Thermal-Hall conductivity and long-lived quasiparticles in CeCoIn$_5$

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Abstract

In CeCoIn$_5$, the thermal conductivity κ_{xx} and Hall conductivity κ_{xy} below T_c display large anomalies below T_c. The strong suppression of the anomalies in weak fields implies the existence of long-lived quasiparticles. We also discuss briefly the Wiedemann-Franz ratio and the existence of a strongly field-dependent spin-fluctuation heat current.

Key words: quasi-particles, heavy fermion, thermal Hall effect
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The heavy fermion system CeCoIn$_5$ displays several interesting properties in its superconducting state. These include the FFLO state in an in-plane magnetic field **H** [1], a large Nernst signal observed at temperatures $T < 30$ K [2], an in-plane resistivity that is T-linear below 20 K, and a Hall coefficient that is strongly T dependent [3]. Recently, Kasahara et al. [4] measured the thermal conductivity $\kappa_{xx}(T, H) = \kappa(T, H)$ and thermal Hall conductivity κ_{xy} and inferred a long quasiparticle (qp) mean-free-path ℓ below $T_c = 2.2$ K.

We report measurements of κ_{ij} in crystals of CeCoIn$_5$ with exceptionally long ℓ. Figure 1a shows $\kappa(T, 0)$ at H=0. Below T_c, $\kappa(T, 0)$ rises steeply to a prominent peak at 1 K, reminiscent of the peak in high-purity YBCO [5]. As shown in Fig. 1b, the peak anomaly – 4-5 times larger than in Ref. [4] – is extremely sensitive to $\mathbf{H}||\mathbf{c}$. Above T_c, the curve of κ displays moderately strong field dependence. Below T_c, however, a sharp quasiparticle peak develops at $H = 0$ and rises rapidly. The narrow spike in κ which reflects the strong suppression of the qp heat current in weak fields. The narrow spike is absent in earlier experiments [4]. In the normal state above the upper critical field H_{c2} (indicated by the step increase), κ remains strongly H dependent.

The thermal Hall conductivity κ_{xy} detects the qp heat current of alone. Above 20 K, κ_{xy} is nearly H-linear to 12 T, as expected of weak-field Hall response. As T falls towards T_c, strong curvature becomes evident below 1 T, while the initial Hall slope increases sharply. Between T_c and 0.5 K, a new anomaly appears in weak H which is the Hall analog of the narrow spike in κ. In weak H, κ_{xy} rises very steeply to a peak centered at 0.1–0.2 T before falling to a “plateau” value. Above H_{c2}, κ_{xy} increases steeply once more to large values.

The unusual behavior of κ and κ_{xy} reveal several interesting low-T features in both the vortex state and the state above H_{c2} at low T. Below T_c, the strong sensitivity of κ and κ_{xy} to weak H shows that the large thermal anomaly shown in Fig. 1a is entirely electronic in origin. It reflects the steep increase in ℓ below T_c. Moreover, the persistence of a large κ_{xy} far below T_c requires a sizeable qp population, which implies the existence of line nodes on the Fermi Surface. This was previously inferred from the 4-fold variation of κ and the heat capacity c_p with field angle [6,7] in crystals with higher degree of disorder.

The curves of κ_{xy}/T below T_c (Fig. 2) show that the qp behavior is qualitatively distinct in

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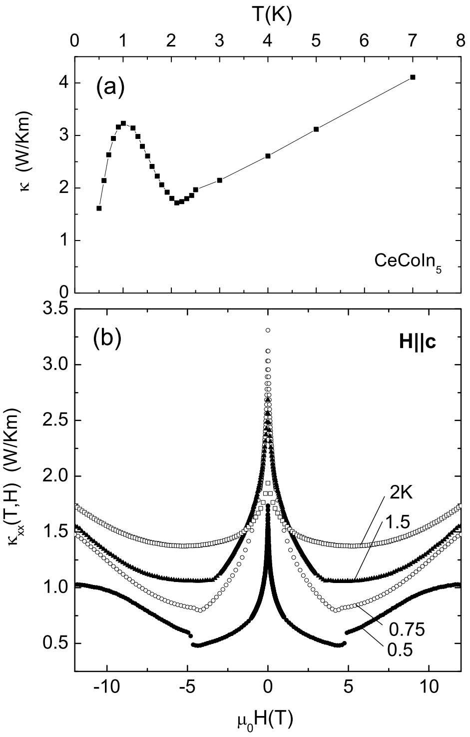

Fig. 1. (Panel a) The T dependence of the in-plane thermal conductivity κ in $H = 0$ in CeCoIn$_5$. The anomaly below T_c is 4–5 times larger than in earlier reports. (Panel b) The field dependence of κ at selected T below T_c. With decreasing T, the zero-field anomaly rises to a sharp, narrow peak. At H_{c2}, κ displays a kink or step.

the vortex-solid state below $H_{c2} \sim 5$ T, and in the normal state above. In the former, κ_{xy}/T assumes a profile that is T independent below 1 K. Interestingly, at the lowest temperatures (0.5–1 K) the value of κ_{xy}/T is independent of T to within the experimental uncertainty. After going through the weak-field peak, the curve settles into a nearly flat portion that extends to 4 T, before rising vertically at H_{c2}. By contrast, the strong field variation of κ_{xy}/T above H_{c2} is striking. In particular, the curvature just above H_{c2} is quite pronounced. These features imply that the scattering rate Γ is strongly suppressed by H, resulting in a significant increase in ℓ.

From the measured Hall conductivity σ_{xy} and κ_{xy} we may find the Wiedemann-Franz ratio [8]. The Lorenz number L is found to lie within 10% of the Sommerfeld value $L = \pi^2/3(k_B/e)^2$. Knowing L at each T above T_c, we infer the qp thermal conductivity $\kappa_e(T,H)$ from the measured conductivity $\sigma = \sigma_{xx}$. Subtracting $\kappa_e(T,H)$ from the observed $\kappa(T,H)$, we find a remaining term that is strongly H dependent even high above T_c. We identify this term with the thermal conductivity $\kappa_s(T,H)$ due to spin fluctuations (the phonon conductivity $\kappa_{ph}(T)$ is H independent). At low T, $\kappa_s(T,H)$ accounts for most of the non-qp heat current.

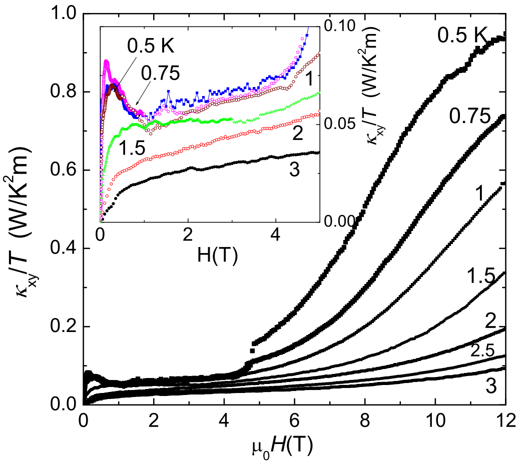

Fig. 2. Curves of the thermal Hall conductivity (divided by T) κ_{xy}/T vs. H. Below 1 K, κ_{xy}/T saturates to a T-independent profile with a prominent anomaly in weak H (inset). At low T, κ_{xy}/T sharply increases above H_{c2} (step feature).

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References

[1] H. A. Radovan et al., Nature 425, 51 (2003). A. Bianchi, et al., Phys. Rev. Lett. 91, 187004 (2003). K. Kakuyanagi et al., Phys. Rev. Lett. 94, 047602 (2005).

[2] R. Bel et al., Phys. Rev. Lett. 92, 217002 (2004).

[3] Y. Nakajima et al., J. Phys. Soc. Jpn. 73, 5 (2004).

[4] Y. Kasahara et al., Phys. Rev. B **72**, 214515 (2005).

[5] Y. Zhang et al., Phys. Rev. Lett. **86**, 890 (2001).

[6] H. Aoki et al., J. Phys. Condensed Matter 16, L13 (2004).

[7] R. Movshovich et al., Phys. Rev. Lett. 86, 5152 (2001).

[8] Y. Zhang et al., Phys. Rev. Lett. **84**, 2219 (2000).