Anomalous quasiparticle transport in the superconducting state of $CeCoIn_5$

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We report on a study of thermal Hall conductivity κ_{xy} in the superconducting state of $CeCoIn_5$. The scaling relation and the density of states of the delocalized quasiparticles, both obtained from κ_{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 ($\varepsilon_F/\Delta \ll \ell/\xi$), in which a peculiar vortex state is expected.

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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, which is believed to be 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.[3–8]

$CeCoIn_5$ 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.[4,9] Closely related to this, the emergence of a spatially inhomogeneous Fulde-Ferrel-Larkin-Ovchinnikov superconducting state has been reported in the vicinity of the upper critical field.[10–13] Recent NMR spectra also have revealed an unusual electronic structure in the vortex core.[13] Moreover, the observation of a QCP in the vicinity of the upper critical field H_{c2} for $H \parallel c$ suggests that superconductivity prevails, preventing the development of the AFM order.[14,15]

Another issue of interest is the increase in the quasiparticle (QP) lifetime below T_c, indicated by thermal conductivity κ_{xx} and microwave experiments.[3,4,6] This feature of $CeCoIn_5$, reminiscent of very clean high-T_c cuprates, is not observed in other HF superconductors. Thermal Hall conductivity κ_{xy}, the nondiagonal 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 κ_{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 another window on QP transport.[16–21]

Here, 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 ℓ directly inferred from the temperature dependence of the thermal Hall angle $\Theta \equiv \tan^{-1}\kappa_{xy}/\kappa_{xx}$. The magnitude of ℓ estimated in this way can be compared to that extracted from the QP thermal diffusivity (i.e., the ratio of thermal conductivity to specific heat) and confirms the unusually small Fermi energy ε_F in $CeCoIn_5$. On the other hand, even a small magnetic field leads to a dramatic decrease in ℓ. This phenomenon, yet to be understood, is unique to $CeCoIn_5$ and ultraclean $YBa_2Cu_3O_7$.[22] We also found that T and H dependence of κ_{xy} supports the d-wave symmetry.

Single crystals of $CeCoIn_5$ (T_c=2.3 K) were grown by the self-flux method. Both κ_{xx} and κ_{xy} were measured in the same crystal by the steady-state method by applying the heat current along the [100] direction with $\boldsymbol{q} \parallel \boldsymbol{x}$ for $\boldsymbol{H} \parallel \boldsymbol{c}$. The thermal gradients $-\nabla_x T \parallel \boldsymbol{x}$ and $-\nabla_y T \parallel \boldsymbol{y}$ were measured by RuO_2 thermometers. Above 0.4 K, no hysteresis was observed in sweeping H.[23] The sign of κ_{xy} is negative, as for the electrical Hall conductivity σ_{xy}.

The inset of Fig. 1 shows the T dependence of κ_{xx}/T. In zero field, upon entering the superconducting state, κ_{xx}/T display a kink and exhibits a pronounced maximum at ~0.8 K.[3,4] Figure 2(a) depicts the H dependence of κ_{xx}. Applying H, κ_{xx} decreases up to H_{c2} after showing an initial steep decrease. Figure 2(b) and the inset depict the H dependence of $|\kappa_{xy}|$. A strong nonlinear H dependence is observed in $|\kappa_{xy}|$. Similar to κ_{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 ~1 K for both κ_{xx} and $|\kappa_{xy}|$ is marked by a pronounced jump, indicating a first-order transition.[4,9] (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

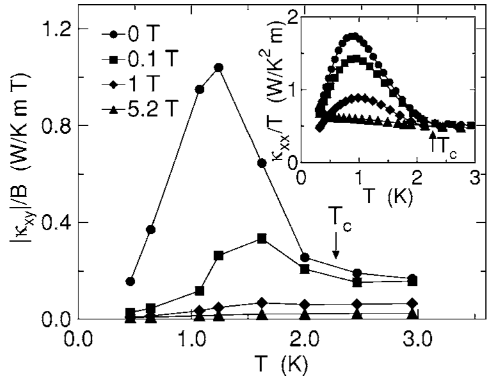

FIG. 1. Temperature dependence of the thermal Hall conductivity divided by $B, |\kappa_{xy}|/B$. The zero-field limit is obtained from the H-linear dependence of $|\kappa_{xy}|$ at low field [see Fig. 3(a)]. Inset: Temperature dependence of the thermal conductivity divided by T, κ_{xx}/T.

$T \leqslant 0.64$ K, $|\kappa_{xy}|$ exhibits a prominent peak at ~ 0.06 T. It should be noted that a similar peak structure in κ_{xy} has also been reported for ultraclean YBCO single crystals.[16] 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 κ_{xx}; as the temperature falls below T_c, it exhibits a pronounced maximum at ~ 1 K. This behavior of $|\kappa_{xy}^0|/B$ again bears a striking resemblance to YBCO.[16,17]

Before discussing the QP transport, let us examine the validity of the "transverse" Wiedemann-Franz (WF) law. Just

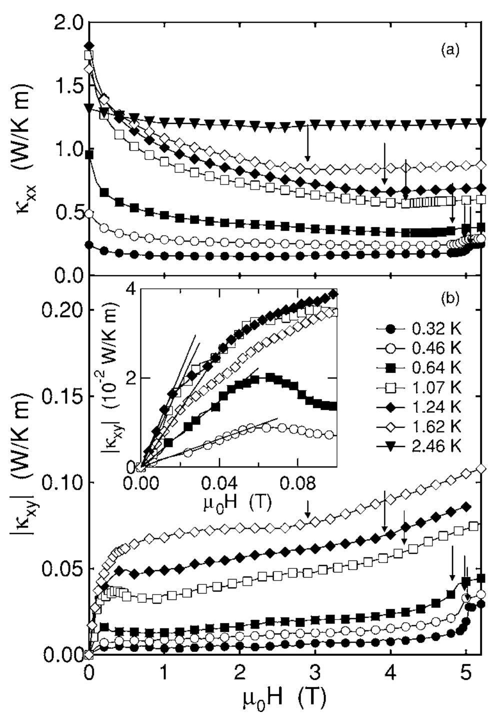

FIG. 2. (a) Field dependence of thermal conductivity κ_{xx}. Arrows indicate H_{c2} determined by resistivity measurements. (b) The same data for the thermal Hall conductivity $|\kappa_{xy}|$. Inset: Thermal Hall conductivity in the low field regime. Thin solid lines represent the initial Hall slope.

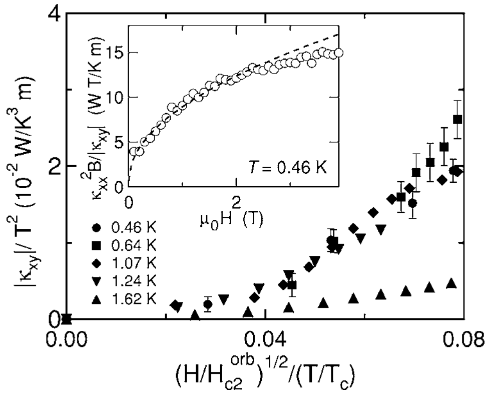

FIG. 3. Scaling plot κ_{xy}/T^2 vs $x=\sqrt{H/H_{c2}^{\mathrm{orb}}}/(T/T_c)$. We used $H_{c2}^{\mathrm{orb}}=12$ T. The data collapse into the same curve at low temperatures. Inset: Field dependence of $\kappa_{xx}^2 B/|\kappa_{xy}|$, which is proportional to the DOS of the delocalized QPs $N_{\mathrm{del}}(E)$ at 0.46 K. The dashed line indicates $\sqrt{H}$ dependence.

above T_c, κ_{xy} and σ_{xy} yield a transverse Lorenz number very close to the expected WF value: $L_{xy}=\lim_{B\to 0}\kappa_{xy}/\sigma_{xy}T \simeq 1.05L_0$ (with $L_0=2.44\times 10^{-8}$ ΩW/K). This result confirms the purely electronic origin of κ_{xy} and conforms with reports for copper and the normal state of YBCO.[19]

We next examine the scaling relation of κ_{xy} with respect to T and H proposed in Ref. 18. A scaling relation of the single variable $x=\sqrt{h}/t$ with $h=H/H_{c2}^{\mathrm{orb}}$ and $t=T/T_c$ is derived as

$$\kappa_{xy} \sim T^2 F_{\kappa_{xy}}(x), \tag{1}$$

where $F(x)$ is a scaling function. As shown in Fig. 3, $|\kappa_{xy}(T,H)|/T^2$ 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.[16] The present scaling relation provides further support for d-wave symmetry in $CeCoIn_5$.[24]

At first glance, the field dependence of κ_{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.[25–29] 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 a $\sqrt{H}$ 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 κ_{xx} observed for $CeCoIn_5$ does not show this behavior. We will argue later that this is a result of an increase of the density of state (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 $\omega_c\tau \ll 1$,

$$\tan\Theta \simeq \omega_c\tau \simeq \frac{eB\ell}{k_F\hbar}, \tag{2}$$

where ω_c is the cyclotron frequency and k_F is the Fermi wave number. Figure 4 shows $|\tan\Theta|/B$ at the zero-field

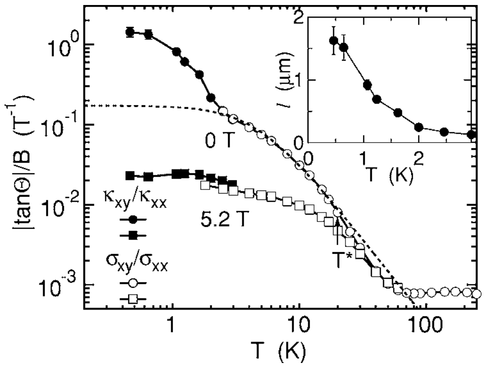

FIG. 4. Temperature dependence of thermal Hall angle (● and ■), $\tan\Theta \equiv \kappa_{xy}/\kappa_{xx}$, and electrical Hall angle (○ and □), $\tan\Theta_e \equiv \sigma_{xy}/\sigma_{xx}$, divided by B in zero-field limit and in the normal state at 5.2 T. The dashed line represents the relation $\lim_{B\to 0}|\cot\Theta_e|/B=a+bT^2$. T^* is the coherence temperature. See text for details. Inset: Temperature dependence of the QP mean free path ℓ in zero field estimated from the thermal Hall angle [Eq. (2)].

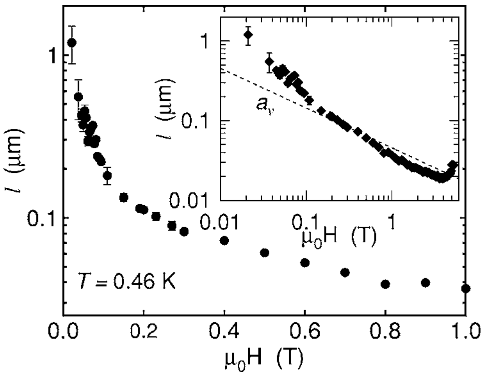

FIG. 5. Field dependence of the QP mean free path estimated from the thermal Hall angle below $H=1$ T at $T=0.46$ K. Inset: The same data up to H_{c2} plotted on a log-log scale. The dashed line represents the average vortex distance $a_v=\sqrt{\Phi_0/H}$.

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 temperature $T^* \simeq 20$ K, shown by the arrow in Fig. 4, the resisitivity 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 $\lim_{B\to 0}|\cot\Theta_e|/B=a+bT^2$ with $a=4.38$ T^{-1} and $b=0.20$ K^{-2}T^{-1}.[30] Below T_c, $|\tan\Theta|/B$ increases much faster than the extrapolated temperature dependence observed above T_c. This enhancement of almost one order of magnitude is direct evidence of a drastic increase in the QP mean free path below T_c. The inset of Fig. 4 shows the value of ℓ below T_c using $k_F=1.85\times 10^9$ cm^{-1}. At $T=0.46$ K, ℓ has a value of 1.6 μm.

An alternative way of estimating the QP mean free path is to use the well-known link between κ_{xx} and the specific heat C_e: $\kappa_{xx}=\frac{1}{3}C_e v_F \ell$. Now, at $T=0.4$ K, with $\kappa_{xx}=0.48$ W/K m and $C_e=0.056$ J/K mol^3, if we take $v_F=2130$ km/s (calculated using a Fermi energy[31] ϵ_F of 15 K and a mass enhancement[32] of $m^*=100m_e$ at H_{c2}), the magnitude of ℓ of 1.1 μm is comparable to that yielded by $\tan\Theta/B$. This quantitative consistency also confirms the very low value of ϵ_F deduced from the temperature dependence of specific heat.[31]

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$(H/H_{c2}^{\rm orb}\lesssim 1/100)$, ℓ 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 $a_v=\sqrt{\Phi_0/B}$ by a dashed line. At low fields, the QP mean free path is several times longer than the intervortex distance, but becomes comparable to 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 κ_{xx} discussed above. In order to check whether the DOS of the *delocalized* QPs, $N_{\rm del}(E)$, displays the expected $\sqrt{H}$ dependence, we can use the conjectures $\kappa_{xx}\propto N_{\rm del}(E)\ell$ 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 $N_{\rm del}(E)$. 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. We note that $\sqrt{H}$ dependence expected in d-wave is not observed in the heat capacity measurements.[5] This may be because that localized QPs within vortex cores also contributes to the heat capacity. As reported by NMR measurements, the vortex core of $CeCoIn_5$ is not in an usual metallic state.[13] Since $\sqrt{H}$ behavior is clearly observed in $N_{\rm del}(E)$, the discrepancy between the gap symmetry inferred from the angle resolved thermal conductivity[4] and heat capacity[5] may be due to the localized QPs within the vortex core.

The strong field dependence of ℓ 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 wave functions and are not scattered.[33] 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.[29,34,35] However, as indicated by small angle neutron-scattering experiments,[36] there is no reason to assume that the vortex lattice in clean $CeCoIn_5$ is strongly distorted.

The initial decrease of ℓ at low fields may be explained without invoking vortex scattering. At very low fields, where the condition $\sqrt{H/H_{c2}^{\rm orb}}<T/T_c$ 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.[25–28] 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 ℓ at higher fields.

Although the $\sqrt{H}$-dependent term in ℓ in a nearly periodic vortex lattice has been argued in Ref. 28, it is an open question whether any deviation of the vortex from the perfect arrangement of the vortex lattice, in principle, produces significant effects. Several peculiarities of $CeCoIn_5$ may lead to unusual vortex-QP scattering. In fact, the very strong suppression of ℓ up to H_{c2}, which is nearly half of $H_{c2}^{\rm orb}$, has never been observed in any other superconductors, including UPd_2Al_3 (Ref. 37) and YNi_2B_2C (Ref. 38) with similar H_{c2} values. One is the possible existence of antiferromagnetism in vortex cores. Several experiments indicate that the AFM phase is superseded by the superconducting transition.[14,15] This, in turn, suggests that the AFM correlation is strongly enhanced in the region around vortex cores.[13,39] 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 confinement energy $\hbar\omega_0 \sim \Delta^2/\varepsilon_F$. For most superconductors, this energy level is negligibly small. For $CeCoIn_5$, however, $\varepsilon_F \sim 15$ K and $\Delta \sim 5$ K, so that $\hbar\omega_0 \sim 1.5$ K and the vortex spectrum becomes important at low temperatures. 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 ($\hbar/\tau$) 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 equivalent to $\ell/\xi \gg \varepsilon_F/\Delta$. In $CeCoIn_5$, $\ell \sim 1$ μm 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 superclean regime, strong enhancement of the vortex viscosity, which leads to anomalous vortex dynamics including an extremely large vortex Hall angle, is expected.[40,41]

To conclude, we have measured the thermal Hall angle 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 enhancement is easily suppressed by a weak magnetic field. These results highlight that $CeCoIn_5$ is unique among superconductors. We found that κ_{xy} displays the scaling 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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