Magnetotransport in Heavy Fermion Metals Ce*M*In$_5$ (*M* = Co, Ir)

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Introduction

An essential ingredient in heavy fermion physics is the Kondo effect which screens the local moments and accounts for the formation of heavy quasiparticles. Competing with this effect is the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction that favors magnetic order. If the latter can continuously be driven to zero temperature by an external control parameter, a quantum phase transition is induced which can evoke fascinating, yet often poorly understood phenomena. Of particular interest are systems in which unconventional superconductivity is observed in the vicinity of such a quantum critical point (QCP). In these cases Cooper pair formation could be facilitated by the presence of (antiferro-)magnetic fluctuations [1] rather than by phononic coupling modes as in the conventional BCS superconductors. Here, the Ce*M*In$_5$ systems (*M* = Co, Ir) have proven to provide an excellent playground for a detailed investigation of the above-mentioned interrelation. Both materials exhibit a superconducting ground state (CeCoIn$_5$ features the highest ambient pressure superconducting transition temperature T_C = 2.3 K of all Ce-based compounds known to date) the unconventional nature of which has manifested itself in a number of properties [2]. The existence of strong antiferromagnetic (AFM) fluctuations has been shown by nuclear quadrupole resonance (NQR) measurements but finds its most prominent display by the realization of an AFM ground state in CeRhIn$_5$. Notably, the latter compound superconducts under pressure $p \geq 0.5$ GPa where the magnetic ordering temperature T_N also starts to decrease [3]. In addition, some analogy between the Ce*M*In$_5$ systems and the cuprate high temperature superconductors was proposed [4].

We conducted highly sensitive measurements of the low-temperature magnetotransport in order to elucidate on these issues. Hall measurements have proven particularly useful for the study of the Fermi surface evolution of heavy fermion metals close to a QCP [5]. The quantum spin fluctuations appear to significantly influence the CeCoIn$_5$ Hall response in a narrow low temperature range at ambient pressure, an effect which is gradually suppressed by applied pressure. In addition, these measurements indicate a dissociation of the quantum (H_{qc}) and superconducting critical field H_{c2}. In CeIrIn$_5$ we find experimental signatures of the presence of a *precursor* state that envelops the superconducting region which may imply that the formation of the superconductivity is preceded by an electronic state hitherto unexplored in this class of materials. The influence of AFM fluctuations is apparent by the observation of two distinct scattering times in these systems, in similarity to observations in the superconducting cuprates. Although the existence of two scattering times in heavy-fermion systems remains to be investigated in adequate detail, this scenario might well be applicable to other systems.

Experimental Details

Measurements of the Hall effect and magnetoresistance (MR) are conducted on single crystalline samples of CeCoIn$_5$ and CeIrIn$_5$ within the temperature range 0.05 K $\leq T \leq$ 2.5 K in the form of isothermal field sweeps. The magnetic field (of up to 15 T) is applied parallel to the crystallographic *c* axes, and the Hall voltage is extracted as the asymmetric component under magnetic field reversal. Low-temperature transformers are used in conjunction with low-noise voltage preamplifiers to enable an effective resolution of better than ±0.01 nV. For measurements under pressure $p \leq$ 1.2 GPa, the samples were mounted in a piston cylinder-type pressure cell using fluorinert 75 as the pressure transmitting medium.

CeCoIn$_5$

In our previous scientific report some preliminary results of ambient pressure Hall effect measurements were already presented [6]. We have extended these measurements to include pressure

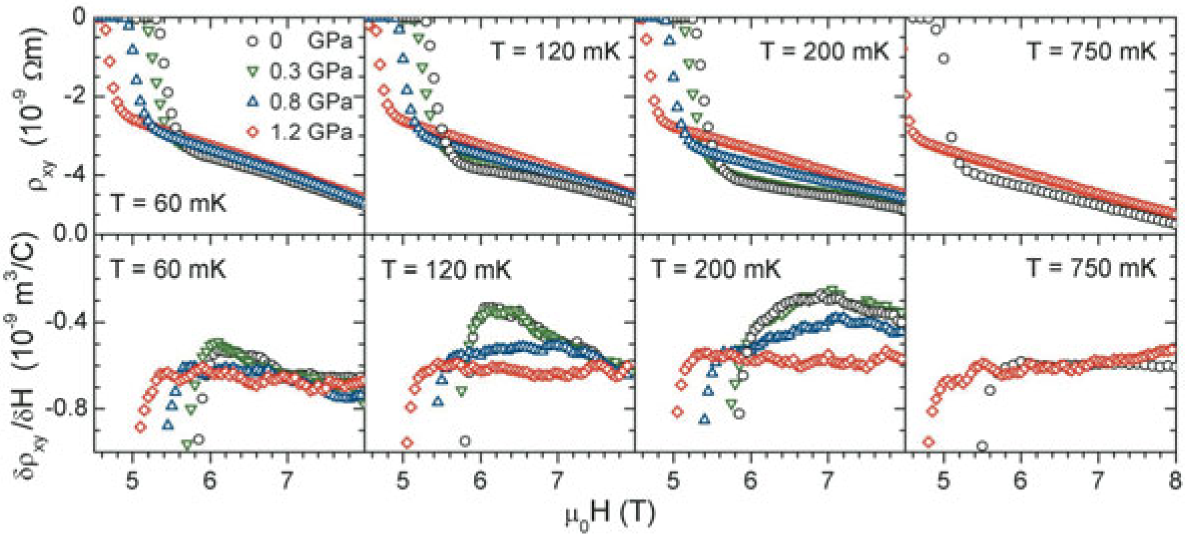

Fig. 1: Hall resistivity ρ_{xy} and the Hall coefficient $R_H = \partial\rho_{xy}/\partial H$ for selected temperatures and pressures. A peak feature is clearly recognizable in $R_H(H)$ at intermediate temperature which can be suppressed by the application of pressure.

studies up to 1.2 GPa [7]. This allows an unambiguous identification of the peak feature observed in the Hall coefficient $R_{\mathrm{H}} = \partial\rho_{\mathrm{xy}}/\partial H$ at low-pressure, Fig. 1. The application of pressure drives Cerium from the usual magnetic Ce^{3+} state towards the non-magnetic Ce^{4+} one. Hence, the AFM spin fluctuations are suppressed and Landau Fermi liquid (LFL) behavior is recovered. This mechanism also manifests itself by an initial increase of $T_{\mathrm{C}}(p)$ with a maximum T_{C} at 1.3 GPa. Results for the non-magnetic reference compound $LaCoIn_5$ agree with those of the Ce compound under high pressure, *i.e.*, in the LFL regime. Consequently, the peak feature can be assigned to deviations from LFL behavior, caused by AFM spin fluctuations. Such a Hall peak feature was very recently also observed in the cuprate superconductors and interpreted in terms of critical fluctuations [8].

As the temperature dependence of the peak in R_{H} tracks the crossover from non-Fermi liquid (NFL) to LFL behavior, it can be used to construct an H–T phase diagram, Fig. 2. Here, $\rho_{\mathrm{xy}}(H)$ values that are influenced by the proximity to superconductivity are not evaluated (hatched area). The field values at which the peak in $R_{\mathrm{H}}(H)$ is observed has been marked by H_{d}. These data compare nicely to results from MR measurements [9]. Most importantly, if $H_{\mathrm{d}}(T)$ is extrapolated to $T \rightarrow 0$ by a simple power law, we find $\mu_0 H_{\mathrm{d}}(0) \approx 4.1$ T. For $T > 0.26$ K, a field scaling can be applied such that a universal peak feature in R_{H} is observed. The field values H_{min} of the peak obtained from this scaling again coincide with reported results [9] and extrapolate to 4.0 T, see Fig. 4(b), a fact that supports our scaling.

The pressure evolution of R_{H}, combined with the value of R_{H} corresponding to the expected LFL value at the lowest T, and the comparison of the field $H_{\mathrm{d}}(T)$ at which the peak is found to the known phase diagram at $p = 0$, suggest that this feature is related to the crossover from NFL to LFL behavior. Thus, our data support the idea of a

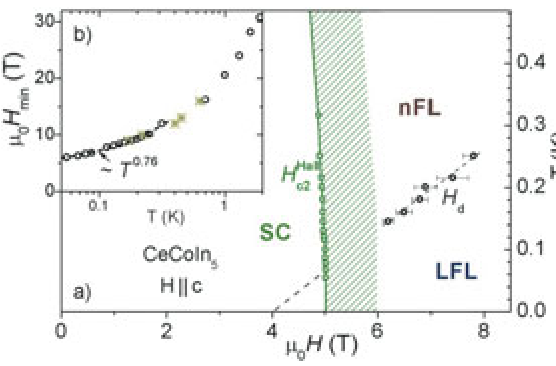

Fig. 2: Low temperature phase diagram of $CeCoIn_5$ as obtained from Hall measurements. The hatched area marks the H range within which SC influences the slope of $\rho_{xy}(H)$ [▫ mark onset of non-zero $\rho_{xy}(H)$]. The values $H_d(T)$ represent the fields at which a peak in R_H can directly be observed. A power law fit extrapolates to 4.1 T at T = 0 (dashed line). (b) Temperature dependence of the scaling field H_{min} used to collapse the peak features observed at different T into a single one. A fit (dashed line) again extrapolates to 4.0 T at T = 0. These values agree well with MR data (green crosses) taken from Ref. [9].

field-tuned QCP in $CeCoIn_5$ which is not exactly located at the upper critical field of superconductivity, H_{c2}. Rather it is within the field range of superconductivity which appears to mask an AFM ordered state generating this QCP. We believe that this disparity does not necessarily rule out the possibility of the AFM spin fluctuations being involved in the *formation* of *d*-wave superconductivity, even if they do not become critical right at H_{c2}. We note that the above mentioned frequent observation of unconventional superconductivity in the vicinity of a QCP in fact supports a disparity of the critical fields.

$CeIrIn_5$

Figure 3 summarizes the phase diagram of $CeIrIn_5$ as determined from our magnetotransport measurements [10]. Two distinguishable crossover lines in this phase diagram are clearly related to a magnetic instability at about 25 T: (i) The LFL to NFL crossover, as determined by deviations from Kohler's scaling rule and (ii) the onset of a coherent Kondo scattering regime, as determined from a crossover in the sign of the MR at H_{coh}. The LFL–NFL crossover is seen to be in good agreement with prior reports and a linear extrapolation indeed intercepts the magnetic field axis at about 25 T. Though the functional form of the coherent to incoherent Kondo regime is non-trivial, a crossing between these two lines is unlikely, and the Kondo coherence would also be expected to vanish at the magnetic instability.

A striking result from the analysis of our magnetotransport data pertains to the observation of a precursor state to superconductivity in $CeIrIn_5$. This state, which is seen as a curve that envelops H_{c2} in Fig. 3, was inferred from the field-dependence of the Hall angle θ_H. Though rarely utilized as a means of investigating heavy-fermion systems, prior work in the superconducting cuprates has demonstrated that its cotangent $\cot\theta_H = \rho_{xx}/\rho_{xy}$ is a quantity of fundamental interest as it is primarily a measure of the charge carrier mobility. A quadratic temperature dependence of $\cot\theta_H$ was observed in the cuprates which appeared to be independent of the charge carrier density and the extent of impurity substitution [11]. Since the resistivity ρ_{xx} is linear in T, this T^2 dependence of $\cot\theta_H$ is thought to be a manifestation of the fact that there are two distinct scattering rates which independently influence the resistivity and the Hall effect (τ_{tr} and τ_H, respectively). Moreover, deviations from the T^2 behavior of $\cot\theta_H$ were interpreted in terms of the onset of the pseudogap state in the cuprates. Our measurement protocol (we conduct isothermal field sweeps) enables us to investigate the magnetic field dependence of this quantity in detail, and $\cot\theta_H$ is seen to have an H^{-1} dependence within a substantial region of the H–T phase space. In the vicinity of the superconducting regime, systematic deviations from this H^{-1} dependence are seen (starting at a critical field H^*), the field and temperature dependence of which is exhibited in Fig. 3. Our measurements clearly indicate the existence of a pseudogap-like precursor state to superconductivity in $CeIrIn_5$, a phenomenon which may be generic to many other heavy-fermion superconductors as well. Interestingly, the critical field of this precursor state scales onto H_{c2}, implying that both of them might arise from the same underlying physical mechanism [10].

The presence of this precursor state appears to crucially influence the normal-state magnetotransport in $CeIrIn_5$. Moreover, it seems to influence τ_{tr} and τ_H in a disparate fashion. This is clearly borne out by two key experimental observations: Firstly, contrary to a prior report [12], the modified Kohler's scaling (which relates the MR to the Hall angle) breaks down within the precursor state. Secondly, a model-dependent

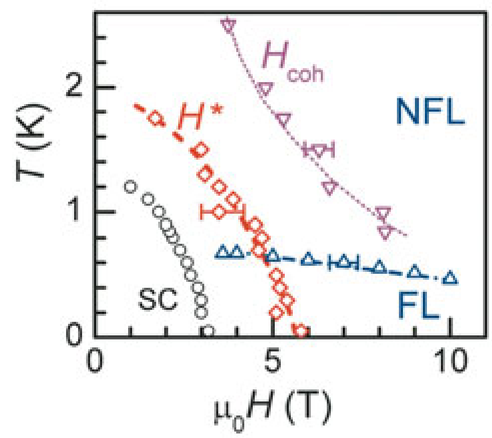

Fig. 3: Low temperature phase diagram of $CeIrIn_5$. The regions of Landau Fermi liquid (FL) and superconducting (SC) behavior are marked. Deviations from Kohler's rule are interpreted as non-Fermi liquid behavior (NFL), the onset of Kondo coherence at H_{coh} is inferred from MR. The existence of a precursor state to SC below H^* is concluded from an analysis of the Hall angle.

single parameter scaling of magnetotransport quantities—using the demarcation H^* (T) of the precursor state—is seen to be applicable *only* for the Hall angle [13]. We showed that the normalized Hall angle $\cot\theta_H(H)/\cot\theta_H(H^*)$ scales very well as a function of the normalized field (H/H^*) [13]. The fact that neither the resistivity nor the Hall effect individually exhibit this scaling implies that the precursor state preferentially influences the Hall channel. This scaling clearly demonstrates that the precursor state in $CeIrIn_5$ represents a fundamental energy scale of the system; in addition to the well recognized energy scales corresponding to the crystal electric field, the intersite coupling and the single-ion Kondo effect. It also re-emphasizes the presence of two distinct scattering times in these systems, in similarity to observations in the superconducting cuprates. Although the existence of two scattering times in heavy-fermion systems remains to be investigated in adequate detail, this scenario might well be applicable to other systems.

Our essential observations of an H^{-1} dependence of the Hall angle (which in turn is used to demarcate the precursor state) and of two distinct scattering times can be adequately described by two theories which have been extensively used earlier in the cuprates. The spin-charge-separation scenario developed by Anderson [14] postulates the formation of two different quasiparticles each of which is associated with the spin and charge degrees of freedom. The two different scattering times then correspond to dissimilar scattering events usually associated with these two different kinds of quasiparticles. On the other hand, the nearly antiferromagnetic Fermi liquid (NAFFL) scenario [15] postulates the modification of scattering rates along different regions of the Fermi surface. This is accomplished by the formation of so-called *hot spots* which represent regions of the Fermi surface where it intersects the AFM Brillouin zone and where scattering becomes singular. Thus, all the transport coefficients are renormalized with respect to the anisotropy associated with the different regions of the Fermi surface. Interestingly, both of these scenarios can explain the observed H^{-1} dependence of the Hall angle. While the spin-charge separation scenario cannot be ruled out, the NAFFL picture is a particularly attractive one here as the crucial influence of AFM spin fluctuations in determining the electronic ground state is also seen in very recent magnetotransport investigations on Cd substituted $CeCoIn_5$ samples.

Two of our key observations—a pseudogap-like precursor state and the existence of two distinct scattering times—are reminiscent of the behavior in the cuprates. They are consistent with a scenario in which incipient antiferromagnetic fluctuations crucially influence the magnetotransport in these two disparate classes of systems by modifying the electron scattering rates along different parts of the Fermi surface. The phenomenon of unconventional superconductivity in the heavy-fermion systems, the high-T_c cuprates, and maybe even the newly discovered iron-oxypnictides can thus possibly be placed on a universal platform: the nature and properties of the electronic ground state are dictated by magnetic fluctuations.

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