Anomalous quasiparticle transport in the superconducting state of CeCoIn$_5$

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We report on a study of thermal Hall conductivity $\kappa_{xy}$ in the superconducting state of CeCoIn$_5$. The scaling relation and the density of states of the delocalized quasiparticles, both obtained from $\kappa_{xy}$, are consistent with $d$-wave superconducting symmetry. The onset of superconductivity is accompanied by a steep increase in the thermal Hall angle, pointing to a striking enhancement in the quasiparticle mean free path. This enhancement is drastically suppressed in a very weak magnetic field. These results highlight that CeCoIn$_5$ is unique among superconductors. A small Fermi energy, a large superconducting gap, a short coherence length, and a long mean free path all indicate that CeCoIn$_5$ is clearly in the superclean regime ($\varepsilon_F/\Delta < \ell/\xi$), in which peculiar vortex state is expected.

Five years after the discovery of superconductivity in CeCoIn$_5$ [1], this compound has become the focus of considerable attention. Indeed, CeCoIn$_5$ occupies a particular place among unconventional superconductors; it shares more features with high-$T_c$ cuprates than any other heavy-fermion (HF) superconductor. Most importantly, superconducting instability arises in the normal state that exhibits pronounced non-Fermi-liquid behavior due to the proximity of an antiferromagnetic (AFM) quantum critical point (QCP) [2]. Several measurements indicate that the superconducting gap has $d$-wave symmetry with line nodes perpendicular to the plane $\{100\}$.

CeCoIn$_5$ exhibits several fascinating properties, which have never been observed in any other superconductor. In a strong magnetic field, the superconducting transition is of the first order, indicating a field-induced destruction of the superconducting state by Pauli paramagnetism [1,3]. Closely related to this, the emergence of a spatially inhomogeneous Fulde-Ferrell-Larkin-Ovchinnikov superconducting state has been reported in the vicinity of the upper critical field $\delta H_{\text{c2}}$ [4]. Recent NMR spectra also have revealed an unusual electronic structure in the vortex core $\delta H_{\text{c2}}$ [5]. Moreover the observation of a QCP in the vicinity of the upper critical field $\delta H_{\text{c2}}$ for $H \parallel c$ suggests that superconductivity prevails, preventing the development of the AFM order $\delta H_{\text{AFM}}$ [6].

Another issue of interest is the increase in the quasiparticle (QP) lifetime below $T_c$, indicated by thermal conductivity $\kappa_{xx}$ and microwave experiments [7,8,9]. This feature of CeCoIn$_5$, reminiscent of very clean high-$T_c$ cuprates, is not observed in other HF superconductors. Thermal Hall conductivity $\kappa_{xy}$, the non-diagonal element of the thermal conductivity tensor in a perpendicular magnetic field, is a powerful probe of this feature; it is purely electronic and the direct consequence of a transverse QP current, while $\kappa_{xx}$ includes both electronic and phononic contributions. Over the past few years, the study of the thermal Hall effect in high-$T_c$ cuprates has opened a new window on QP transport [10,11,12,13,14,15].

In this Letter, we report on a study of longitudinal and transverse thermal conductivities of CeCoIn$_5$. The results highlight a steep increase in the QP mean free path $\ell$ directly inferred from the temperature dependence of the thermal Hall angle $\Theta \equiv \tan^{-1} \kappa_{xy}/\kappa_{xx}$. The magnitude of $\ell$ estimated in this way can be compared with that extracted from the QP thermal diffusivity (i.e. the ratio of thermal conductivity to specific heat) and confirms the unusually small Fermi energy $\varepsilon_F$ in CeCoIn$_5$. On the other hand, even a small magnetic field leads to a dramatic decrease in $\ell$. This phenomenon, yet to be understood, is unique to CeCoIn$_5$. We also found that $T$- and $H$-dependence of $\kappa_{xy}$ supports the $d$-wave symmetry.

Single crystals of CeCoIn$_5$ ($T_c = 2.3$ K) were grown by the self-flux method. Both $\kappa_{xx}$ and $\kappa_{xy}$ were measured by the steady-state method by applying the heat current along the $[100]$ direction with $q \parallel x$ for $H \parallel c$. The thermal gradients $-\nabla_x T \parallel x$ and $-\nabla_y T \parallel y$ were measured by RuO$_2$ thermometers. Above 0.4 K, no hysteresis was observed in sweeping $H$. The sign of $\kappa_{xy}$ is negative, as for the electrical Hall conductivity $\sigma_{xy}$.

The inset of Fig. 1 shows the $T$-dependence of $\kappa_{xx}/T$. In zero field, upon entering the superconducting state, $\kappa_{xx}/T$ display a kink and exhibits a pronounced maximum at $\sim 0.8$ K [2,3]. Figure 2 (a) depicts the $H$-dependence of $\kappa_{xx}$. Applying $H$, $\kappa_{xx}$ decreases up to $H_{\text{c2}}$ after showing an initial steep decrease. Figure 2(b) and the inset depict the $H$-dependence of $|\kappa_{xy}|$. A strong non-linear $H$-dependence is observed in $|\kappa_{xy}|$. Similar to $\kappa_{xx}$, the absolute slope of $|\kappa_{xy}|$ versus $H$ at high fields is reduced as the temperature is lowered. The transition to the normal state below $\sim 1$ K for both $\kappa_{xx}$ and $|\kappa_{xy}|$ is marked by a pronounced jump, indicating a first-order
Fig. 1: Temperature dependence of the thermal Hall conductivity divided by \( B \), \( |\kappa_{xy}|/B \). The zero field limit is obtained from the \( H \)-linear dependence of \( |\kappa_{xy}| \) at low field (see Fig. 3(a)). Inset: Temperature dependence of \( \kappa_{xx}/T \) in \( H \).

transition \[4\,\[5\]. (In CeCoIn\(_5\) the upper critical field determined by the orbital effect \( H_{c2}^{orb} \) is nearly 2.5 times larger than \( H_{c2} \); \( H_{c2}^{orb} \gtrsim 12 \, T \).)

At low fields, as shown in the inset of Fig. 2(b), \( |\kappa_{xy}| \) exhibits a steep increase with a linear dependence on \( H \). At \( T \lesssim 0.6 \, K \), \( |\kappa_{xy}| \) exhibits a prominent peak at \( \sim 0.06 \, T \). It should be noted that a similar peak structure in \( \kappa_{xy} \) has also been reported for ultraclean YBCO single crystals \[11\]. In Fig. 1, we plot the \( T \)-dependence of \( |\kappa_{xy}|/B \) and the initial Hall slope \( \kappa_{xy}^{(0)}/B \equiv \lim_{B \to 0} |\kappa_{xy}|/B \). The overall temperature dependence of \( |\kappa_{xy}^{(0)}/B \) is similar to \( \kappa_{xx} \); as the temperature falls below \( T_{c} \), it exhibits a pronounced maximum at \( \sim 1 \, K \). This behavior of \( |\kappa_{xy}^{(0)}/B \) again bears a striking resemblance to YBCO \[11\,\[12\].

Before discussing the QP transport, let us examine the validity of the “transverse” Wiedemann-Franz (WF) law. Just above \( T_{c} \), \( \kappa_{xy} \) and \( \sigma_{xy} \) yield a “transverse” Lorenz number very close to the expected WF value: \( L_{xy} = \lim_{B \to 0} \kappa_{xy}/\sigma_{xy}T \simeq 1.05 L_{0} \) (with \( L_{0} = 2.44 \times 10^{-8} \, \Omega \, \text{W/K} \)). This result confirms the purely electronic origin of \( \kappa_{xy} \) and conforms with reports for copper and the normal state of YBCO \[14\].

We next examine the scaling relation of \( \kappa_{xy} \) with respect to \( T \) and \( H \) proposed in Ref. \[13\]. A scaling relation of the single variable \( x = t/\sqrt{h} \) with \( t = T/T_{c} \) and \( h = H/H_{c2}^{orb} \) is derived as

\[
\kappa_{xy} \sim T^{2} F_{\kappa_{xy}}(x),
\]

where \( F(x) \) is a scaling function. As shown in Fig. 3, \( |\kappa_{xy}(T, H)|/H^{2} \) collapses into a common function of \( x \) at \( x \lesssim 0.07 \) at low temperatures within the error bar, suggesting a scaling relation, although not as prominent as in YBCO \[11\]. The present scaling relation provides further support for \( d \)-wave symmetry in CeCoIn\(_5\) \[15\].

At first glance, the field dependence of \( \kappa_{xx} \) does not look like what is expected for a nodal superconductor. In contrast to fully gapped superconductors, heat transport in nodal superconductors is dominated by contributions from delocalized QP states rather than bound states associated with vortex cores \[18\,\[20\,\[21\,\[22\,\[23\].

The most remarkable effect on the thermal transport is the Doppler shift of the QPs in the presence of supercurrents around vortices. Usually, this effect leads to \( \sqrt{H} \) increase in the population of delocalized QPs and a subsequent increase in \( \kappa_{xx}(H) \) that is nearly proportional to \( \sqrt{H} \), as experimentally observed in several unconventional superconductors. The field dependence of \( \kappa_{xx} \) observed for CeCoIn\(_5\) does not show this behavior. We will argue below, that this is a result of an increase of the DOS compensated by a reduction of the mean free path, both induced by the magnetic field.

The QP mean free path is directly provided by the thermal Hall angle in the weak field limit \( \omega_{c} \tau \ll 1 \),

\[
\tan \Theta \simeq \omega_{c} \tau \simeq \frac{eBt}{k_{F} \hbar},
\]

where \( \omega_{c} \) is the cyclotron frequency, \( k_{F} \) is the Fermi wave number. Figure 4 shows \( |\tan \Theta|/B \) at the zero field limit and at 5.2 T, slightly above \( H_{c2} \), as a function of \( T \), together with the electrical Hall angle \( |\tan \Theta_{e}| \equiv \sigma_{xy}/\sigma_{xx} \) divided by \( B \). The magnitude of \( |\tan \Theta|/B \) coincides well with that of \( |\tan \Theta_{e}|/B \) at the zero field limit, but at 5.2 T it is slightly larger. Below the coherence tem-
temperature, $T^* \approx 20$ K shown by the arrow in Fig. 4, the resistivity exhibits $T$-linear behavior. Below $T^*$, the cotangent of the electrical Hall angle for $B \to 0$ was reported to display a $T^2$ behavior, as shown by the dashed line, which represents $\lim_{B \to 0} \cot \Theta_c/B = a + bT^2$ with $a = 4.38$ T$^{-1}$ and $b = 0.20$ K$^{-2/3}$. Below $T_c$, $|\tan \Theta_c|/B$ increases much faster than the extrapolated temperature dependence observed above $T_c$. This enhancement of almost one order of magnitude is a direct evidence of a drastic increase in the QP mean free path below $T_c$. The inset of Fig. 4 shows the value of $\ell$ below $T_c$ using $k_F = 1.85 \times 10^9$ cm$^{-1}$. At $T = 0.46$ K, $\ell$ has a value of 1.6 $\mu$m.

An alternative way of estimating the QP mean free path is to use the well-known link between $\kappa_{xx}$ and the specific heat $C_v$: $\kappa_{xx} = \frac{1}{2} C_v \rho T \ell$. Now, at $T = 0.4$K, with $\kappa_{xx} = 0.48$ W/K and $C_v = 0.056$ J/K mol $^\circ$, if we take $\rho = 2130$ km/s (calculated using a Fermi energy, $\epsilon_F$, of 15K $^\circ$, and a mass enhancement of $m^* = 100m_e$ $^\circ$), the magnitude of $\ell$ of 1.1 $\mu$m is comparable to that yielded by $\tan \Theta_c/B$. This quantitative consistency also confirms the very low value of $\epsilon_F$ deduced from the temperature dependence of specific heat $^\circ$.

Figure 5 displays the field dependence of the QP mean free path at $T = 0.46$ K. As seen in the figure, the magnetic field dramatically suppresses the QP mean free path. Even at $H = 0.1$ T ($H/H_{c2}^{\circ} \lesssim 1/100$), $\ell$ is reduced by one order of magnitude. The inset of Fig. 5 shows the data on a log-log scale. For comparison, we plot the average distance between vortices $a_v = \sqrt{\Phi_0/E_B}$ by a dashed line. At low fields, the QP mean free path is several times longer than the intervortex distance, but becomes comparable with $a_v$ at higher fields. This strong variation in the QP mean free path with magnetic field appears to be the origin of the unexpectedly flat field dependence of $\kappa_{xx}$ discussed above. In order to check whether the DOS of the delocalized QPs, $N_{del}(E)$, displays the expected $\sqrt{H}$ dependence, we can use the conjectures $\kappa_{xx} \propto N_{del}(E)\ell$ and $|\kappa_{xy}|/(B\kappa_{xx}) \propto \ell$. Plotting $\kappa_{xx}^2 B/|\kappa_{xy}|$ as a function of $H$ reveals the field dependence of $N_{del}(E)$. As seen in the inset of Fig. 3, this ratio displays a field-dependence close to the $\sqrt{H}$ behavior expected for a $d$-wave superconductor.

The strong field dependence of $\ell$ is a feature that is not yet understood. There are two lines of thought to understand the QP transport. It has been argued that low energy QPs in a periodic vortex lattice are described by Bloch wavefunctions and are not scattered $^\circ$. In contrast, in a strongly disordered vortex lattice, QP scattering is caused by Andreev scattering on the velocity field associated with the vortices. In this case, the QP mean free path is proportional to $a_v$. This argument was used to explain the ”plateau” in $\kappa_{xx}(H)$ observed in Bi2212, in which the vortex lattice is strongly distorted $^\circ$. However, as indicated by small angle neutron scattering experiments $^\circ$, there is no reason to assume that the vortex lattice in clean CeCoIn$_5$ is strongly distorted.

The initial decrease of $\ell$ at low fields may be explained without invoking vortex scattering. At very low fields, where the condition $\sqrt{H/H_{c2}^{\circ}} < T/T_c$ is satisfied, thermally excited QPs dominate over Doppler shifted QPs. It has been shown that in this regime the DOS enhanced by the Doppler shift leads to a suppression of the impurity scattering time $^\circ$. It is yet to be seen if this can explain the magnitude of the decrease observed
at very low fields. It does not seem to be relevant to the 
$H$-dependence of $\ell$ at higher fields.

Although $\sqrt{H}$-dependent term in $\ell$ in a nearly peri-
odic vortex lattice has been argued in Ref. [22], it is open 
question whether any deviation of the vortex from the 
perfect arrangement of the vortex lattice in principle pro-
duces significant effects. Several peculiarities of CeCoIn$_5$
may lead to unusual vortex-QP scattering. In fact, the
very strong suppression of $\ell$ up to $H_c2$ has never been ob-
served in any other superconductors, including UPd$_2$Al$_3$
[27] and YNi$_2$B$_2$C [28] with similar $H_c2$ values. One is the 
possible existence of antiferromagnetism in vortex cores.
Several experiments indicate that the AFM phase is su-
peredced by the superconducting transition [10]. This in 
turn suggests that the AFM correlation is strongly en-
chanced in the region around vortex cores [4]. In this 
case the QPs may be significantly scattered by the AFM 
fluctuation in the core region. Further investigation is
strongly required to clarify the origin of the peculiar QP 
transport in CeCoIn$_5$.

Another feature to be considered is the energy scale of 
the QP spectrum in the vortex core set by the confine-
ment energy $\hbar\omega_0 \sim \Delta^2/\varepsilon_F$. For most superconductors,
this energy level is negligibly small. For CeCoIn$_5$ how-
ever, $\varepsilon_F \sim 15$ K and $\Delta \sim 5$ K, so that $\hbar\omega_0 \sim 1.5$ K and 
the vortex spectrum becomes important at low tempera-
tures. Moreover, when a vortex moves, energy dissipation 
is produced by the scattering of QPs within the vortex 
core. If the broadening of the QP states $(\hbar/\tau)\sim 1$ turns out 
to be much smaller than the energy scale of the spectrum 
within the core, $\omega_0\tau \gg 1$, the vortex system enters a new 
regime (the superclean regime) that is difficult to access 
in most superconductors. The superclean condition is equiva-
lent to $\ell/\xi \gg \varepsilon_F/\Delta$. In CeCoIn$_5$, $\ell \sim 1 \mu$m and 
$\xi \sim 5$ nm yields $\ell/\xi \sim 200$ at low fields, which is much 
larger than $\varepsilon_F/\Delta \sim 3$. This is in sharp contrast to other 
superconductors in which $\ell/\xi \ll \varepsilon_F/\Delta$.

In the super-
clean regime, strong enhancement of the vortex viscosity, 
which leads to anomalous vortex dynamics including an 
 extremely large vortex Hall angle, is expected [32].

To conclude, we have measured the thermal Hall an-
gle of CeCoIn$_5$ and found that it indicates a dramatic 
increase in the quasiparticle mean free path below $T_c$. In 
spite of the presence of a periodic vortex lattice, this en-
hancement is easily suppressed by a weak magnetic field.
These results highlight that CeCoIn$_5$ is unique among 
superconductors. We found that $\kappa_{xy}$ displays the scal-
ning relation expected for $d$-wave symmetry. Moreover 
the DOS of the delocalized quasiparticles obtained from 
the thermal Hall conductivity, are consistent with $d$-wave 
symmetry. Finally, the results indicate that CeCoIn$_5$ is 
in the superclean regime.

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