Multigap superconductivity in heavy fermion systems

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Abstract. Heavy fermion superconductors are largely studied for their unconventional ground states. We present results on the skutterudite compound PrOs$_4$Sb$_{12}$ ($T_c \approx 1.8\,K$), and on the heavy-fermion CeCoIn$_5$ ($T_c \approx 2.3\,K$), where both the low field and the low temperature behaviour of their thermal conductivity yield evidence for multigap superconductivity.

1. Introduction

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, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Indeed, these compounds are known to have a complex Fermi surface (FS), with unequal weight of the f character among the various sheets [11, 12]. Hence mass renormalization (density of states) may vary by more than an order of magnitude [11] among the different sheets, and so may inter and intra band coupling strength. Ingredients for multigap superconductivity (MGSC) are therefore present, and may overcome impurity scattering and interband interactions.

Experiments sensitive to the temperature or field dependence of the excitation spectrum may reveal 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 happen to be the light bands (of weak f-character) [3, 6, 10]: both the small gap $\Delta_0^S$ 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) [13]:

$$H_{c2}/H_{c2}^S \sim \left(\frac{\Delta_L/v_F^S}{\Delta_S/v_F^L}\right)^2$$  \hspace{2cm} (1)

In this paper, we discuss the thermal conductivity of PrOs$_4$Sb$_{12}$ and CeCoIn$_5$, both heavy-fermion superconductors, with emphasis on its temperature dependence in zero and very low field, probing the excitation spectrum and the existence of $H_{c2}^S$. 

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Figure 1. Thermal conductivity of PrOs$_4$Sb$_{12}$ in zero field: full line is the multi-gap fit of the electronic contribution (dotted circles). Dotted line is the estimated phonon contribution. Data at 2.5T reveal the normal state behaviour.

Figure 2. Thermal conductivity of CeCoIn$_5$: suppression of inelastic scattering yield a huge increase below $T_c$, but at 10mK, $\kappa/T$ is still larger than $\kappa/T(T_c)$. The data at 6T reveal the normal state behaviour (except for magnetoresistance effects).

2. Experimental

The PrOs$_4$Sb$_{12}$ (cubic filled skutterudite structure with space group Im3) sample (sample A) has been extracted (gently “ground down” against the disk of a diamond saw) from a conglomerate of several small cubes of PrOs$_4$Sb$_{12}$, grown by the Sb-flux method [14]. Sample A displays a single sharp (less than 0.03 K wide) superconducting transition on specific heat measurements with $T_c \approx 1.75$ K [6]. Its residual resistivity ($\rho$) ratios (RRR) is rather good for this system: $\rho(300 \text{ K})/\rho(T_c) \sim 30$. These signatures of high sample quality allow us to use thermal transport at very low temperatures as a sensitive probe of its low lying energy excitations.

The CeCoIn$_5$ (tetragonal system) single crystal (sample B) has been grown by the In-flux method and cut along the a axis. Sample quality for CeCoIn$_5$ is usually less a problem than in PrOs$_4$Sb$_{12}$, and we measured a sharp superconducting specific heat anomaly (less than 0.49 K wide) with an onset at $T_c \approx 2.35$ K, and $\rho(300 \text{ K})/\rho(T_c) \sim 6$, $\rho(300 \text{ K})/\rho(T \rightarrow 0, 6T) \sim 96$ [10].

Thermal conductivity $\kappa(T,H)$ measurements were conducted on a dilution refrigerator by a standard two-thermometers-one heater steady-state method down to 10 mK and up to 6 T. The thermometers were thermalized on the samples 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 (sample B) and the quality (samples A and B) of the electrical contacts (resistance $R_c \approx 10m\Omega$ on sample A and $\approx 30m\Omega$ for sample B). The same contacts were used to measure the electric resistivity of the samples by a standard four-point lock-in technique. The reliability of the experimental setup was checked against the Wiedemann-Franz law, yielding a good agreement (within 5%) at the lowest temperature in the normal phase for all samples[6, 10].

All measurements under field for samples A were made with the field parallel to the heat current in the a direction, whereas for sample B, the field was either parallel to the heat current or along the c axis (perpendicular to the heat current).
3. Temperature dependence of $\kappa$ in zero field

In Fig. 1, we report the temperature dependence of $\kappa/T$ in zero field of sample A. $\kappa/T$ has dropped by about two orders of magnitude from $T_c$ down to 30 mK, with a clean $T^3$ behaviour of $\kappa$ below 100 mK. An estimation of the phonon thermal conductivity is reported in figure 1, based on the deviation from the Wiedemann-Franz law above $T_c$ and the $T^3$ behaviour below 100mK (see ref. [6] for details), yielding a mean free path of order $l_{ph}^0 \approx 60 \mu m \approx$ (the crystal thickness), below 100mK.

The electronic contribution $\kappa^{el}(T)$ is deduced from substraction of this estimated phonon contribution, and its determination should be very robust up to $T \leq 0.6K$ (region with dominant elastic impurity scattering). It can be normalized to the ”normal state contribution”, deduced from field measurements at 2.5 $T$, above $H_{c2}(T)$. The most striking feature is that an exponential drop is observed, pointing toward a fully open gap on all Fermi sheets, but it is not possible to fit $\kappa^{el}(T)$ if one assumes a BCS gap corresponding to $T_c = 1.729K$: $\kappa^{el}/T$ starts to rise at much lower temperatures than expected, requiring a smaller gap value. However, the data can be quantitatively reproduced within a multigap-superconductivity scenario, when we include a small $\Delta_S(T)$ and a large $\Delta_L(T)$ gap function with the same $T_c$, and two associated conduction channels: $\kappa^{el}(T) = n_S \cdot \kappa^{el}_S + (1 - n_S) \cdot \kappa^{el}_L / T$. The best data fit is then obtained for a zero temperature gap ratio of about $\Delta_L/\Delta_S(T \to 0) \sim 3$ with $\Delta_S(T \to 0) \sim 1K$, and a ”weight” for the small gap band $n_S \sim 0.35$.

Figure 2(a) shows the temperature dependence of $\kappa/T$ in zero field and in the normal phase (under a magnetic field of 6$T$), the WF law being satisfied below 100mK [10]. 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)). A key factor is the dominant role of inelastic scattering at $T_c$, which strongly limits the normal state thermal conductivity. 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, we used magneto-resistivity and thermal conductivity data under field to estimate this value to about 10 $WK^{-\rm 2 m}^{-1}$.

Nevertheless, even with this value of $\kappa_n(0)/T$, we can see that at 0.1 K (0.043$T_c$), $\kappa/T$ is at most 0.5 $\kappa_n(0)/T$. At 10 mK (0.004$T_c$), where it is still far above the estimated universal limit [4] and still displays a strong temperature dependence, $\kappa/T$ 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 ref. [15]). So in CeCoIn$_5$ the thermal conductivity ($\kappa/T$) 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 0.1K, 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 $\kappa(T)/T$ (figure 2).

So the picture emerging from the temperature dependence of $\kappa$ in zero field for PrOs$_4$Sb$_{12}$ and CeCoIn$_5$ is that of multigap superconductors, with a small gap having no nodes in the first case and line of nodes in the last one.

4. Temperature dependence of $\kappa$ in low field

Further strong support to multigap superconductivity in PrOs$_4$Sb$_{12}$ comes from the field measurements. On figure 1, we can see that a magnetic field of 100mT (only 4% of $H_{c2}(0)$) is enough to restore more than 30% of the normal state heat transport. This robust feature, similar to observations in MgB$_2$ [16], confirms MGSC in PrOs$_4$Sb$_{12}$ [6]. The characteristic field scale $H_{c2}$ for the vortex core overlap of the small band gap can be estimated from equation 1: assuming as in [2] that the small gap band is also a light carrier band, with $vf_{s}\sim vf_{L} \sim 5$. We then get $H_{c2}^S \sim 10mT$, which is of the order of $H_{c1}$ and seems reasonable owing to the measured
It is also seen from expression 1 that the main reason for the smallness of \( H_{c2}^S \) in heavy fermion systems comes from the fact that small gap bands are also light bands (of weak f-character): both the small gap and the large Fermi velocity of this band contribute to the enhancement of the associated effective coherence length (\( \xi \approx h v_F/\Delta \)), and so to the large ratio \( H_{c2}/H_{c2}^S \).

In CeCoIn\(_5\), the effect is even stronger, even though the lack of a quantitative estimate of \( \Delta_S \) prevents direct estimation of \( H_{c2}^S \). But it is seen on figure 2 that for a field of 8mT (\(< 10^{-3}H_{c2}\)), just above \( H_{c1} \), the "normal state" constant \( \kappa/T(T) \) behaviour is indeed recovered below 100mK, with a very large value of \( \kappa/T \approx 1/5\kappa_n/T(0) \). This is to be contrasted with the field behaviour of unconventional superconductors, where Doppler shift of the excitation spectrum essentially leads to a positive shift of the whole curve of \( \kappa(T,H) \) at low temperatures (see for example [17]), but not to a complete change of the temperature dependence, which appear in the present case because the dominant contribution to \( \kappa(T) \) switches entirely from superconducting to normal state behaviour.

5. Conclusion

The presence of a very small gap and field scale yield so dramatic changes on \( \kappa(T,H) \) that they give “evidences” for multigaps, even without quantitative analysis. For both systems, the presence of the small gap on the light carrier bands reveals quantitatively the role of strong correlations in the pairing mechanism, and support that multiband superconductivity should be expected in those systems where strong correlations do not equally affect all FS sheets.

Acknowledgments

We benefited from many enlightening discussions with K. Izawa, K. Behnia, K. Miyake, H. Harima and I. Vekhter. This work has been supported by the grant “ANR-ICENET”.

References

[1] Suderow H, Vieira S, Strand J-D, Bud’ko and Canfield P C 2004 Phys. Rev. B 69, 060504
[2] Measson M-A, Braithwaite D, Fluquet J, Seyfarth G, Brison J-P, Lhotel E, Paulsen C, Sugawara H, and Sato H 2004 Phys. Rev. B 70 064516
[3] Seyfarth G, Brison J-P, Measson M-A, Fluquet J, Izawa K, Matsuda Y, Sugawara H and Sato H 2005 Phys. Rev. Lett. 95 107004
[4] Tanatar M A, Piafline J, Nakatsuji S, Hawthorn D G, Boaknin E, Hill R-W, Ronning F, Sutherland M, Taillefer L, Petrovic C, Canfield P C and Fisk Z 2005 Phys. Rev. Lett. 95 067002
[5] Yogi M, Nagai T, Imamura Y, Mukuda H, Kitaoka Y, Kikuchi D, Sugawara H, Aoki Y, Sato H and Harima H 2006 J. Phys. Soc. Jpn. 75 124702
[6] Seyfarth G, Brison J-P, Measson M-A, Braithwaite D, Lapertot G and Fluquet J 2006 Phys. Rev. Lett. 97 236403
[7] Xiao H, Hu T, Almasan C C, Hayles T A and Maple M B 2006 Phys. Rev. B 73 184511
[8] Rourke P M C, Tanatar M A, Ture C S, Berdeklis J, Petrovic C and Wei J Y T 2005 Phys. Rev. Lett. 94 107005 and comments Phys. Rev. Lett. 96 259701 (2006), 96 259702, 96 259703
[9] Kasahara Y, Iwasawa T, Shishido H, Shibachii T, Behnia K, Haga Y, Matsuda T D, Onuki Y, Sigrist M and Matsuda Y 2007 Phys. Rev. Lett. 99 116402
[10] Seyfarth G, Brison J-P, Knebel G, Aoki D, Lapertot G, and Fluquet J 2008, Phys. Rev. Lett. 101 046401
[11] for a recent review : Settai R, T akeuchi T and ¯Onuki Y 2007 J. Phys. Soc. Jpn. 76 051003
[12] Maehira T, Hotta T, Ueda K, and Hasegawa A 2003 J. Phys. Soc. Jpn. 72 854
[13] Tewordt L and Fay D 2003 Phys. Rev. B 68 092503
[14] Izawa K, Nakajima Y, Goryo J, Matsuda Y, Osaki S, Sugawara H, Sato H, Thalmeier P and Maki K 2003 Phys. Rev. Lett. 90 117001
[15] Suderow H, Brison J-P, Huxley A D and Fluquet J 1997 J. Low Temp. Phys. 108 11
[16] Sologubenko A V, Jun J, Kazakov S M, Karpinski J and Ott H R 2002 Phys. Rev. B 66 014504
[17] Suderow, H, Brison, J-P, Huxley A and Fluquet J 1998 Phys. Rev. Lett. 80 165