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Striking similarities between HTSC and quasi-2D HF $CeRIn_5$

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Abstract

We report our measurements of transport coefficients of quasi-2D HF $CeRIn_5$ in the normal state, in the vicinity of a QCP and in the superconducting state. In the normal state, we observed a T-linear resistivity, a T^2-dependence of $\cot\theta_H$ (θ_H is the Hall angle), the violation of Kohler's rule, and a giant Nernst coefficient. In the superconducting state, on the other hand, we found a rapid increase of the quasiparticle (QP) mean free path as the temperatures is reduced below T_c. The density of states (DOS) of delocalized QPs obtained from the thermal Hall coefficient is consistent with a d-wave pairing symmetry. Moreover, the angular dependence of thermal conductivity indicates that the gap function has a d-wave symmetry with line nodes perpendicular to the *ab*-plane. These results bear a striking resemblance to those obtained for the high-T_c cuprates. This similarity implies that the fluctuation and excitation spectrum near a 2D antiferromagnetic QCP could be universal.

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Keywords: Quantum critical point; Transport coefficients; d-Wave symmetry; $CeCoIn_5$

One of the most remarkable issues in the physics of strongly correlated electron systems, including heavy fermion (HF) compounds, organics and high-T_c cuprates, is anomalous transport properties. Especially, when these materials are located in the vicinity of a quantum critical point (QCP), their transport coefficients show strong deviation from those of a Landau Fermi liquid [1,2], that describes conventional metals. For instance, in high-T_c cuprates, the normal state transport properties above the pseudogap temperature is quite unusual; resistivity exhibits a T linear dependence over a wide temperature range, the Hall angle θ_H varies as $\cot\theta_H \propto T^2$ [3], and the magnetoresistance (MR) displays a strong violation of the Kohler's rule [4]. It is generally believed that the abundance of low-lying spin fluctuations seriously modifies the quasiparticle masses and scattering cross-sections. As a result, a new excitation structure is developed and often gives rise to anomalous transport properties. Moreover, such excitations sometimes gives rise to unconventional superconductivity, in which Cooper pairs have angular momentum greater than zero [5]. Therefore, the clarification of their normal state transport properties is crucial to understand the mechanism of the novel superconductivity. However, despite extensive studies on non-Fermi liquid behavior near to QCPs, a lot of properties in the normal state remain unsolved. In particular, the role of the magnetic excitations in determining the transport properties is not clarified yet.

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Recently, the fascinating properties of the 2D heavy fermion $CeRIn_5$ (R = Co, Rh, Ir) have attracted a lot of attention following the discovery that the material is also a superconductor [6]. One of the most important features of the normal state is that it exhibits a pronounced non-Fermi liquid behavior owing to the materials proximity to an antiferromagnatic (AF) QCP: the electronic specific heat $\gamma = C/T \propto -\log T$, the uniform susceptibility $\chi_0 \propto 1/(T-\theta)$ [6] and NMR relaxation rate $(T_1T)^{-1} \propto T^{-3/4}$ [7,8] in contrast to T-independent Fermi liquid behavior. It should be noted that $CeCoIn_5$ has a resemblance to high-T_c cuprates; (1) its electronic structure is quasi-2D, (2) its superconducting gap symmetry most likely belongs to the d-wave class, and (3) a possible existence of a pseudogap has been suggested.

In this work, we report our measurements of transport coefficients for the quasi 2D HF superconductor $CeCoIn_5$ in the normal state, in the vicinity of QCP and in the superconducting state. We discuss the results of the Hall coefficient, thermal Hall coefficient, the Nernst coefficient, the electrical resistivity and thermal conductivity in terms of AF fluctuations, comparing them with those in high-T_c cuprates.

First, we discuss transport properties in the normal state. The inset of Fig. 1a shows the temperature dependence of the dc resistivity ρ_{xx}. With decreasing temperature, ρ_{xx} exhibits a slight increase, followed by a broad maximum around $T_{coh} \sim 40$ K. At low temperature below $T^* \sim 20$ K, ρ_{xx} displays an almost perfect T linear behavior in contrast to the T^2 dependence expected from Fermi liquid theory. On the other hand, as shown in Fig. 1a the Hall coefficient $R_H \equiv \frac{d\rho_{xy}}{dH}$ in the limit of $H \to 0$ is almost independent of T above T_{coh} and its magnitude is close to $R_H \sim 1/|ne|$. Below T^*, absolute value of R_H is strongly enhanced and becomes much larger than $1/|ne|$ [9,10]. The enhancement of $|R_H|$ is suppressed when the system approaches the Fermi liquid regime under pressure [10]. Moreover, we found that the Hall angle varies as $\cot\theta_H \equiv \frac{\rho_{xx}}{\rho_{xy}} \propto T^2$ as shown in Fig. 1b. The Hall angle in $CeCoIn_5$ bears a resemblance to that in high-T_c cuprates.

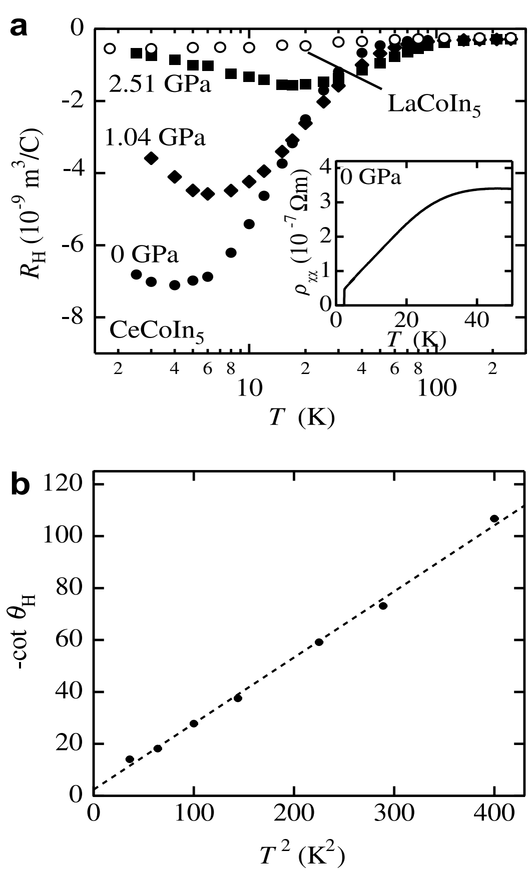

Fig. 1. (a) Temperature dependence of R_H of $CeCoIn_5$ under pressure and that of $LaCoIn_5$ and (b) $\cot\theta_H$ plotted as a function of T^2. The inset shows temperature dependence of ρ_{xx} at ambient pressure.

In ordinary HF systems, R_H is mostly positive and is much larger than $1/|ne|$ at high temperatures. After showing a maximum at slightly below T_{coh}, R_H decreases rapidly with decreasing T. The Hall coefficient in the ordinary HF system can be decomposed into two term; $R_H \equiv R_H^n + R_H^a$. Here, R_H^n is the ordinary Hall coefficient due to the Lorentz force and R_H^a is the so-called "anomalous Hall coefficient" due to skew scattering. The former term is almost independent of T while the latter has a strong T-dependence and is approximately proportional to the uniform susceptibility, $R_H^a \propto \chi_0\rho_{xx}$ or $\propto \chi_0$.

It is clear that the Hall coefficient of $CeCoIn_5$ is different from those in ordinary HF compounds; R_H at high $T > T_{coh}$ is nearly T independent with a very small value and is not scaled either by $\chi_0\rho_{xx}$ or by χ_0. This result indicates that R_H^a in $CeCoIn_5$ is negligibly small and that the T-dependence of R_H observed at low temperatures is mainly governed by R_H^n. It should be noted that a strongly T-dependent R_H^n is incompatible with a conventional Fermi liquid. Recently, it has been pointed out that the Fermi liquid approach should be significantly modified due to the backflow effect arising from strong electron correlations [11,12]. The strong enhancement of the Hall coefficient in $CeCoIn_5$ can be explained by the backflow effect.

Next, we discuss MR in $CeCoIn_5$. In an ordinary Fermi liquid metal, MR should obey Kohler's rule: $\Delta\rho(H) \propto \frac{H^2}{\rho_{xx}(0)}$. In Fig. 2a, $q \equiv \Delta\rho_{xx}(H)\rho_{xx}(0)/H^2$ is plotted as a function of T at various fields. This quantity is not constant either in T or in H, indicating a strong violation of Kohler's rule. It is pointed out in the standard AF spin fluctuation theory that the MR in the vicinity of a QCP is also strongly affected by the staggered susceptibility χ_Q, which depends on H and T, and Kohler's rule should be accordingly modified to $\frac{\Delta\rho_{xx}(H)}{\rho_{xx}(0)} \propto (\frac{\chi_Q H}{\rho_{xx}(0)})^2 \propto (\rho_{xx}(0)\sigma_{xy}(H))^2$ [11,12]. To examine the "modified" Kohler's rule, we plot the quantity $p \equiv \Delta\rho_{xx}(H)/\sigma_{xy}^2(H)\rho_{xx}^3(0)$ as a function of T. As shown in Fig. 2b, p is nearly constant below $T^* = 20$ K, providing strong support for the validity of the modified Kohler's rule. Thus one can conclude from this result that the AF spin fluctuations near to a QCP play an important role in determining the magnetoresistance.