( \Delta \sigma_{xx}(H) \equiv \sigma_{xx}(H) - \sigma_{xx}(0) \) are given as

\[
\sigma_{xx}(0) \sim \tau_{cold}, \tag{6}
\]

\[
\sigma_{xy} \sim \xi_{AF}^2 \tau_{cold}^2 H, \tag{7}
\]

and

\[
\Delta \sigma_{xx} \sim \xi_{AF}^4 \tau_{cold}^3 H^2. \tag{8}
\]

Here, we have dropped the higher terms with respect to \( \tau_{cold} H \) since \( \Delta \rho/\rho_0 \ll 1 \) in the present experiment, which suggests that the relation \( \omega_c \tau \ll 1 \) is satisfied. In the
presence of AF fluctuation, $\xi_{AF}$ depends on $T$ as $\xi_{AF}^2 \propto 1/(T + \theta)$, where $\theta$ is the Weiss temperature. Moreover, according to AF spin fluctuation theory, $\tau_{cold}$ is nearly inversely proportional to $T$; $\tau_{cold} \propto 1/T$\textsuperscript{23}. When $T \gg \theta$, we then obtain the temperature dependence of the resistivity, $\rho_{xx} = \sigma_{xx}^{-1}$, Hall coefficient, $R_H = \sigma_{xy}/\sigma_{xx}^2 H$, and the Hall angle as

$$\rho_{xx} \propto \tau_{cold}^{-1} \propto T,$$

$$R_H \propto \xi_{AF}^2 \propto \frac{1}{T},$$

and

$$\cot \Theta_H \propto T^2.$$

By definition, the magnetoresistance is given by

$$\frac{\Delta \rho_{xx}(H)}{\rho_{xx}(0)} = \frac{-\Delta \sigma_{xx}(H)}{\sigma_{xx}(0)} \left( \frac{\sigma_{xy}(H)}{\sigma_{xx}(0)} \right)^2.$$

Using the relation $\Delta \sigma_{xx}(H)/\sigma_{xx}(0)^2 \sim T^{-1}$, given by Eqs. (7) and (8), the magnetoresistance is obtained as

$$\frac{\Delta \rho_{xx}(H)}{\rho_{xx}(0)} = (\tan \Theta_H)^2 \left( \frac{\sigma_{xy}(H)}{\sigma_{xx}(0)} \right)^2 \cdot (C - 1),$$

where $C$ is a constant and is $\sim 10$-$100$ for CeMIn$_5$. Since $\sigma_{xx}(H)/\sigma_{xx}(0) \sim 1$ at low fields, $\Delta \rho_{xx}(H)/\rho_{xx}(0)$ is well scaled by $\tan^2 \Theta_H$. Thus Eqs. (9), (10), (11), and (13) reproduce the salient features of resistivity, Hall coefficient, Hall angle, and magnetoresistance observed in CeIrIn$_5$, respectively.

The $H$-dependence of $R_H$ shown in the insets of Fig. 4(a) reinforces the conclusion that the AF fluctuations govern the electron transport phenomena in CeIrIn$_5$ (also in CeRh$_{0.2}$Ir$_{0.8}$In$_5$). The enhancement of $|R_H|$ below $T_{coh}$ is strongly suppressed by magnetic fields and approaches that of $R_H$ of LaIrIn$_5$. This is consistent with the recovery of the Fermi liquid state in magnetic fields by the suppression of AF fluctuations\textsuperscript{23}.

The upturn behavior of $R_H$ for CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$ at low temperatures below $T_m$ shown in Figs. 4(a) and (b) is also observed in CeCoIn$_5$\textsuperscript{22,23,24}. This phenomenon can be explained by the reduction of backflow effect due to the effect of the impurity scattering. Below $T_m$, isotropic impurity scattering becomes dominant and the backflow effect due to anisotropic scattering is relatively reduced\textsuperscript{22,23}. To obtain more insight into the impurity effect, we compare the resistivity values at $T_m$. The small open circles in the insets of Figs. 2(a) and (b) indicate the resistivity at $T_m$ where $R_H$ shows a minimum. The values of the resistivity at $T_m$ are nearly pressure independent and close to $\sim 5 \mu\Omega$cm and $\sim 8 \mu\Omega$cm in CeIrIn$_5$ and CeRh$_{0.2}$Ir$_{0.8}$In$_5$, respectively. We note that these values are close to the values of $\rho_{xx}$ at $T_m$ for CeCoIn$_5$.

We here discuss the difference between CeIrIn$_5$ and CeCu$_2$(Si$_{1-x}$Ge$_x$)$_2$. For CeCu$_2$(Si$_{1-x}$Ge$_x$)$_2$ in the second superconducting dome, anomalous behavior in transport and thermodynamic properties are observed near the pressure $P_c$, where $T_c$ shows a maximum. For instance, $\alpha$ in Eq. (11) approaches unity and residual resistivity $\rho_0$ exhibits a maximum near $P_c$\textsuperscript{23}. For CeIrIn$_5$, on the other hand, $\alpha$ approaches the Fermi liquid value at $P \sim 3$ GPa, where $T_c$ shows a maximum. Moreover, the residual resistivity decreases with pressure as shown in the insets of Fig. 2 which could be caused by the backflow or enhancement of impurity scattering near AF QCP\textsuperscript{24}. These results indicate that there seems to be crucial differences in the transport phenomena between CeIrIn$_5$ and CeCu$_2$(Si$_{1-x}$Ge$_x$)$_2$.

The presence of the AF fluctuations in CeIrIn$_5$ has been reported by the measurements of the nuclear magnetic resonance (NMR) relaxation rate $T_1^{-1}$\textsuperscript{11}. According to NMR results, AF fluctuations are strongly suppressed with pressure and there is no indication of the AF fluctuations at $P \geq 1$ GPa\textsuperscript{11}. The present results indicate that the transport measurements are more sensitive to the AF fluctuations than NMR experiments.

We finally comment on the superconducting gap structure in CeIrIn$_5$. Recent measurements of the anisotropy of the inter- and in-plane thermal conductivity for CeIrIn$_5$ suggest a hybrid gap structure\textsuperscript{31} whose symmetry is different from $d_{x^2-y^2}$ for CeCoIn$_5$ (Refs. 35, 39, 40) and (most probably) for CeRhIn$_5$. However, very recent thermal conductivity measurements under rotated magnetic fields suggest that the superconducting gap structure for CeIrIn$_5$ has $d_{x^2-y^2}$ symmetry\textsuperscript{35} which implies that the AF spin fluctuations are important for the occurrence of the superconductivity for CeIrIn$_5$, which is consistent with the present work.

V. CONCLUSION

We have investigated the detailed electron transport properties by applying pressure in the normal state of CeRh$_{0.2}$Ir$_{0.8}$In$_5$ and CeIrIn$_5$, which locates in the first and second superconducting dome, respectively. We observed striking non-Fermi liquid behaviors below $T_{coh}$, including non-quadratic $T$-dependence of the resistivity, large enhancement of the Hall coefficient at low temperatures ($|R_H| \gg 1/|n_e|$), and the violation of the Kohler’s rule in the magnetoresistance $\Delta \rho_{xx}(H)/\rho_{xx} \neq F(\mu_0 H/\rho_{xx})$. Moreover, we showed that the cotangent of Hall angle $\cot \Theta_H$ varies as $T^2$, and the magnetoresistance is quite well scaled by the Hall angle as $\Delta \rho_{xx}/\rho_{xx} \propto \tan^2 \Theta_H$. These non-Fermi liquid properties, particularly the Hall effect, are suppressed by pressure and magnetic fields. The observed transport anomalies are common features of CeIrIn$_5$, CeCoIn$_5$, CeRhIn$_5$, and high-$T_c$ cuprates. These results lead us to conclude...
that the non-Fermi liquid behavior observed in the transport properties in CeIrIn₃ originates not from the Ce-valence fluctuations but from the low-lying excitation due to the AF fluctuations that still remain in the second dome away from the first dome in the proximity to the AF QCP.

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