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Precursor state to superconductivity in $CeIrIn_5$: Unusual scaling of magnetotransport

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We present an analysis of the normal-state Hall effect and magnetoresistance in the heavy-fermion superconductor $CeIrIn_5$. It is demonstrated that the modified Kohler's scaling—which relates the magnetoresistance to the Hall angle—breaks down prior to the onset of superconductivity due to the presence of a precursor state to superconductivity in this system. A model-independent single-parameter scaling of the Hall angle governed solely by this precursor state is observed. Neither the Hall coefficient nor the resistivity exhibits this scaling, implying that this precursor state preferentially influences the Hall channel.

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I. INTRODUCTION

The variety of low-temperature electronic ground states observed in heavy-fermion systems primarily arises from two competing fundamental physical processes: the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction favoring magnetic order and the Kondo effect that screens the local moments.[1] Of particular interest are systems in which the magnetic order can be driven to zero temperature. If this takes place in a continuous fashion it is referred to as a quantum critical point (QCP). The often observed existence of unconventional superconductivity in the vicinity of such a QCP has added to the interest in these exotic phase transitions, as it suggests that Cooper pair formation could be governed by the presence of (antiferro-) magnetic fluctuations.[2] The Ce-115 systems (of the form $CeMIn_5$, with $M=$ Co, Ir, or Rh) have proven to be an interesting playground where manifestations of these intrinsic energy scales are unambiguously observed.[3] For instance, in the ambient pressure superconductor $CeCoIn_5$, the QCP can be approached[4] with applied magnetic fields of the order of the superconducting upper critical field $H_{c2}(0)$. The antiferromagnetic order observed in $CeRhIn_5$ can be suppressed by applying pressure of the order of 1.6 GPa which, again, results in a superconducting ground state.[5] In $CeIrIn_5$, though the superconducting regime is reasonably separated[6] from the (possibly metamagnetic) QCP, signatures of the presence of antiferromagnetic fluctuations in the vicinity of superconductivity have been observed.[7] Besides unconventional superconductivity, experimental signatures such as the presence of line nodes in the superconducting gap structure[8] and anomalous magnetotransport have also brought into focus the remarkable similarities which these systems share with the high-temperature superconducting cuprates.[9]

One of the outstanding puzzles presented by these complex materials is the changing low-energy excitations of the normal state prior to the formation of the superconducting state. In the cuprates for instance, it is now understood that superconductivity is preceded by the opening of a *pseudogap* in the electronic density of states.[10] Typically, this state is associated with experimental signatures such as a deviation from the linear temperature dependence of resistivity[11] or a decrease in the spin-lattice relaxation rate $(1/T_1)$ in nuclear-magnetic-resonance measurements,[12] and is now considered an intrinsic energy scale of these systems. Recently, experiments have indicated that a precursor state to superconductivity may also exist in the Ce-based heavy-fermion metals. The Ce-115 systems have been exemplary in this aspect, with the presence of such a precursor state being inferred from measurements such as resistivity,[13] nuclear quadrupole resonance,[14] the Hall angle,[15] and the Nernst effect.[16] Here, we report on the analysis of the normal-state magnetotransport in $CeIrIn_5$. To this end, prior[15] and new simultaneous measurements of isothermal Hall effect and magnetoresistance are evaluated. We demonstrate that the modified Kohler's scaling—relating the magnetoresistance to the Hall angle—breaks down prior to the onset of superconductivity due to a change in the Hall scattering rate. Moreover, the critical field $H^*(T)$ of the precursor state to superconductivity—as determined from a change in the Hall mobility—has been used to scale the temperature- and field-dependent Hall angle $\theta_H=\cot^{-1}(\rho_{xx}/\rho_{xy})$. The fact that a similar scaling procedure fails for the individual properties, i.e., the resistivity ρ_{xx} and the Hall coefficient $R_H=\rho_{xy}/\mu_0 H$, suggests that this precursor state preferentially affects the Hall channel.

II. EXPERIMENTAL DETAILS

The resistivity and Hall-effect measurements were conducted as isothermal field sweeps on high-quality single crystals of $CeIrIn_5$ in magnetic fields $\mu_0 H \leq 15$ T and in the temperature range $0.05\text{ K} < T < 2.5$ K. The magnetic field was applied along the crystallographic c axis, and a current of 20 μA was applied along the ab plane. The Hall voltage was obtained as the asymmetric component under magnetic field reversal.

III. RESULTS AND DISCUSSION

Figure 1(a) depicts the isothermal Hall coefficient $|R_H|$ as a function of applied field H for different temperatures. The sharp drop in $|R_H|$ corresponds to the onset of superconductivity. The magnetic field dependence of the transverse resis-

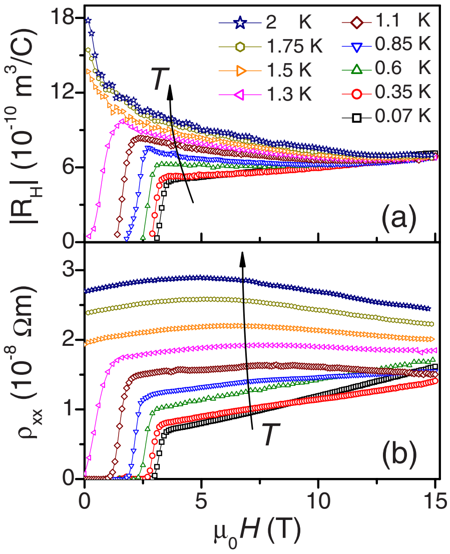

FIG. 1. (Color online) Magnetic field dependence of (a) the Hall coefficient $|R_H|$ and (b) the resistivity ρ_{xx} measured at selected temperatures. The sharp drop corresponds to the onset of superconductivity.

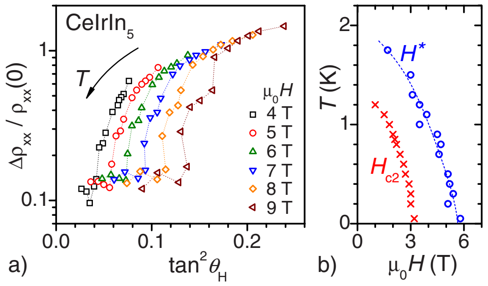

FIG. 2. (Color online) (a) Magnetoresistance vs squared tangent of the Hall angle θ_H revealing strong deviations from the modified Kohler's rule. Here, temperature is an implicit parameter as indicated. (b) Part of the H-T phase diagram of CeIrIn$_5$ exhibiting the boundary of superconductivity and its precursor state (marked by H_{c2} and H^*, respectively).

tivity ρ_{xx} is plotted in Fig. 1(b). Besides the onset of superconductivity, a crossover in the sign of the magnetoresistance corresponding to the onset of a coherent Kondo state is visible in the high-temperature data sets. Though this crossover from an incoherent to a coherent Kondo scattering regime is a characteristic feature of the heavy-fermion metals, many similarities in the normal-state magnetotransport of the superconducting cuprates and the Ce-115 systems have recently come to light. For instance, the resistivity ρ_{xx} has a linear temperature dependence, the Hall coefficient R_H varies approximately as $1/T$, and the Hall angle follows a $\cot\theta_H \propto T^2$ dependence in these conceptually different classes of materials. In the cuprates, theoretical support for these experimental observations have relied on the rather extraordinary idea that in contrast to conventional metals, the transverse Hall scattering rate (τ_H^{-1}) in the cuprate metals is a distinct entity as compared to the transport scattering rate (τ_{tr}^{-1}).[17,18] Since the resistivity is governed by τ_{tr}^{-1} and R_H by the ratio τ_H/τ_{tr}, it follows that $\cot\theta_H$ is a manifestation of the transverse relaxation rate τ_H^{-1} alone. In conventional metals (with an isotropic single-scattering rate), the magnetoresistance $[\rho_{xx}(H)-\rho_{xx}(0)]/\rho_{xx}(0)$ arising due to the orbital motion of charge carriers is known to scale as a function of $H/\rho_{xx}(0)$ (Kohler's rule[19]). A natural consequence of the presence of two scattering rates was the reformulation of this scaling rule to relate the transverse magnetoresistance with the Hall angle.[20] This scaling of the form $[\Delta\rho_{xx}/\rho_{xx}(0)] \propto \tan^2\theta_H$ has been successfully applied to magnetotransport data in both the cuprates as well as in all the Ce-115 compounds. In CeIrIn$_5$ for instance, it was recently demonstrated[21] that this scaling works in a wide temperature range down to about 2 K, but this study did neither extend down to the precursor nor the superconducting regime [cf. Fig. 2(b)]. The vital question remained whether the superconducting condensate emerges from within the phase space where this scaling is obeyed. Figure 2(a) exhibits the modified Kohler's scaling as determined from our magnetotransport data. Clearly, the scaling procedure mentioned above is *not* applicable down to the lowest accessible temperatures. This observation is in line with the inference that the formation of the superconducting condensate in CeIrIn$_5$ is preceded by a precursor state as determined by a change in the Hall mobility.

In the heavy-fermion metals, the crystal electric field and the single-ion Kondo effect provide two fundamental energy scales that crucially influence its physical properties. An additional energy scale of importance[22,23] is related to the intersite coupling between the local moments due to the RKKY interaction. In this context, it is important to clarify whether this precursor state to superconductivity in CeIrIn$_5$ represents an intrinsic energy scale of the system, and to discern the manner in which it influences the normal-state magnetotransport. One powerful tool of identifying intrinsic energy scales in strongly correlated systems is the quest for universal trends of, and relationships between, measured physical quantities. In the heavy-fermion systems, early attempts to scale physical properties using a single energy scaling parameter met with only limited success.[24] However, in the cuprates it has been demonstrated[25–27] that a single-parameter scaling of experimental data was possible by using the energy scale of the pseudogap alone. By normalizing any measured electrical or thermal transport quantity $f(x)$ along with its variable x by the corresponding values at the onset of the pseudogap [$f(x^*)$ and (x^*), respectively] the measured data could be made to collapse into a single universal curve. Thus, the scaling is of the form $f(x)/f(x^*) \propto F(x/x^*)$. Consequently, the normalized Hall coefficient ($|R_H(H)|/|R_H(H^*)|$) is plotted as a function of normalized field (H/H^*) for CeIrIn$_5$ in Fig. 3(a). Here, the values of H^* [Fig. 2(b)] were deduced from a quadratic fit to the experimental values determined earlier from the change in the Hall mobility.[15] Figure 3(b) shows the equivalent scaling for the magnetoresistance, i.e., $\rho_{xx}(H)/\rho_{xx}(H^*)$ as a function of H/H^*. Interestingly, neither $R_H(H)$ nor $\rho_{xx}(H)$ scale onto a universal curve implying that both of these quantities have significant contributions which are not scaling invariant.

A priori, there is no simple explanation of the nature of these *non*-scaling-invariant contributions to R_H and ρ_{xx}. One possibility which cannot be ruled out is the influence of dis-

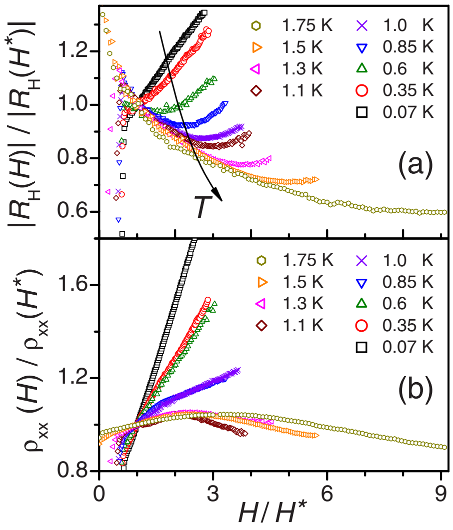

FIG. 3. (Color online) (a) The scaled field dependences of the normalized Hall coefficient $|R_H|(H)/|R_H|(H^*)$ and (b) the normalized resistance $\rho_{xx}(H)/\rho_{xx}(H^*)$ plotted as a function of the normalized field (H/H^*) for CeIrIn$_5$.

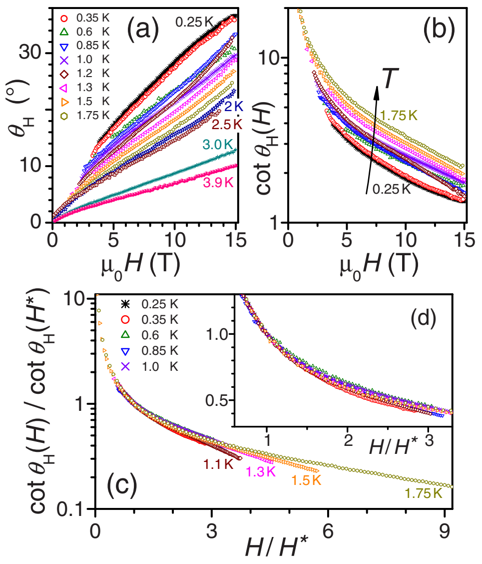

FIG. 4. (Color online) Field dependence of (a) the Hall angle θ_H and (b) its cotangent cot θ_H. (c) Scaling of both cot θ_H and field H with respect to H^* reveals a collapse of the data into a single generic curve. The inset (d) shows an expanded view of the regime in the vicinity of the precursor state.

order in these systems, with impurity scattering not being scaling invariant. This problem can be circumvented by the analysis of the Hall angle. From prior work on the cuprates it is known that the cotangent of the Hall angle (which is directly related to the charge-carrier mobility) is a quantity of basic interest.[18] It has been shown that cot θ_H follows a T^2 dependence, independent of the extent of impurity substitution as well as the charge-carrier density.[28] This relative insensitivity of cot θ_H to material properties (which is related to the fact that it does *not* depend on τ_{tr}) has led to the conjecture that it is an even more fundamental property than R_H. Moreover, deviations from cot $\theta_H \propto T^2$ have been used to identify the onset of the pseudogap state in the cuprates.[29] Fig. 4(a) presents the isotherms of the field-dependent Hall angle as measured in CeIrIn$_5$, indicating that θ_H is quasilinear as a function of H. If the different electronic states in CeIrIn$_5$ are manifestations of a change in the geometry of the Fermi surface, this should be visible in the field dependence of the Hall angle which measures the effective deflection of charge carriers by the applied magnetic field. However, the lack of any observable features at fixed values of θ_H suggests that there is no abrupt change in the geometry of the Fermi surface, at least in the range of our measurements. Here, it is emphasized that θ_H attains a value of more than 30° at large fields, which is substantially larger than what is commonly observed in the cuprates. The field dependence of cot θ_H is depicted in Fig. 4(b). In line with the earlier analysis, the normalized Hall angle cot $\theta_H(H)$/cot $\theta_H(H^*)$ is plotted as a function of normalized field H/H^* in Fig. 4(c), with an expanded view of the region in the vicinity of the precursor state shown in Fig. 4(d). A good scaling behavior is obtained, an observation which is remarkable in view of the fact that such a scaling procedure was found to be ineffective for both $\rho_{xx}(H)$ and $R_H(H)$, Fig. 3. Deviations from scaling are observed in the high-T high-H incoherent Kondo regime,[15] where the applied magnetic field overwhelmingly suppresses magnetic fluctuations. This scaling of cot θ_H unambiguously implies that the precursor state observed in CeIrIn$_5$ represents an intrinsic energy scale of the system, which influences the magnetotransport in a substantial region of the field-temperature phase space. Note that the scaling of the critical field $H^*(T)$ of the precursor state with the superconducting critical field $H_{c2}(T)$ suggests that they may arise from the same underlying mechanism.[15] This provides a natural link between the normal-state properties of CeIrIn$_5$ and the superconductivity in this system.

The fact that scaling is observed in cot θ_H clearly suggests that the precursor state is primarily associated with the transverse Hall scattering rate τ_H^{-1}. However, it would be erroneous to conclude that the precursor state is associated *only* with τ_H^{-1} since this state is also identified by a subtle feature in the magnetoresistance.[15] Nevertheless, the lack of scaling in both ρ_{xx} and R_H suggests that the magnetic field seemingly influences τ_H^{-1} preferentially as compared to τ_{tr}^{-1}. Interestingly, this is also in agreement with prior results on underdoped cuprates where it was suggested that the formation of a pseudogap primarily affects the Hall channel, and has little effect on the diagonal conductivity.[30] Moreover, the observation of scaling *only* in cot θ_H re-emphasizes the presence of two distinct scattering processes, which selectively influence the resistivity and the Hall angle in this heavy-fermion metal. This could possibly be a feature of many heavy-fermion metals, though an authoritative claim on this aspect can only be made after experimental evidence from a number of such systems is gathered. The primary impediment here is that—unlike in the superconducting cuprates—measurements of the Hall angle *and* the resistivity in the heavy-fermion metals have been rather scarce. To the best of our knowledge, the only systems in which both quantities have been reported are the primary members of the Ce-115 family, and the system YbRh$_2$Si$_2$. Interestingly, in *all* these systems, a linear temperature dependence of resistivity is accompanied by a quadratic temperature dependence of the Hall angle in an appreciable temperature range.[15,31–33] This is particularly striking, considering the fact that the low-temperature ambient-pressure electronic ground states of these systems are considerably different. As already mentioned, in $CeCoIn_5$ a putative magnetic field induced QCP is masked by an unconventional superconducting state,[3] whereas in $CeIrIn_5$ superconductivity appears to be well separated from the zero-temperature magnetic instability[6] and in $CeRhIn_5$ long-range antiferromagnetic order is found[34] below 3.8 K. Moreover, the prototype quantum critical system $YbRh_2Si_2$ also features a magnetic field induced QCP but shows no hint of superconductivity down to the lowest measured temperatures.[35] The fact that all these systems—despite their varying ground states—exhibit similar magnetotransport anomalies suggests that, in addition to the cuprates, the scenario of two scattering times might be a generic feature of many heavy-fermion metals.

The observed anisotropy in the magnetic field response of the scattering rates in $CeIrIn_5$ may arise as a consequence of coupling of the quasiparticles to incipient antiferromagnetic fluctuations.[36,37] Such a coupling might then renormalize the scattering rates along different directions of the Fermi surface. There exists a body of work to imply that this might indeed be the case in the Ce-115 systems. For instance, investigations of the angular-dependent resistivity in $CeCoIn_5$ have indicated the presence of two distinct regimes in their magnetic field dependences, separated by a critical angle θ_c, which in turn is governed by the intrinsic anisotropy.[38] Moreover, recent thermal-conductivity measurements indicated that the superconducting gap of $CeIrIn_5$ may have a $d_{x^2-y^2}$ symmetry: a signature that the superconductivity is strongly influenced by the presence of antiferromagnetic fluctuations.[39] These fluctuations are themselves inferred to be anisotropic in nature,[7] with the magnetic correlation length along the basal plane being larger than along the c axis, $\xi_{ab} > \xi_c$. The two corresponding scattering rates appear to be influenced by the low-lying precursor state in a disparate fashion. In $CeIrIn_5$, it has been observed that cot θ_H increases anomalously in the precursor state.[15] Since cot $\theta_H = 1/\omega_c \tau_H$ this suggests that τ_H^{-1} is *enhanced* in the precursor state—provided, of course, that the effective mass m^* remains constant. This is in contrast to observations in the related system $CeCoIn_5$, where it was found that τ_{tr}^{-1} *reduces* at the onset of the precursor state.[13]

IV. CONCLUSIONS

In summary, the analysis of the normal-state magnetotransport in $CeIrIn_5$ reveals that the modified Kohler's plot (relating the magnetoresistance to the Hall angle) breaks down prior to the onset of superconductivity, presumably due to the presence of a precursor state to superconductivity. Moreover, the Hall angle obeys a single-parameter scaling unambiguously governed by this precursor state. The absence of scaling in R_H and ρ_{xx} is clearly indicative of the presence of two distinct scattering times, similar to observations in the cuprate superconductors. This could very possibly be a generic feature of many heavy-fermion superconductors. The fact that *only* the Hall angle is scaled by the precursor state also implies that this state preferentially influences the Hall channel and has a relatively weaker influence on the resistivity. It is imperative to map the evolution and symmetry of both the superconducting as well as the precursor state by more direct probes, e.g., in order to formulate a theoretical basis for the observed phenomena.

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