Thermal conductivity in B-phase of UPt$_3$

K. Maki $^{a,1}$, P. Thalmeier $^b$

$^a$Max-Planck-Institute for the Physics of Complex Systems, Nöthnitzer Str. 38, 01187 Dresden, Germany
and Dept. of Physics and Astronomy, University of Southern California, Los Angeles, CA 90089-0484, USA

$^b$Max-Planck-Institute for the Chemical Physics of Solids, Nöthnitzer Str. 40, 01187 Dresden, Germany

Abstract

We have shown that the magnetothermal conductivity in the vortex state in unconventional superconductors provides a powerful technique to access the nodal locations in the superconducting order parameter $\Delta(\mathbf{k})$. We shall explore this technique in the B phase of UPt$_3$ for low temperatures and fields and derive expressions for the thermal conductivity with the $E_{2u}$ order parameter.

Key words: magnetothermal conductivity; unconventional superconductivity; UPt$_3$

Perhaps UPt$_3$ with 3 distinct superconducting phases A, B and C is one of the most well studied Heavy Fermion superconductors[1]. Both thermal conductivity data and Pt- NMR data point to the triplet superconductor of $E_{2u}$-type[2,3] with nodal points at $\theta = 0$ and $\pi$ and the horizontal nodal line at $\theta = \frac{\pi}{2}$, where $\theta$ and $\varphi$ are the polar coordinates designating $\mathbf{k}$, the quasiparticle wave vector (see Fig. 1). However there are no experiments which directly indicate the nodal points and lines in $\Delta(\mathbf{k})$ in UPt$_3$. Here we limit ourselves to the B-phase where the order parameter is supposed to be given by

$$\Delta(\theta, \varphi) = \frac{3}{2} \sqrt{3} \Delta \exp(\pm 2i\varphi) \cos \theta \sin^2 \theta$$

(1)

and calculate the quasiparticle DOS and the thermal conductivity in the limit $\tilde{v}\sqrt{eH} \ll T \ll \Delta(0)$ for arbitrary magnetic field ($\mathbf{H}$) direction given by the polar and azimuthal field angles $\theta$ and $\phi$ respectively. Here $\tilde{v} = (v_{a}v_{c})^{\frac{1}{2}}$ is the characteristic Fermi velocity and these quantities are evaluated within semiclassical approximation[4–8].

The quasiparticle DOS for the B-phase in the superclean limit ($\Gamma \Delta \ll \tilde{v}\sqrt{eH}$) is given by

$$\frac{N(\theta)}{N_{0}} = \frac{g(0)}{\sqrt{3}} \frac{1}{\tilde{v}\sqrt{eH}} I_{B}(\theta)$$

(2)

where

$$I_{B}(\theta) = \alpha \sin \theta + \frac{2}{\pi} E(\sin \theta)$$

(3)

and $E(\sin \theta)$ is the complete elliptic integral, $N_{0}$ is the DOS in the normal state and $\alpha = \frac{v_{c}}{v_{a}} = 1.64$ [1] is the anisotropy of Fermi velocities. The angular dependence

1 E-mail:maki@mpipks-dresden.mpg.de
of $I_B(\theta)$ is shown in Fig. 2. It determines the $\theta$-dependence of specific heat, spin susceptibility etc. which are given by

$$C_\phi = \frac{X_\phi}{XN} = 1 - \frac{\rho_s(H)}{\rho_s(0)} = g(0)$$  \hspace{1cm} (4)

where $\rho_s$ is the superfluid density.

Similarly the thermal conductivity $\kappa_{xx}$ for $T \ll \hbar v / e H \ll \Delta(0)$ in the superclean limit is given by

$$\frac{\kappa_{xx}}{\kappa_n} = \frac{2}{3} \frac{\Delta^2}{\Delta^2 - \Delta y^2} \sin^2 \theta \left[ \cos^2 \theta K(\sin \theta) - \cos^2 \theta K(\sin \theta) \right]$$

and the thermal Hall coefficient $\kappa_{xy}$ by

$$F_{xx}^H(\theta, \phi) = \frac{2}{\pi} \frac{\sin^2 \theta}{\pi} \phi \left[ \frac{1}{3} \frac{\Delta^2}{\Delta^2 - \Delta y^2} \sin^2 \theta \right]$$

The $\theta$-dependence of $\kappa_{ij}$ ($ij=xx,zz,xy$) is again shown in Fig. 2. As in YNi$_2$B$_2$C[9] the cusp in $C_\phi$ and $\kappa_{xx}$ indicates the presence of point nodes in the $\Delta(k)$ of UPt$_3$. Furthermore $\phi$ is the angle between the heat current and the magnetic field projected on the $ab$-plane and $K(\sin \theta)$ is again a complete elliptic integral. In the limit $\theta = \pi$, $I_B(\pi) = \alpha + \frac{\pi}{2}$ and then

$$\kappa_{xx} \sim \frac{1}{\pi} \left( 1 - \frac{1}{3} \cos(2\phi) \right); \hspace{1cm} \kappa_{xy} \sim \frac{2}{3} \sin(2\phi)$$

In Fig. 3 we show the $ab$-plane $\phi$-dependences of $\kappa_{xx}$ and $\kappa_{xy}$. The maximum in $\kappa_{xx}$ occurs for heat current $\perp H$ when the Doppler shift of quasiparticle energies is most effective and we have $\kappa_{xx} (\phi = \frac{\pi}{2}) / \kappa_{xx} (\phi = 0) = 2$.

We have shown earlier that the nodal directions in a variety of unconventional superconductors are accessible[4,5]. For example from the magnetothermal conductivity in Sr$_2$RuO$_4$, it is concluded that the nodes are horizontal and lie around $k_c = \pm \frac{\pi}{2}[10,11]$. This indicates that the interlayer coupling plays the crucial role in Sr$_2$RuO$_4$. Also $d_{x^2-y^2}$-symmetry in Heavy Fermion superconductor CeCoIn$_5$[13] and organic superconductors[14] have been established in a similar way.

References

[9] K. Izawa et al., cond-mat/0205178