Heat conduction in the heavy fermion superconductor UPd$_2$Al$_3$

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Abstract

We present preliminary measurements of the thermal conductivity of the heavy fermion superconductor UPd$_2$Al$_3$ for the normal and superconducting states at low temperatures. As $T\to0$, the superconducting state is characterized by a finite linear term, about 10% of the normal state value, which suggests a residual density of low energy quasiparticle states. This agrees qualitatively with resonant impurity scattering theories applied to exotic superconductors with nodes in the gap structure. Comparisons are made with theory and with other U-based superconductors, such as URu$_2$Si$_2$ and UPt$_3$. PACS numbers: 74.70.Tx, 74.25.Fy
Heavy ferromion superconductors (HFS) have drawn much attention since their discovery in the mid-80’s, yet the nature of the order parameter remains a focus of intense research. Discovered in 1991, UPd2Al3 exhibits co-existing antiferromagnetism and superconductivity, with the highest $T_c$ (2 K) and magnetic moment ($0.85\mu_B/U$) of all the HFS. NMR relaxation rates show a power law T dependence suggestive of a gap with a line of zeroes on the Fermi surface. However, the T dependence of the specific heat [1] and the penetration depth [3] are quite close to that expected for an s-wave gap. In this paper, we make a preliminary study of the gap structure using thermal conductivity.

The polycrystalline sample was grown and annealed using RF induction heating in ultrahigh vacuum. We measured the thermal conductivity $\kappa$ using the steady-state technique, with one heater and two thermometers. The normal state thermal conductivity $\kappa_N$ was obtained by applying a field $H>H_c(0)$. This sample has a $T_c$ of 1.86 K and an RRR of 36 ($\rho_0 = 3.8\mu\Omega cm$). The positive magnetoresistance is roughly 20% in 4.5T.

To use $\kappa$ as a probe of gap structure, it is necessary to separate the contributions from all the heat carriers. Let us first consider the normal state (Fig. 1). In a field of 4.5 T, the Lorentz number $L=\kappa\rho/T$ at 100 mK is $2.32 \times 10^{-8} W\Omega K^{-2}$, which is $0.95L_0$ ($L_0=2.44 \times 10^{-8} W\Omega K^{-2}$), in agreement with the Wiedemann-Franz law. In the absence of inelastic scattering, whose effect on $\kappa$ is unlikely to exceed 10% below 1 K, such behaviour is expected from electrons. As a result, we take the electronic part of $\kappa_N/T$ to be $L_0/\rho_0$ from 0 to 1 K. From inelastic neutron scattering [4], the antiferromagnetic magnons have a short life-time of about $3 \times 10^{-13}$ s. With the magnon velocity, we get a mean free path of 13 Å. Since the spin wave excitation spectrum is gapless and linear in q, the specific heat $c_{mag}$ goes as $T^3$. Then the magnon $\kappa$ can be estimated by $\kappa_{mag}=c_{mag}v_{mag}l_{mag}/3$, where $c_{mag}=25.4$ Jm$^{-3}$K$^{-4}$×T$^3$, $v_{mag}=4.5 \times 10^3$ ms$^{-1}$ and $l_{mag}=13$ Å. At 1 K, $\kappa_{mag}=5.0 \times 10^{-4}$ mWcm$^{-1}$K$^{-1}$, which is negligible compared to the data. Furthermore, spin-waves are not found to be affected by the superconducting transition [4]. For these reasons, we attribute the measured $\kappa$ entirely to phonons and electrons. Therefore, the roughly linear increase in $\kappa_N/T$ seen in Fig. 1 must be due to phonons. Then, using $\kappa_{ph}=c_{ph}v_{ph}l_{ph}/3$, where the specific heat $c_{ph}=8.0 \times T^3$
Jm$^{-3}$K$^{-4}$ \cite{5} and the average sound velocity $v_{ph}=5.73 \times 10^{3}$ ms$^{-1}$ (from elastic constants \cite{5}), we estimate the phonon mean free path $\Lambda_{ph}$ to be 50 $\mu$m at 0.6K. By 175 mK it has increased to 160 $\mu$m, roughly 1/4 the sample size. These are surprisingly long phonon mean free paths for a metal. Assuming the dominant scattering of phonons to come from grain boundaries and electrons, we can estimate the boundary scattering rate $B$ and the e-ph coupling strength $E$ from:

$$\kappa_{ph} = \frac{k_B^4 T^3}{2\pi^2 \hbar^3 v_{ph}} \int_0^{\infty} dx \frac{x^4 e^x(e^x - 1)^{-2}}{B + E \pi x T}$$ \hspace{1cm} (1)

A fit to $\kappa_N(T)$-$\kappa_N(0)$ using Eq.(1) yields $B=1.5 \times 10^6$ s$^{-1}$ and $E=5.9 \times 10^6$ K$^{-1}$s$^{-1}$, which means that electron scattering dominates at all but the lowest temperatures. This value of $E$ is somewhat less than in URu$_2$Si$_2$ ($1.5 \times 10^7$) \cite{6}, and much less than in Nb ($2 \times 10^9$) \cite{8} and V($3 \times 10^9$). This anomalously weak e-ph coupling is the most unusual feature of the normal state $\kappa$ in UPd$_2$Al$_3$.

Let us now turn to the superconducting state data, shown as the lower curve in Fig. 1. The two main observations are: 1) the existence of a substantial intercept in $\kappa/T$, 2) the similarity in the slopes of $\kappa/T$ and $\kappa_N/T$ at low T. A smooth extrapolation of the data to T=0 gives a limiting $\kappa/T=0.6-0.8$ mWK$^{-2}$cm$^{-1}$, about 10% of the normal state value $L_0/\rho_0$, likely due to residual quasiparticle excitations. Now, as seen in BCS superconductors such as Nb \cite{8}, the large reduction in the number of quasiparticles available for scattering phonons at low T should cause a major increase in $\Lambda_{ph}$. If the rise in $\kappa_N/T$ is due to phonons scattering off electrons, one would expect the slope of $\kappa/T$ in the superconducting state to increase dramatically. It does not. In fact, it seems that the non-electronic contribution to $\kappa_N/T$ is unaffected by superconductivity. Whether other scattering mechanisms play a role requires further study. At this stage, we adopt the following simple procedure: the electronic thermal conductivity $\kappa_e/T$ in the superconducting state is obtained by subtracting from the H=0 data in Fig. 1 the slope of $\kappa_N/T$. The result is shown in Fig. 2, normalized by $L_0/\rho_0$.

A finite limiting value for $\kappa_e/T$ is one of the major predictions of current theories of transport in unconventional superconducting states (see \cite{9,10}, and references therein). A
missing U-atom acts as a Kondo impurity in a compensated lattice, causing multiple scattering and large phase shifts $\delta_0=\pi/2$. Within such a resonant impurity scattering model, a line of nodes in the gap can give a finite intercept in $\kappa/T$ vs $T$ [9]. Such a linear term arises from node smearing due to impurities, which leaves part of the Fermi surface gapless, with a residual density of low energy quasiparticle states. The simplest candidate gap structures are based on a spherical Fermi surface [9,11]. A polar gap has a line of nodes along the equator, an axial gap point nodes at the poles and the hybrid gaps both line and point nodes with the gap approaching zero at the poles either with a linear (type I) or quadratic (type II) $k$-dependence. Calculations such as those performed for UPt$_3$ [9] give the curves shown in Fig. 2 [11]. The unitary limit is assumed, inelastic scattering neglected and the impurity scattering rate taken to be $\Gamma_0 \equiv \frac{1}{2\tau} = 0.3T_c$ [11], in agreement with the value determined from de Haas-van Alphen measurements [12]. The comparison in Fig. 2 shows that the theory predicts the right magnitude for the residual linear term, which is independent of the way we treat the phonons. This is not true for the $T$ dependence, thus the discrepancy seen in Fig. 2 must be taken with caution.

It is interesting to compare with other HFS. In UPt$_3$ single crystals, there is no evidence for a finite intercept [13]. This may be due to a lower impurity scattering rate, in accordance with the lower residual resistivities (0.23 and 0.61 $\mu\Omega$cm). However, since $T_c$ is 0.5 K, estimates yield $\Gamma_0 \approx 0.1-0.2 \ T_c$ [13], while a fit to UPt$_3$ data would have $\Gamma_0 \approx 0.05T_c$ or less [9]. As for URu$_2$Si$_2$, a large residual $\kappa/T$ – approximately 30% of the normal state value – was observed for a crystal with $\rho_0 = 9.5 \ \mu\Omega$cm [7]. Roughly speaking, this makes sense within the theory since $\rho_0$ is 3 times greater than in our UPd$_2$Al$_3$ sample. Finally, we point out that in URu$_2$Si$_2$, the phonon contribution is more easily explained. The slope in $\kappa/T$ in the superconducting state at low $T$ is roughly 4 times steeper than in the normal state, consistent with the idea that phonons conduct better due to the loss of electrons, their main scatterers. Again, it is puzzling that in UPd$_2$Al$_3$, with a comparable e-ph coupling, the loss of electrons appears to have no affect on the phonons.

In conclusion, although the identification of the order parameter remains an issue of
debate in HF superconductors, the possibilities are being constrained. In this work on UPd$_2$Al$_3$, we see a clear gapless behaviour which suggests the presence of a line of nodes, consistent with NMR results and calculations based on resonant impurity scattering.

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FIGURES

FIG. 1. Thermal conductivity of UPd$_2$Al$_3$, divided by temperature, for H=0 (solid circles) and H=4.5T>H$_c$(0) (open circles).

FIG. 2. Normalized electronic thermal conductivity (see text). The data (points) are compared with resonant impurity scattering calculations ([9]) using spherical harmonics for 3 gaps with a line node: polar (solid line), hybrid I (dashed line) and hybrid II (dotted line) [11].
\( T_{c} = 1.86 \text{ K} \)

\( \Gamma_{0} = 0.3T_{c} \)