Multigap Superconductivity in the Heavy-Fermion System $CeCoIn_5$

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New thermal conductivity experiments on the heavy-fermion superconductor $CeCoIn_5$ down to 10 mK rule out the suggested existence of unpaired electrons. Moreover, they reveal strong multigap effects with a remarkably low "critical" field H_{c2}^S for the small gap band, showing that the complexity of heavy-fermion band structure has a direct impact on their response under magnetic field.

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Heavy-fermion (HF) superconductors are largely studied for the rich variety of their unconventional ground states. Recently, the question of "multigap superconductivity" has emerged in these systems, both to account for some unusual features observed in their excitation spectrum and for the properties of their mixed phase [1–11]. Indeed, these compounds are known to have a complex Fermi surface (FS), with unequal weight of the f character among the various sheets [12,13]. Hence mass renormalization (density of states) may vary by more than an order of magnitude [12] among the different sheets, and so may inter- and intraband coupling strength. Ingredients for multigap superconductivity are therefore present, leaving for experiments to probe whether they survive impurity scattering and interband interactions.

Relevant experiments are those sensitive to the temperature or field dependence of the excitation spectrum: a multigap superconductor has a kind of multicomponent order parameter, with different amplitudes of this order parameter among the various FS sheets. This leads to the presence of a small gap on the most weakly coupled bands, and so to an enhanced low energy excitation spectrum. But a multigap superconductor also has, in addition to the upper critical field H_{c2}, a smaller field scale H_{c2}^S, because in the mixed state the superconducting order parameter is basically suppressed in the weakly coupled bands for fields below H_{c2} (vortex core overlap in the small gap band above H_{c2}^S). This second effect is particularly strong in HF systems, since small gap bands are also light bands (of weak f character) [3,5]: both the small gap Δ_0^S and the large Fermi velocity v_F^S contribute to the enhancement of the associated effective coherence length $\xi_0^S \approx \hbar v_F^S/\Delta_0^S$, and so to the large ratio (index L represents the large gap band) [14]

$$H_{c2}/H_{c2}^S \sim \left(\frac{\Delta^L v_F^S}{\Delta^S v_F^L}\right)^2. \tag{1}$$

In this Letter, we discuss thermal conductivity $\kappa(T, H)$ results on the 115 compound $CeCoIn_5$. It is until now the HF superconductor with the highest T_c at ambient pressure [15], with the still puzzling property of a quantum critical point at or very close to H_{c2} [16,17]. A particular interest of thermal transport in the case of HF superconductors, underlined by recent studies on multigap properties [3–5] is that it is not sensitive to mass renormalization, so that the contribution of the bands with light masses (and small gap) has equal weight than those with heavy masses (and large gap): the same studies on specific heat or nuclear relaxation time T_1 for example would probably miss the multigap effects due to the negligible contribution of the light carrier bands. The main outcome of our study is the existence of a very low field scale $H_{c2}^S \sim H_{c2}/1000$, which was overlooked by previous studies [4,18–21], mostly concentrating on the properties around the quantum critical point or the FFLO phase at higher fields. Moreover, the achievement of measurements down to lower temperatures (10 instead of 50 mK in [4]) not only rules out the claim of the existence of unpaired electrons [4], it also allows a new qualitative analysis of the zero field temperature dependence of κ, which, like the very small field scale, strongly supports a multigap scenario [7,8,10,11].

In such a clean system, transport experiments at very low temperatures are challenging owing to the very large thermal conductivity. Indeed, contact resistances may imply a large temperature gradient between the sample and the cold point of the fridge, when forcing a temperature gradient within the sample. Then, small heat leaks through the thermometers (for example) may induce sizable mistakes on the measured values. It may explain the large dispersion of results from the literature. We restrict the comparison of our results to those of Tanatar *et al.* [4], who checked the Wiedemann-Franz (WF) law, hence dismissing important experimental problems.

The $\kappa(T, H)$ measurements have been performed on a dilution fridge by a standard two-thermometers-one heater steady-state method down to 10 mK in zero or low field, and down to 30 mK up to 6 T. The heat current is always aligned along the a axis (in-plane transport) of the single crystal (dimensions $\sim 2.1 \times 0.13 \times 0.14$ mm^3), and the magnetic field is applied either parallel to the heat current or along the c axis (perpendicular to the heat current). The carbon thermometers are thermalized on the sample by gold wires, held by silver paint on gold stripes evaporated on the surface of the sample after ion gun etching. The gold stripes are essential for the stability and the quality of the electrical contacts (resistance $R_c^e \approx 30$ mΩ at 4 K [5]), and even more important for reliable thermal contacts between the sample and the thermometers. The thermal resistance of these contacts obeys the WF law at low temperatures [5]. The thermal resistance of the Kevlar fibers isolating the thermometers against the fridge is about 3 orders of magnitude higher. The same contacts and gold wires were used to measure the electric resistivity ρ of the sample by a standard four-point lock-in technique.

Sample quality has been characterized by specific heat (Fig. 1): the onset ($T_c \approx 2.3$ K) of the sharp superconducting specific heat jump ($\approx$0.04 K wide) corresponds to the upturn in $\kappa(T)/T$, and to zero electric resistance. Further, we find $\rho(300\text{ K})/\rho(T_c, 0\text{ T}) \sim 6$ and $\rho(300\text{ K})/\rho(T \to 0, 6\text{ T}) \sim 96$.

Figure 2(a) shows the temperature dependence of κ/T in zero field and in the normal phase (under a magnetic field of 6 T), the WF law being satisfied only below 100 mK [see Fig. 2(b)]. Our data roughly correspond to the earlier report in [4], except at very low temperatures [see Fig. 2(c)]: at $T = 10$ mK, we find $\kappa(T)/T \approx 0.7$ W K^{-2} m^{-1} and extrapolate (linearly for $T \to 0$) to any value below 0.3 W K^{-2} m^{-1}, which is far lower than 1.7 W K^{-2} m^{-1}, extrapolated in [4] (lowest measurement at 50 mK). This difference in the very low temperature results leads to distinct conclusions on the nature of the superconducting state in $CeCoIn_5$ (see below). An experimental reason for this discrepancy might be the use of indium solder in [4], which leads to very good electric, but bad thermal contacts (in zero field) when indium becomes superconducting.

It is remarkable that even at 10 mK ($T/T_c \approx 4.3 \times 10^{-3}$), $\kappa(T)/T$ remains larger than its value at T_c [Fig. 2(a)]. Of course, a key factor is the dominant role of inelastic scattering at T_c, which strongly limits the normal state thermal conductivity. Upon entry in the superconducting state, this strong inelastic scattering is rapidly suppressed, leading to the observed large increase of $\kappa(T)/T$ just below T_c [Fig. 2(a)]. So the low temperature value of $\kappa(T)/T$ should be compared not to the value at T_c, but to what would be the normal state value [$\kappa_n(0)$] at $T \to 0$ without superconductivity. As the WF law is valid at very low temperature [Fig. 2(b)], we used resistivity and thermal conductivity data under field to estimate this value. At T_c, the resistivity is governed mainly by the inelastic term, and magnetoresistance between 0 and 6 T is of the order of only 30% (data not shown here). Below 100 mK, magnetoresistance yields a stronger effect, since ρ decreases by a factor of $\sim$1.5 between H_{c2} and $H \to 0$ if one extrapolates a H^2 fit of $\rho(H > H_{c2})$ data. Hence a conservative estimate of the "maximum" value of $\kappa_n(0)/T$ would be twice the value measured at 6 T, and so about 10 W K^{-2} m^{-1}. With the value of in-plane Fermi velocity $v_F \approx 7500$ ms^{-1}

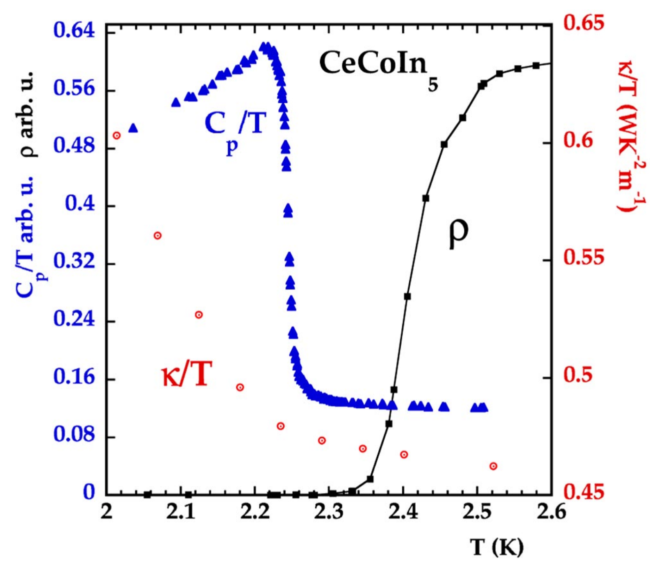

FIG. 1 (color online). Specific heat $C_p(T)/T$, electric resistivity $\rho(T)$, and thermal conductivity $\kappa(T)/T$ in zero field around T_c. The small width (0.04 K) of the specific heat jump and the coincidence with the upturn in $\kappa(T)/T$ document the good sample quality. As common in the 115 compounds, the resistive transition (midheight) lies about 10% higher.

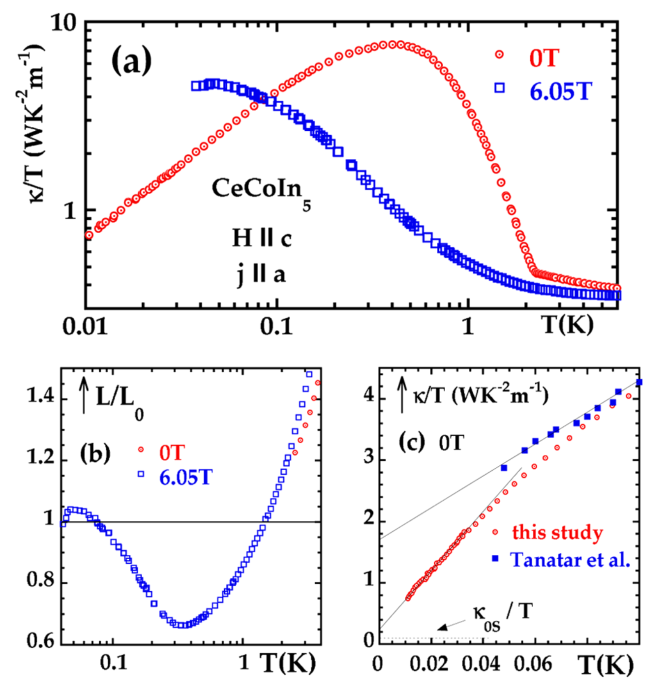

FIG. 2 (color online). (a) Thermal conductivity $\kappa(T)/T$ of $CeCoIn_5$ across its superconducting transition at $T_c = 2.3$ K, down to 10 mK. A huge increase is observed below T_c in zero field, owing to the suppression of inelastic scattering. The data at 6 T give a normal state behavior, but they include the effect of the strong positive magnetoresistance. (b) Normalized Lorenz number $L(T)/L_0$, which approaches 1 (within 5%) below 0.1 K at 6 T. (c) Comparison of our very low temperature results in zero field with those of Tanatar *et al.* [4]. The dotted line marked "κ_{0S}/T" corresponds to the universal limit [4].

(from H_{c2} [22]), and a specific heat Sommerfeld coefficient for $T \rightarrow 0$ of $C_p/T \approx 1\ \mathrm{J\,mol^{-1}\,K^{-2}} \approx 10^4\ \mathrm{J\,K^{-2}\,m^{-3}}$, we get from the simple kinetic formula $\kappa = 1/3 C_p v_F l$ a mean free path $l \approx 0.4\ \mu\mathrm{m}$, a reasonable value for this system (in the isostructural compound $CeIrIn_5$, mean free path as measured by the Dingle temperature extracted from quantum oscillation measurements of the FS for fields above 9 T ranges from 0.06 to 0.45 μm [23]).

With this value of $\kappa_n(0)/T$, we can see that at 0.1 K ($0.043T_c$), κ/T is at most 0.5 $\kappa_n(0)/T$. At 10 mK ($0.0043T_c$), where it is still far above the estimated universal limit [4] and still displays a strong temperature dependence, κ/T is still $0.07\kappa_n(0)/T$. By comparison, for UPt_3, which is a reference unconventional superconductor with a hybrid gap, and which should therefore have "many" low energy excitations, at $T/T_c \approx 0.04$ the measured value of $\kappa(T)/T$ is only $0.01\kappa_n(0)/T$ (see data in [24]). So in $CeCoIn_5$ the thermal conductivity (κ/T) relative to $\kappa_n(0)/T$ remains still almost 10 times larger than in UPt_3, for a ratio T/T_c 10 times smaller. This demonstrates that below 0.1 K, the thermal excitations above a gap of standard amplitude even with line and point nodes, give a negligible contribution to $\kappa(T)/T$ in $CeCoIn_5$: $\kappa(T)/T$ can only be controlled by a "very small" gap value, obviously with nodes owing to the power law dependence of $\kappa(T)/T$ (Fig. 2).

The picture emerging from this analysis is that of a multigap superconductor, having line of nodes on the large gap (NMR [25–27] or magnetic penetration depth [28,29] results), but also on the (very) small gap (present measurements). Theoretical modeling is, however, required in order to put numbers on the value of this lower gap. The present measurements also rule out the claim of unpaired electrons [4] which got theoretical support from a recent proposal of interior gap superconductivity [30], a new superconducting state leading naturally to unpaired electrons. However, it was recently stressed that the large anisotropy of the FS in $CeCoIn_5$ makes this state implausible, and that interband interactions between electrons would always induce a finite order parameter on all FS sheets below T_c [31]. Moreover, it would have also implied that the large gap band is a light carrier band [30], which contradicts the observation of a very small H_{c2}^S (see below). Our zero field $\kappa(T)/T$ at the lowest temperatures remains compatible with the universal limit [4], and conforms to the theoretical analysis [31], which could not explain such "unpaired electrons," even in the presence of a small amount of impurities.

Eventually, the present results are also at odds with the opposite proposal of the very disputed point contact spectroscopy measurements [8], which claimed evidence for multigap superconductivity but emphasized the presence of "giant gaps" with a lower one at $2\Delta/k_BT_c \approx 9$ and a higher one with $2\Delta/k_BT_c \approx 24$. Our measurements point to the existence of a small gap with a ratio $2\Delta/k_BT_c$ much smaller than in the usual weak coupling single gap scheme, believed to be valid in UPt_3.

From these zero field results, we can also expect a strong low field dependence of κ/T in $CeCoIn_5$, as measured in MgB_2 [32] or $PrOs_4Sb_{12}$ [3,5,33]. Figure 3 (field cooled from above T_c) shows that indeed, for very low fields, a "normal state" (constant) $\kappa(T)/T$ behavior is restored below 100 mK with a very large value of κ/T, at 8 mT ($\approx 1.6 \times 10^{-3} H_{c2}$) it is about $1/5\kappa_n(0)$. Field scans at 25 mK (Fig. 4, zero field cooled) showed some hysteresis close to H_{c1} (usual difference between field cooled–zero field cooled), and a difficulty to recover the initial zero field values due to trapped remanent field and huge sensitivity of κ/T to very small fields. However, they reveal completely new behavior: whereas in MgB_2 or $PrOs_4Sb_{12}$, a plateau is reached at intermediate fields within a monotonous increase of κ/T up to $\kappa_n(0)/T$ at H_{c2}, $CeCoIn_5$ shows an abrupt initial jump at H_{c1} (Fig. 4), followed by a decrease at intermediate fields, and a (known [20]) first order transition at H_{c2}.

The main (new) point is the initial jump of κ/T above H_{c1}, which is rather isotropic (same maximum value for both field orientations), and points to a very low effective H_{c2}^S, typically smaller than H_{c1}: the full contribution to κ/T of the small gap band would be recovered already just above H_{c1}. Such a small value of H_{c2}^S is in qualitative agreement [see expression (1)] with a very small gap on a band with light masses, as exists in $CeCoIn_5$ [34].

A key factor to explain the decrease of $\kappa(H)/T$ above 20 mT, contrasting with MgB_2, $PrOs_4Sb_{12}$, or UPt_3, is probably that the mean free path in zero field is very large,

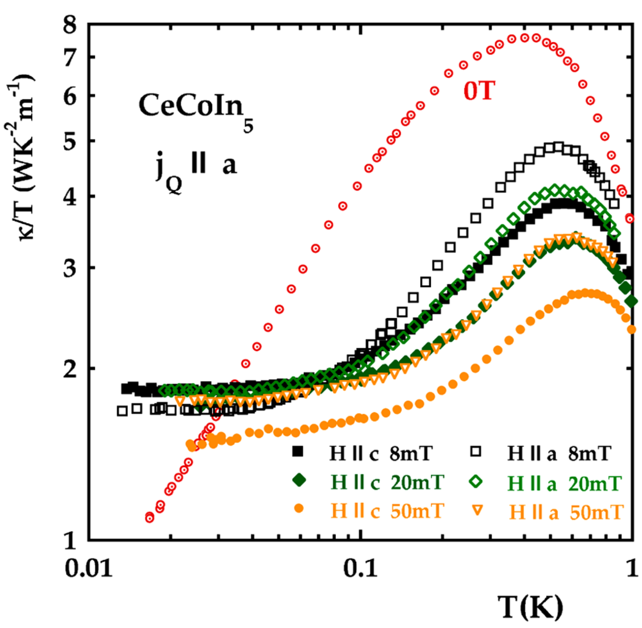

FIG. 3 (color online). Very low field behavior of $\kappa(T)/T$ of $CeCoIn_5$ (field cooled), with the heat current parallel to the a axis, and the magnetic field either parallel to c (full symbols) or parallel to the heat current (open symbols). At these low fields, a constant $\kappa(T)/T$ behavior is recovered below 0.1 K, representing at 8 mT ($\approx 1.6 \times 10^{-3} H_{c2}$) about $1/5\kappa_n(0)$. It points to the presence of a field scale much lower than H_{c2}.

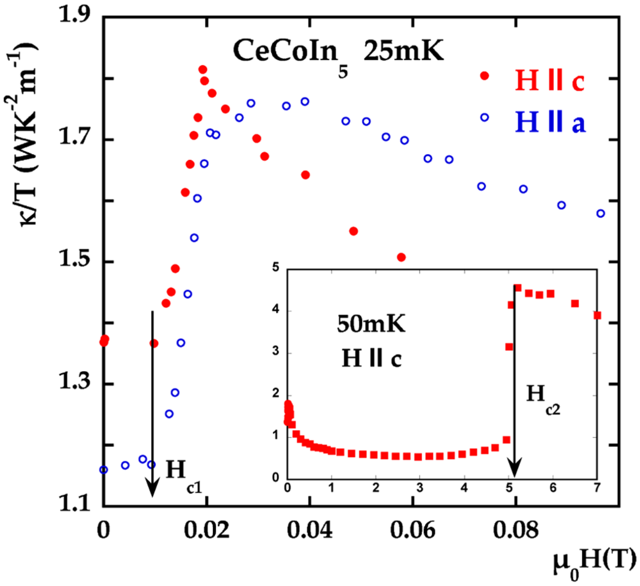

FIG. 4 (color online). Field scans of κ/T (zero field cooled) for both field directions at 25 mK up to 0.1 T, revealing a jump of κ/T as soon as the applied field is above the penetration field H_{c1} in the sample: H_{c2}^S, is lower than H_{c1}. Inset: field scan up to 7 T at 50 mK, $H \parallel c$, with a jump at H_{c2} [20].

so that vortex scattering [35] of the small gap carriers might contribute significantly as a new limiting mechanism. Therefore, it is surprising that the decrease of $\kappa(H)$ beyond the initial jump (Fig. 4) is only twice steeper for the magnetic field perpendicular to the heat current rather than parallel. However, it is not in contradiction with theoretical quantitative estimations [36].

One could also think that Doppler shift of the large gap excitation spectrum will restore inelastic scattering of the small gap band by the delocalized excitations: the field behavior of d-wave superconductors is known to be complex [37–39], and hand-waving arguments too rough, but this effect is nevertheless expected to be weak at very low temperature, as inelastic scattering in the normal state below 0.1 K is already very small: see the behavior of $\kappa(T, H = 6\ \mathrm{T})$, Fig. 2. Clearly, more quantitative information can be gained only with a realistic theoretical model (like for the exploration of the angular dependence of specific heat and thermal conductivity under magnetic field [37]), as also needed for the zero field results.

However, the presence of a very small gap or of a very small field scale yield so dramatic changes on $\kappa(T, H = 0)$ or $\kappa(T \to 0, H)$ respectively that they yield "evidences" for multigaps, even without a quantitative analysis. Our work also experimentally clarifies (negatively) the fundamental issue about the possibility of interior gap superconductivity in metals, and urges to make conclusions only after reaching ultimate experimental exploration (notably very low temperatures). By contrast, the presence of a very small gap in $CeCoIn_5$ on the light carrier bands reveals quantitatively the role of strong correlations in the pairing mechanism, and promotes the concept that multiband superconductivity should be expected in those systems where strong correlations do not equally affect all FS sheets.

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