Anomalous *f*-electron Hall effect in the heavy-fermion system $CeTIn_5$ (T=Co, Ir, or Rh)

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The in-plane Hall coefficient $R_H(T)$ of $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$, and their respective nonmagnetic lanthanum analogs are reported in fields up to 90 kOe and at temperatures from 2–325 K. $R_H(T)$ is negative, field independent, and dominated by skew scattering above ~50 K in the Ce compounds. $R_H(H\rightarrow 0)$ becomes increasingly negative below 50 K and varies with temperature in a manner that is inconsistent with skew scattering. Field-dependent measurements show that the low-T anomaly is strongly suppressed when the applied field is increased to 90 kOe. Measurements on $LaRhIn_5$, $LaIrIn_5$, and $LaCoIn_5$ indicate that the same anomalous temperature dependence is present in the Hall coefficient of these nonmagnetic analogs, albeit with a reduced amplitude and no field dependence. Hall angle (θ_H) measurements find that the ratio $\rho_{xx}/\rho_{xy}=\cot(\theta_H)$ varies as T^2 below 20 K for all three Ce-115 compounds. The Hall angles of the La-115 compounds follow this T dependence as well. These data suggest that the electronic-structure contribution dominates the Hall effect in the 115 compounds, with f electron and Kondo interactions acting to magnify the influence of the underlying complex band structure. This is in stark contrast to the situation in most 4f and 5f heavy-fermion compounds where the normal carrier contribution to the Hall effect provides only a small, T-independent background to R_H.

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I. INTRODUCTION

The discovery of f-electron compounds that display a unique combination of competing ground states promotes advances in the field of Kondo physics by challenging our understanding of the underlying many-body interactions.[1] The flurry of research activity associated with the $Ce_nT_mIn_{3n+2m}$ (T=Co, Ir, or Rh; n=1 or 2; m=0 or 1) compounds certainly fits this description.[2,3] The compounds that reside within this "family" exhibit essentially all of the many ground states that have been observed in f-electron systems, including paramagnetism, antiferromagnetism, and exotic ambient-pressure and pressure-induced superconductivity. These compounds also exhibit a mixture of essentially all known f-electron phenomena, including a Kondo-renormalized ground state, Fermi-liquid behavior, and both pressure-induced and ambient-pressure non-Fermi-liquid (NFL) behavior in the vicinity of a antiferromagnetic quantum-critical point (QCP).[3] To date, our understanding of f-electron Kondo systems has rested, in part, on the competition between Kondo and Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions.[4] The complex phase diagram defined by the $Ce_nT_mIn_{3n+2m}$ family challenges this understanding.

The $Ce_nT_mIn_{3n+2m}$ family contains three distinct subgroups, each with differing degrees of anisotropy. The first subgroup (m=0) contains a single member, the cubic antiferromagnet (AFM) $CeIn_3$. At ambient pressure, $CeIn_3$ orders magnetically at T_N=10 K and has a slightly enhanced Sommerfeld coefficient γ ($\equiv C_p/T$ as $T\rightarrow 0$) of 100 mJ/mol K^2 (Ref. 5). An applied pressure of $P_c\approx 25$ kbar drives T_N to zero,[6,7] leads to NFL behavior,[8] and produces a superconducting state with a maximum transition temperature T_c =0.2 K. The second subgroup (n=m=1) contains three known Ce-based members, $CeCoIn_5$, $CeIrIn_5$, and $CeRhIn_5$. These tetragonal Ce-115 compounds have a quasi-two-dimensional (2D) structure that is composed of a cubic $CeIn_3$ element separated by a TIn_2layer. $CeRhIn_5$ is an ambient pressure antiferromagnet (T_N=3.8 K) with an enhanced γ $\approx$400 mJ/mol K^2 (Ref. 9). Superconductivity occurs at T_c =2.1 K in a pressure of 16 kbar.[9] In contrast, ambient-pressure unconventional[10–12] superconductivity occurs in both $CeIrIn_5$ (T_c=0.4 K) (Ref. 13) and $CeCoIn_5$ (T_c =2.3 K).[14] In both superconductors, many-body interactions produce a highly renormalized mass state [$\gamma(CeIrIn_5)$ =0.75 J/mol K^2, $\gamma(CeCoIn_5)\approx$1 J/mol K^2] that becomes evident in the specific heat $C_p(T)$ below 10 K. $CeCoIn_5$ exhibits clear NFL behavior in resistivity $\rho(T)$ and $C_p(T)$ data, indicating that this compound resides near a antiferromagnetic quantum-critical point.[12,15] While the specific heat of $CeIrIn_5$ exhibits Fermi-liquid behavior just above T_c, $\rho(T)$, thermal expansion, and $1/T_1$ data suggest that this compound may be close to a QCP as well.[12,16] The third subgroup (n=2, m=1) is composed of three double-layer members Ce_2TIn_8 (T=Rh, Ir, Co). These Ce-218 compounds exhibit the same phenomena seen in the Ce-115 materials, including paramagnetic[17] and AFM[18] ground states, pressure-induced and ambient pressure superconductivity,[19,20] and NFL behavior.[21]

Anisotropy is a feature common to nearly all of the properties exhibited by the Ce-115 compounds. In part, these anisotropies stem from the tetragonal 115 lattice structure. Band structure calculations and de Haas-van Alphen (dHvA) measurements indicate that the 115 materials have a complicated quasi-2D Fermi surface (FS) composed of multiple electron and hole orbits.[22–26] When considering the properties of the 115 compounds, it is critical to differentiate between phenomena that are controlled by prosaic single-electron physics and those determined by correlated electron interactions.

The Hall effect provides a useful means of elucidating the relative importance of single-electron (i.e., conventional electronic structure) and many-body interactions in f-electron systems. The Hall effect in these systems is strongly influenced by the scattering of charge carriers via the orbital angular momenta of localized electrons.[27–29] In most f-electron compounds, this orbital skew-scattering effect dominates the Hall coefficient $R_H(T)$ at temperatures greater than the characteristic Kondo temperature T_K. In contrast, the electronic-structure component is generally a small, temperature-independent contributor to $R_H(T)$. Many-body correlations frequently dominate the Hall coefficient as the system approaches the Kondo temperature from above.[29,30] At and below T_K, $R_H(T)$ is influenced by the onset of coherence and the development of the Abrikosov-Suhl resonance in the electronic density of states near the Fermi energy.[31,32] For these reasons, T- and H-dependent Hall measurements provide insights into the relative importance of electronic structure and many-body interactions in the physical properties of f-electron compounds.

We have measured the in-plane Hall coefficients of $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$, and their respective nonmagnetic lanthanum analogs in fields up to 90 kOe and at temperatures from 2 to 325 K. The Hall effect is dominated by skew scattering above ~50 K in the Ce-115 compounds, and a precipitous negative drop is present in the in-plane Hall coefficient below 50 K that is inconsistent with incoherent orbital scattering. This same temperature dependence, but with a more modest, T-dependent amplitude, is evident in Hall measurements on the nonmagnetic analogs $LaRhIn_5$, $LaIrIn_5$, and $LaCoIn_5$, signifying that the Hall effect in the Ce-115 materials is dominated by the conventional Hall carrier contribution. Measurements on the Ce-115 compounds indicate that the Hall anomaly present below 50 K can be suppressed significantly by a 90 kOe field, suggesting that field-dependent many-body Kondo interactions influence the unusual Hall effect intrinsic to the 115 electronic structure. Lastly, Hall angle (θ_H) measurements indicate that the ratio $\rho_{xx}/\rho_{xy}=\cot(\theta_H)$ varies as T^2 below 20 K in all three Ce-115 compounds; La-115 $\cot(\theta_H)$ data between 30 and 100 K vary quadratically with temperature too. This Hall angle temperature dependence has been observed in high-T_c cuprates[33] as well, and somehave speculated that this behavior is linked to antiferromagnetic spin fluctuations due to a nearby QCP.[34,35] While it is tempting to make the same connection for these Ce heavy-fermion compounds, the fact that $\cot(\theta_H)\approx T^2$ in all six 115 compounds suggests that this temperature dependence is unconnected with QCP-related spin fluctuations.

II. EXPERIMENTAL DETAILS

Single crystal Ce-115 and La-115 transport samples were produced with an indium flux-growth technique. X-ray diffraction on powdered crystals indicates that the crystals are single-phase and form in the primitive tetragonal $HoCoGa_5$ structure. While the excess In flux is critical for growing the crystals, residual indium has the negative side effect of contaminating essentially all transport measurement on as-grown samples. To eliminate this problem, all samples employed in this study were polished and then prescreened via $\rho(T)$ and magnetic susceptibility $\chi(T)$ measurements to ensure that no extrinsic (In) superconductivity was evident at 3.4 K.

Hall measurements were made on single-crystal samples that were cut and polished into thin Hall bars with sample thicknesses ranging from 0.1 to 0.4 mm. All Hall coefficients reported here are in-plane measurements with the magnetic field applied along the c axis. The standard four-terminal contact arrangement was used, and the contacts were made with silver conductive epoxy. The longitudinal resistivity (ρ_{xx}) and the Hall voltage V_H were measured with a low-frequency resistance bridge. Systematic errors associated with Hall contact misalignment were eliminated by ascribing the asymmetric component of the field-reversed transverse voltage to the Hall voltage, $V_H(H)=[V_H(+H)-V_H(-H)]/2$.[36] The Hall coefficient was calculated from the standard expression $R_H=V_Ht/IH$, where I is the applied current flowing perpendicular to the applied field H, and t is the sample thickness.

The Hall measurements were made in fields from 1–90 kOe in order to examine the R_H field dependence and to determine the Hall coefficient in the low-field limit, $R_H(H\rightarrow 0)$. The Hall coefficient is extremely field dependent in the Ce-115 compounds below 20 K; this strong field-dependence coupled with the fact that $V_H=0$ in the zero-field limit means that some care is required to accurately determine $R_H(H\rightarrow 0)$. We employed two methods in determining $R_H(H\rightarrow 0)$ from the measured Hall voltages. In method one, $R_H(H)$ was determined from the measured $V_H(H)$ in fields ranging from 1–90 kOe, and $R_H(H\rightarrow 0)$ was calculated by extrapolating the data to $H=0$. In method two, $R_H(H\rightarrow 0)$ was determined from the zero-field limit of the Hall resistivity field derivative, $R_H(0) = \partial\rho_{xy}/\partial H$, where $\rho_{xy}=V_Ht/I$. Both methods produce $R_H(H\rightarrow 0)$ values that are identical within experimental error. In contrast to the strongly field-dependent Hall voltage in the Ce-115 compounds, the La-115 materials exhibit a field-independent Hall coefficient (i.e., $\rho_{xy}\propto H$). As such, the T-dependent La-115 Hall data reported in Sec. III were measured in 10 kOe.

III. RESULTS

A. Properties of $LaTIn_5$ (T=Co, Ir, and Rh)

The La-115 compounds are isostructural analogs of the Ce-115 compounds. As such, the La-115 transport properties are indicative of the nonmagnetic contributions to transport in the Ce compounds. The characteristics of these La-115 compounds are, for the most part, unremarkable, and typical of a nonmagnetic intermetallic system. $LaRhIn_5$, $LaIrIn_5$, and $LaCoIn_5$ exhibit a temperature-independent Pauli paramagnetic susceptibility, and the resistivity varies linearly with temperature above ~50 K. Room-temperature resistivities range from 10–20 $\mu\Omega$ cm, while anisotropic resistivity measurements on $LaRhIn_5$ find that the nonmagnetic electronic anisotropy inherent in the tetragonal 115 structure is relatively small.[37] The low-temperature (10 K) magnetoresistance (MR) of $LaRhIn_5$ and $LaIrIn_5$ is positive and grows quadratically with field. These properties are consistent with a simple metallic system.

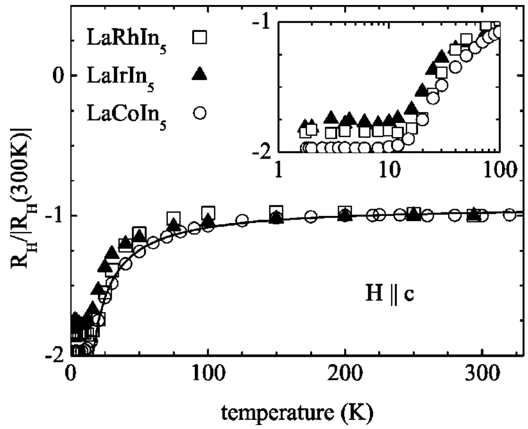

FIG. 1. In-plane Hall coefficients ($H=10$ kOe) plotted as a function of temperature for $LaRhIn_5$, $LaIrIn_5$, and $LaCoIn_5$. Low-temperature data are highlighted in the inset. The data are normalized by the absolute value of each compound's 300 K Hall coefficient. The solid line is a fit to the $LaCoIn_5$ data utilizing Eq. (1).

The temperature-dependent in-plane Hall coefficients of the three La-115 compounds are displayed in Fig. 1. All three La-115 compounds exhibit a negative Hall coefficient, with 300 K values of −7.5, −5.1, and -4.2×10^{-10} m^3/C for the Co, Rh, and Ir compounds, respectively. R_H is nearly temperature independent above 100 K, drops monotonically below 100 K, and begins to saturate below 20 K. The inset to Fig. 1 shows that R_H is essentially T independent below 10 K for the three La-115 compounds. While the data displayed in Fig. 1 were measured in a 10 kOe field, measurements made in fields from 1 to 90 kOe show that R_H is field independent ($\rho_{xy}\propto H$) at 5, 10, 50, 100, and 300 K. The data in Fig. 1 are normalized by the absolute value of each compound's 300 K Hall coefficient to underscore the fact that R_H follows essentially the same temperature-dependence in all three La-115 compounds. The data above 20 K are well described by the expression

$$R_H^{(La)} = R_H^{\infty} + \frac{1}{a+bT}, \qquad (1)$$

where R_H^{∞}, a, and b are fitting parameters. Equation (1) was used to produce the fit to the normalized $LaCoIn_5$ data that is shown in Fig. 1; the fitting parameters are $a=0.07$, $b=-0.06\ K^{-1}$, and $R_H^{\infty}=-0.93$. Surprisingly, the same expression (with $R_H^{\infty}=0$) describes the normal-state Hall response in both $YBa_2Cu_3O_7$ and MgB_2.[33,38,39] The substantial T dependence present below 100 K in the La-115 data is quite unusual, since metals typically have a nearly constant Hall coefficient. A T-dependent Hall coefficient is usually a sign that the underlying electronic structure is composed of multiple electron and hole bands with differing mobility temperature dependencies. Band-structure calculations and dHvA measurements do find that the La-115 electronic structure is very complex,[22–26] so the La-115 R_H temperature dependence appears to be a reflection of the 115 electronic structure.

We next consider the La-115 Hall angle (θ_H), which is plotted as $-\cot(\theta_H)$ vs T^2 in Fig. 2. θ_H is defined as the angle

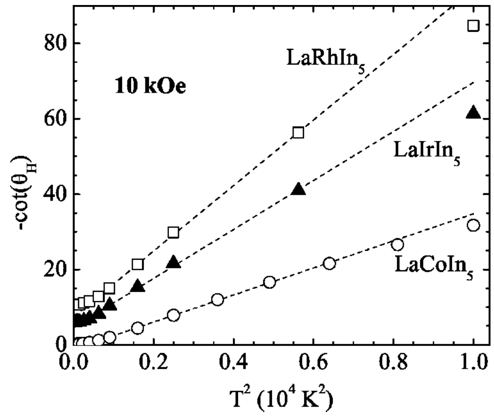

FIG. 2. The in-plane Hall angle $\cot(\theta_H)$ plotted as a function of T^2 for $LaRhIn_5$, $LaIrIn_5$, and $LaCoIn_5$. The dashed lines are linear fits to the data. For clarity the Ir and Rh data have been vertically offset by 5 and 10, respectively.

between the applied current and the resulting electric field, and it is determined experimentally via $\cot(\theta_H)=\rho_{xx}/\rho_{xy}=\rho_{xx}/R_H H$. The data fall on a straight line from roughly 30–100 K for all samples, indicating that $\cot(\theta_H)$ varies with the temperature as

$$\cot(\theta_H) = \alpha + \beta T^2. \qquad (2)$$

This quadratic temperature dependence occurs over precisely the same temperature range as where R_H is extremely temperature dependent. The T^2 behavior results from the combination of a resistivity that varies linearly with T and a Hall coefficient that varies inversely with T. The Hall angle of both $YBa_2Cu_3O_7$ (Refs. 33 and 38) and MgB_2 (Ref. 39) follow the same anomalous temperature dependence. The La-115 compounds exhibit a conventional Hall angle temperature dependence $[\cot(\theta_H)\sim T]$ only above 100 K, where R_H is nearly constant.

B. Properties of Ce*T*In$_5$ (T=Co, Ir, and Rh)

Figure 3 shows the magnetic resistivity ρ_{mag} of $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$ plotted as a function of temperature

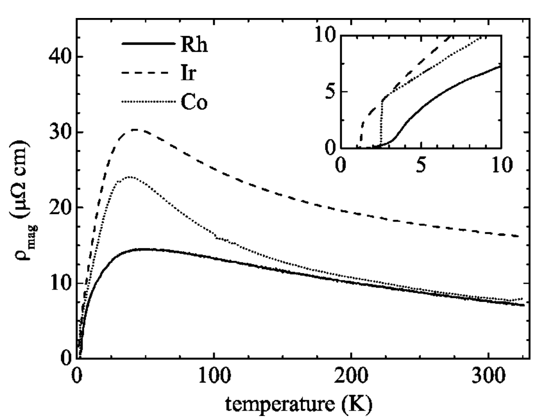

FIG. 3. Magnetic-scattering contributions to the in-plane resistivity plotted as a function of temperature for $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$; data below 10 K are highlighted in the inset.

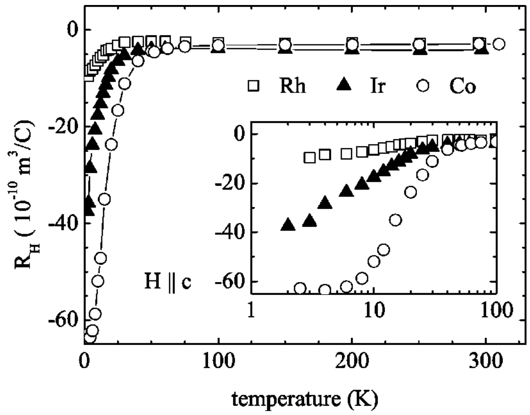

FIG. 4. Low-field ($H \rightarrow 0$) in-plane ($H \| c$) Hall coefficients plotted as a function of temperature for $CeRhIn_5$ (□), $CeIrIn_5$ (▲), and $CeCoIn_5$ (○). Low-temperature data are highlighted in the inset.

from 1–325 K. The resistivity contribution from magnetic scattering is calculated by subtracting the electron-phonon contribution (the resistivity of the nonmagnetic La analog) from the Ce-115 resistivity, $\rho_{mag}=\rho_{Ce}-\rho_{La}$. $\rho_{mag}(T)$ exhibits a broad maximum located below 50 K in all three compounds; the coherence temperature T_{coh} is defined by the temperature where the resistivity peaks. Although the resistivity maximum in the $CeRhIn_5$ data is not as pronounced as those in the $CeIrIn_5$ and $CeCoIn_5$ data, ρ_{mag} varies roughly as $-\ln(T)$ in each of the Ce-115 materials for $T > T_{max}$. The inset to Fig. 3 shows the low-temperature behavior of the magnetic resistivity. The superconducting transitions in $CeIrIn_5$ and $CeCoIn_5$ are clearly evident as abrupt drops in ρ_{mag} at their respective transport T_c's, while the onset of magnetic order at T_N (3.8 K) in $CeRhIn_5$ leads to a more subtle inflection-point anomaly. Just above their superconductivity transitions, $\rho(T)$ for $CeIrIn_5$ and $CeCoIn_5$ varies with temperature as $T^{1.3}$ and $T^{1.0}$, respectively.[13,15] These power laws differ from that of a Fermi liquid ($\rho \sim T^2$), and are suggestive of non-Fermi-liquid behavior.

Figure 4 shows the low-field ($H \rightarrow 0$) Hall coefficients of $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$ plotted as a function of temperature between 2 and 300 K; the low-temperature behavior is highlighted in the figure's inset. $R_H(T)$ is electronlike at all temperatures, and the precipitous drop that occurs in the Hall response of all three materials below 50 K is certainly the most prominent feature in the data. The data displayed in the inset indicate that the Hall response saturates below 4 K, and that the drop in $R_H(T)$ occurs at roughly the same temperature (~40 K) in the three compounds. While the three Ce-115 compounds all show signs of the same drop in R_H below 40 K, the feature is far more prominent for $CeCoIn_5$ and $CeIrIn_5$ than for $CeRhIn_5$. The Hall voltage in $CeCoIn_5$ drops to zero below 2.3 K for fields less than H_{c2} due to the onset of superconductivity (these data are omitted for clarity in Fig. 4). With regard to the AFM transition in $CeRhIn_5$, no discernable anomaly is present in R_H at or below T_N. At higher temperatures, R_H is weakly temperature dependent in all three Ce-115 compounds. The Hall coefficients of $CeRhIn_5$ and $CeIrIn_5$ have a positive slope above 50 K; between 50 and 300 K, $|R_H|$ grows by 25% for $CeRhIn_5$, and 9% for $CeIrIn_5$. The $CeCoIn_5$ Hall coefficient shows no such positive slope above 100 K; instead, the $CeCoIn_5$ Hall response drops by roughly 10% between 100 and 300 K. The 300 K Hall coefficient is nearly the same in the three Ce-115 compounds, and the room temperature value (-3.5×10^{-10} m^3/C) corresponds to an *effective* carrier concentration of 2.9 $e^-/f.u.$

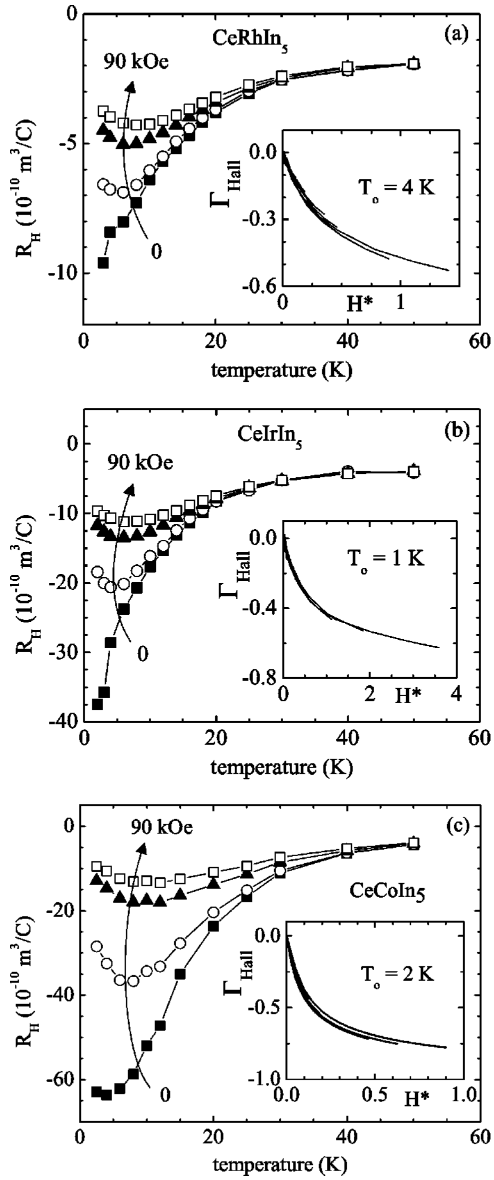

FIG. 5. $R_H(T)$ measured in various applied fields plotted as a function of temperature for $CeRhIn_5$ (a), $CeIrIn_5$ (b), and $CeCoIn_5$ (c). Data are shown at four fields: $H \rightarrow 0$ (■),10 kOe (○), 50 kOe (▲), and 90 kOe (□). The insets show isotherms of the relative change in the field-dependent Hall coefficient Γ_{Hall} plotted as a function of the scaled field H^* with $\beta=2$ (see text); the data were measured at fixed temperatures between 4 and 30 K, and the T_o parameters used to determine H^* are listed in each inset.

Figure 5 displays the Ce-115 Hall coefficients for temperatures below 60 K when measured in four different fields ($H \rightarrow 0$, 10, 50, and 90 kOe). Increasing field strength qualitatively influences the Hall response in the three Ce-115 compounds in the same manner. The data indicate that the Hall response is extremely field dependent in the same temperature region where it is also very temperature dependent. The most important feature of the data is that the large negative drop present below 40 K in the zero-field Ce-115 data is progressively diminished as the applied field is increased. While a field of 90 kOe does not eliminate the drop in R_H that occurs below 40 K, the magnitude of the effect is diminished to the point where the Hall response in the Ce-115 compounds is comparable to that seen in the La-115 nonmagnetic analogs. Increasing the field above roughly 5 kOe also produces a shallow minimum in R_H that is centered between 5 and 10 K. Below 15 K, the R_H field dependence decreases monotonically with increasing field: changing the field from the zero-field limit to 10 kOe reduces R_H by roughly 50%, while the Hall response in 50 and 90 kOe differ by less than 10% relative to $R_H(H \rightarrow 0)$. The extreme field dependence exhibited by the Ce-115 compounds is in stark contrast to the field-independent Hall response exhibited by the La-115 compounds in the same temperature range. Measurements on $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$ at 50, 100, and 300 K in fields between 1 and 90 kOe indicate that the Hall response becomes field independent at these elevated temperatures.

The field-dependent Hall data shown in Fig. 5 satisfy a scaling relationship that is similar to one used in analyzing single-impurity magnetoresistance data.[37,40–45] Following the standard definition of the relative magnetoresistance, $\Delta\rho(H)/\rho(H=0)$, we define the relative change in the Hall coefficient as

$$\Gamma_{Hall}(H) = \frac{R_H(H) - R_H(H \rightarrow 0)}{R_H(H \rightarrow 0)}. \quad (3)$$

Isotherms of the field-dependent Hall response can be superimposed by plotting Γ_{Hall} as a function of the transformed field parameter H^* defined by

$$H^* = \frac{H}{(T + T_o)^{\beta}}. \quad (4)$$

The insets in Fig. 5 show Γ_{Hall} plotted versus H^* for (a) $CeRhIn_5$, (b) $CeIrIn_5$, and (c) $CeCoIn_5$. In constructing these plots, the scaling parameter β was set to two, and the values used for the thermal scaling parameter T_o are listed in the insets. Each inset contains ten superimposed isotherms that were measured at temperatures ranging from 4–25 K (8–30 K for $CeCoIn_5$), and each isotherm is composed of Hall data that was measured in fields ranging from 1–90 kOe. Scaling works best for $\beta = 2 \pm 0.1$, and the T_o values can be varied by ±0.3 K without adversely effecting the analysis; attempts to use the spin-1/2 MR exponent ($\beta=1$)[40] were unsuccessful, regardless of the value used for T_o. Qualitatively, Γ_{Hall} varies with H^* in roughly the same manner for all three Ce-115 compounds. Quantitatively, the $CeCoIn_5$ data are a stronger function of H^* than are the $CeRhIn_5$ and $CeIrIn_5$ data.

We turn now to the Ce-115 Hall angle, which is plotted as $-\cot(\theta_H)$ vs T^2 in Fig. 6. The data fall on straight lines for temperatures less than 30 K, indicating that $\cot(\theta_H)$ varies

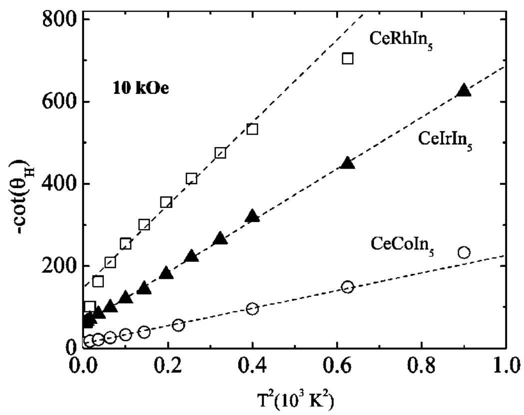

FIG. 6. In-plane Hall angle $\cot(\theta_H)$ plotted as a function of T^2 for $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$. The dashed lines are linear fits to the data. The $CeIrIn_5$ data has been vertically offset by 50 for clarity.

with temperature in a manner consistent with Eq. (2). While 10 kOe Hall data were used in constructing Fig. 6, essentially the same temperature dependence results if data at other fields are used; all that changes is the overall magnitudeof $\cot(\theta_H)$. The temperature range over which the data follow a quadratic temperature dependence are as follows: 8–20 K for $CeRhIn_5$, 4–30 K for $CeIrIn_5$, and 3–25 K for $CeCoIn_5$. $\cot(\theta_H)$ is nearly constant at higher temperatures because R_H and ρ_{xx} both become weakly T dependent above 50 K. As with the La-115 compounds, the Ce-115 data vary quadratically with temperature in the same temperature range where R_H exhibits considerably temperature dependence. The one important difference between the Ce and La Hall angle data concerns the temperature range over which $\cot(\theta_H)$ varies quadratically with temperature. For the La-115 compounds quadratic behavior is evident from 30–100 K, while the Ce-115 compounds show this behavior over a more limited temperature range.

IV. DISCUSSION

The Ce-115 Hall response is very different from what is observed in most Ce Kondo-lattice systems. The canonical Ce heavy-fermion Hall effect is dominated by a positive skew scattering contribution that dwarfs the conventional charge-carrier contribution.[29] In contrast, the Hall effect in the Ce-115 compounds appears to be governed by the conventional charge-carrier contribution. After disentangling the relative contributions from these two mechanisms it will become clear that Kondo interactions and f-electron effects play an important part in determining the temperature and field dependence exhibited by the Hall effect in the 115 compounds.

The Hall response in heavy-fermion compounds is produced by a contribution from skew scattering R_H^{skew} and the ordinary Hall effect R_H^o,

$$R_H = R_H^{skew} + R_H^o. \quad (5)$$

The skew scattering term stems from interactions between the large Ce spin state and the applied field that produce a

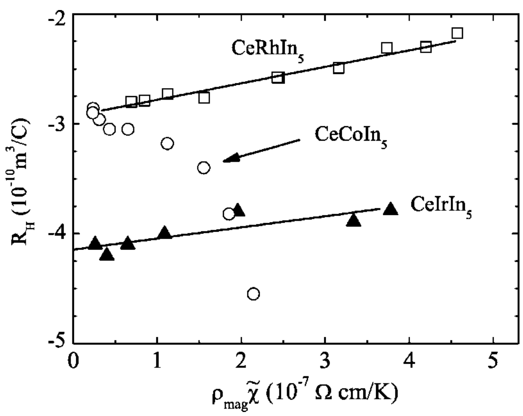

FIG. 7. R_H plotted vs $\rho_{mag}\tilde{\chi}$ for $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$. Temperature is an implicit parameter in this figure; 300 K data appear on the left side of the plot and 40 K data appear to the right. The solid lines are linear fits to the Rh and Ir data.

left-right asymmetry in charge-carrier scattering. As first expressed by Fert and Levy,[29] the skew scattering terms takes the form

$$R_H^{skew} = \xi \rho_{mag}\tilde{\chi}, \tag{6}$$

where $\tilde{\chi}=\chi/C$ is the reduced magnetic susceptibility and C is the Curie constant. For $T \gg T_K$ the parameter ξ becomes

$$\xi = -\frac{5}{7} g \frac{\mu_B}{k_B} \sin\,\delta \cos\,\delta, \tag{7}$$

where δ is the phase shift produced by incoherent Kondo scattering, g is the magnetic ion's Landé g factor, μ_B is the Bohr magneton, and k_B is the Boltzmann constant. As the system is cooled below T_{coh}, incoherent Kondo scattering dies off; calculations based on the periodic Anderson Hamiltonian suggest that $R_H \sim \rho_{mag}^2$ in the coherent regime.[30] These theoretical results indicate that, starting from $T=0$, R_H^{skew} should increase rapidly from zero, achieve a broad maximum at the temperature where ρ_{mag} peaks, and gradually decrease at higher temperatures. The Hall effect in many Ce, U, and Yb heavy-electron systems behave in this manner.[28,29,31,46–49] These compounds exhibit a positive skew-scattering Hall response because the repulsive single-impurity scattering potential leads to a negative phase shift.

Careful analysis of the Hall data indicates that skew scattering is a minor contributor to the overall Hall response in the Ce-115 compounds. This is particularly true below 50 K, where the large negative drop in the Hall coefficient is inconsistent with skew scattering. The most obvious inconsistency is that the low-T anomaly occurs below the coherence temperature where any skew-scattering contribution should be dropping to zero. Additionally, the sign of the Hall feature is inconsistent with skew scattering, R_H does not peak at T_{coh}, and the sharp drop in the Hall response cannot be fit to $\rho_{mag}\tilde{\chi}$. Skew scattering only becomes a significant contributor to the Hall effect above 50 K. This is shown in Fig. 7 where $R_H(T)$ is plotted versus $\rho_{mag}\tilde{\chi}$ for temperatures from 40 to 300 K. The $CeRhIn_5$ and $CeIrIn_5$ Hall data vary linearly with $\rho_{mag}\tilde{\chi}$, as predicted by Eq. (6). The parameters determined from the figure are $\xi=0.016$ K/T and $R_H^o=-2.9\times10^{-10}$ m^3/C for $CeRhIn_5$, and $\xi=0.010$ K/T and $R_H^o=-4.1\times10^{-10}$ m^3/C for $CeIrIn_5$. The resulting phase shifts ($\delta_{Rh}=-0.042$ rad and $\delta_{Ir}=-0.025$ rad) are consistent with those reported for other Ce heavy-fermion systems.[28,29,49] For $CeCoIn_5$ R_H does not scale with $\rho_{mag}\tilde{\chi}$. This suggests that any skew-scattering contribution present in the Co material is overwhelmed by the conventional Hall term. The skew scattering contribution evident in the Ce-115 Hall data is small, in part, because ρ_{mag} is five to ten times smaller than in other heavy-fermion systems.

Similarities in the Hall response of the Ce- and La-115 compounds below 100 K imply that the second term in Eq. (5) is responsible for the anomalous drop present in the Ce-115 data. dHvA measurements[26] indicate that the La and Ce compounds share essentially the same electronic structure, so the conventional Ce-115 Hall term should mimic that of the La-115 materials. Band-structure calculations and dHvA measurements indicate that the 115's are compensated materials ($n_e=n_h$) with multiple electron and hole Fermi surfaces that form complex 2D and 3D structures.[23,24,26] The Hall effect of a multiband system is determined by the weighted sum of the contributions from each band. Qualitatively, a temperature-dependent Hall coefficient can occur when multiple electron and hole bands cross the Fermi energy and the bands have mobilities with different temperature dependencies.[50] The situation for the 115's is even more complicated since the electron and hole conduction bands give rise to highly anisotropic Fermi surfaces, and, presumably, anisotropic relaxation times. This description also applies to the electronic structures of MgB_2 and $YBa_2Cu_3O_7$, both of which also have a Hall coefficient described by Eq. (1).[33,39] While the presence of a complex FS qualitatively accounts for the temperature-dependent La-115 Hall coefficient, it does not address the question of why R_H becomes increasingly negative below 100 K. The electronlike Hall response may occur because the electron extremal orbits seen in $LaRhIn_5$ dHvA spectra tend to have lighter masses, and hence larger mobilities, than the extremal hole orbits.[26]

Despite their similarities, there are also significant differences in the Ce-115 and La-115 Hall response. The most obvious difference is that the Hall anomalies are much larger in the Ce-115 compounds. The Hall response of $CeCoIn_5$ changes by a factor of 20 between 100 and 4 K; the Hall coefficients of $CeRhIn_5$ and $CeIrIn_5$ change by a factor of 4 and 10, respectively, over the same temperature range. In comparison, the Hall response at 100 K and 4 K differ by only a factor of 2 in the La-115 compounds. These differences presumably stem from the influence of the f-electrons that are present in the Ce compounds. If we assume that the Ce-115 Hall response $R_H^{(Ce)}$ is the sum of a skew scattering term and a term proportional to the La-115 coefficient, $R_H^{(Ce)}$ can be expressed as

$$R_H^{(Ce)}(H,T) = R_H^{skew}(T) + \alpha_f(H,T) R_H^{(La)}(T), \tag{8}$$

where α_f is defined as the f-electron Hall weighting function. Figure 8 shows $\alpha_f(H\rightarrow 0)$ (symbols) plotted versus temperature for the three Ce-115 compounds; the solid line in the

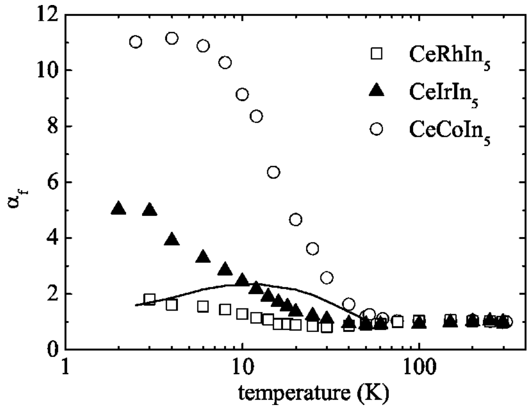

FIG. 8. The low-field f-electron Hall weighting function α_f plotted as a function of temperature for $CeRhIn_5$, $CeIrIn_5$, and $CeCoIn_5$. The solid line shows α_f in a field of 90 kOe for $CeCoIn_5$.

figure shows α_f (90 kOe) for $CeCoIn_5$. α_f was determined from Eq. (8) by combining Ce and La Hall data with the skew-scattering contribution determined from the analysis associated with Fig. 7 (we assume $R_H^{skew}=0$ for $CeCoIn_5$). α_f is unity from roughly 50–300 K, indicating that the conventional Hall contribution in the Ce compounds matches what is measured for the La-115's. Below 50 K, α_f monotonically increases with decreasing temperature, and saturates below 3 K; the rise in α_f begins at 45 K for $CeCoIn_5$ and 25 K for both $CeRhIn_5$ and $CeIrIn_5$. These onset temperatures indicate that the f-electron contribution to the Hall effect begins to grow at roughly the same temperature where the resistivity peaks. As such, the growth in α_f evident below 50 K appears to be correlated with the commencement of Kondo coherence.

The extremal orbit masses observed in dHvA spectra can provide a simple explanation for the connection between the Ce-115 Hall response and Kondo interactions below 50 K. Those measurements[51] on $CeCoIn_5$ detect a heavy hole orbit with a mass $(87m_o)$ that is consistent with the large electronic specific-heat coefficient observed experimentally.[14] In comparison, the $CeCoIn_5$ electron orbits are significantly lighter ($\sim 15\ m_o$). This extreme electron-hole mass asymmetry would lead to a mobility asymmetry, and, ultimately, an even larger negative Hall anomaly than is seen in $LaCoIn_5$. Although the differences are not as extreme, $CeIrIn_5$ and $CeRhIn_5$ also exhibit asymmetries in their respective hole and electron masses.[23,24,26] Of the three Ce-115 compounds, $CeRhIn_5$ has the smallest electron-hole mass asymmetry, and the least amount of $4f$ character in its Fermi surface;[22,26] these FS features are consistent with the fact that $CeRhIn_5$ also has the smallest low-T Hall anomaly in the Ce-115 series. The enhanced low-T Ce-115 carrier masses are a direct result of the Kondo interactions that produce the large electronic contribution to $C_p(T)$. The Kondo resonance gradually develops with decreasing temperature, so that the carrier masses will not be heavy for $T \gg T_K$. The temperature dependence shown by the f-electron Hall weighting function is then simply a reflection of the carrier mass enhancement that gradually develops as the system is cooled below T_{coh}.

The substantial field dependence present in the Ce-115 Hall response offers confirming evidence that field-dependent many-body interactions are responsible for the sizable difference between the Ce and La low-T Hall anomalies. An applied magnetic field has a deleterious effect on the heavy-fermion state because it tends to broaden the Kondo resonance and shift it below the Fermi energy.[52–54] The f-electron contribution to the FS drops, in turn, and the Sommerfeld coefficient and the large zero-field effective mass are reduced.[52,55] The solid line in Fig. 8 shows that the f-electron contribution to the $CeCoIn_5$ Hall effect is substantially reduced in 90 kOe; the same is true for $CeRhIn_5$ and $CeIrIn_5$. These results are consistent with the large field-induced reduction of the $CeCoIn_5$ carrier mass observed in dHvA measurements.[51] The analysis used in Sec. III B to parametrize $R_H(H,T)$ data also shows a link between the Ce-115 Hall response and Kondo interactions. The H-T scaling analysis used on the Ce-115 Hall data is similar to the parametrization that can be applied to single-impurity MR data.[40] The MR of a spin-1/2 Kondo system typically follows the H-T scaling expressed by Eq. (4) with $\beta=1$, and $T_o=T_K$. The Ce-115 T_o values listed in Fig. 8 are roughly consistent with the Kondo temperatures estimated from low-T Sommerfeld coefficients.[9,13,14] Hence, the $R_H^{(Ce)}(H,T)$ data and $\alpha_f(H,T)$ values are consistent with a field-induced suppression in the f-electron character of the Ce-115 Fermi-surface states; furthermore, H-T Hall data scaling is consistent with Kondo energy scales of a few degrees Kelvin.

Our analysis bears some resemblance to the two-fluid Kondo lattice model proposed by Nakatsuji *et al.*[56] This model divides a Kondo lattice system into a Kondo-gas component (analogous to a Kondo-impurity phase) and a Kondo-liquid component (analogous to a coherent heavy-fermion phase), with the temperature-dependent evolution of Kondo-lattice properties controlled by the mixing parameter $f(T)$. The gas phase, characterized by a single-ion Kondo scale T_K, dominates the system's properties at high temperatures. The liquid phase, characterized by the intersite coupling energy scale T^*, begins to influence the system's physical properties at temperatures less than T^*. A two-fluid analysis[57,56] of $\chi(T)$ and $C_p(T)$ data finds that the energy scales in $CeCoIn_5$ are $T_K=1.7$ K and $T^*=45$ K. The model's crossover from local-moment behavior at high temperatures to itinerant heavy-fermion behavior at low temperatures, and the energy scales derived for $CeCoIn_5$, accurately describe the Ce-115 $R_H(T)$ data. It is particularly noteworthy that the increasing importance of the heavy Kondo-liquid phase below T^* in the two-fluid model provides a simple explanation for the rise in $\alpha_f(T)$ that occurs in the Ce-115 Hall data below 50 K.

Lastly, we consider the significance of the $\cot(\theta_H) \sim T^2$ behavior present in the 115 Hall data. The same T dependence is present in high-T_c cuprate data[33,38] and some have suggested that this is linked[34] to a QCP. The NFL behavior evident in the physical properties of $CeCoIn_5$ (and possibly $CeIrIn_5$) below ~ 5 K might also be related to a QCP. As such, it is tempting to ascribe the $\cot(\theta_H)$ temperature dependence in these two Ce-115 materials to critical spin fluctuations associated with a nearby QCP. This interpretation appears untenable since the Hall angle data of $CeRhIn_5$ and the three La-115 compounds—all of which show no QCP-related phenomena—also exhibit the $\cot(\theta_H) \sim T^2$ behavior. A more credible conclusion is that the quadratic Hall-angle temperature dependence results from the peculiar "conventional" Hall response, intrinsic to the 115 electronic-structure.

V. CONCLUSIONS

The Hall response of the Ce-115 compounds differs markedly from that of most Kondo systems. $R_H^{(Ce)}$ is dominated by the conventional Hall effect, rather than that due to skew scattering. This comes about because of the complex electronic structure intrinsic to the 115 system. The field and temperature-dependent variation of the Ce-115 Hall coefficients below 50 K are consistent with the same Kondo interactions that also influence other transport and thermodynamic properties. These results indicate that conventional transport mechanisms cannot always be ignored in interpreting the physical properties of f-electron systems.

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