Thermal conductivity in B- phase of UPt_3

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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 supeconducting 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 $\vartheta = 0$ and π and the horizontal nodal line at $\vartheta = \frac{\pi}{2}$, where ϑ and φ 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

$$\Delta(\vartheta,\varphi) = \frac{3}{2}\sqrt{3}\Delta\exp(\pm 2i\varphi)\cos\vartheta\sin^2\vartheta \tag{1}$$

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 θ and ϕ 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 $(\Gamma\Delta)^{\frac{1}{2}} \ll \tilde{v}\sqrt{eH}$ (Γ is the quasiparticle scattering rate) is given by

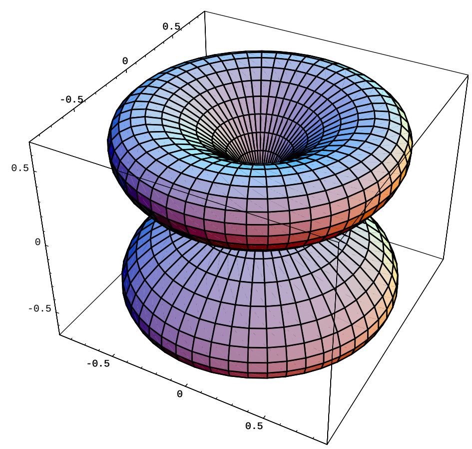

Fig. 1. Polar plot of $|\Delta(\vartheta,\varphi)|$ in B- phase.

$$\frac{N(0)}{N_0} = g(0) = \frac{1}{\sqrt{3}}\tilde{v}\sqrt{eH}I_B(\theta) \tag{2}$$

where

$$I_B(\theta) = \alpha\sin\theta + \frac{2}{\pi}E(\sin\theta) \tag{3}$$

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

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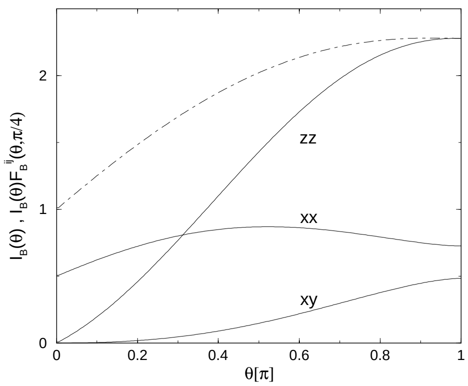

Fig. 2. Polar field angle dependence of $I_B(\theta)$ (dashed-dotted) and $I_B(\theta)F_B^{ij}(\theta, \frac{\pi}{4})$ (ij= xx, zz, xy) which determine the θ-dependence of DOS g(0), thermal conductivities $(\kappa_{xx}, \kappa_{zz})$) and Hall coefficient (κ_{xy}) respectively.

of $I_B(\theta)$ is shown in Fig. 2. It determines the θ- dependence of specific heat, spin susceptibility etc. which are given by

$$\frac{C_s}{\gamma_N T} = \frac{\chi_s}{\chi_N} = 1 - \frac{\rho_s(H)}{\rho_s(0)} = g(0) \tag{4}$$

where ρ_s is the superfluid density.

Similarly the thermal conductivity κ_{xx} for $T \ll \tilde{v}\sqrt{eH} \ll \Delta(0)$ in the superclean limit is given by

$$\begin{aligned} \frac{\kappa_{zz}}{\kappa_n} &= \frac{2}{3}\frac{v_a v_c}{\Delta^2}(eH)I_B(\theta)F_B^{zz}(\theta) \\ \frac{\kappa_{xx}}{\kappa_n} &= \frac{1}{3}\frac{v_a^2}{\Delta^2}(eH)I_B(\theta)F_B^{xx}(\theta) \\ F_B^{zz}(\theta) &= \sin\theta \\ F_B^{xx}(\theta,\phi) &= \frac{2}{\pi}\Big[\sin^2\phi E(\sin\theta) + \cos(2\phi)\frac{1}{3\sin^2\theta} \\ &\quad \cdot\Big(\cos^2\theta K(\sin\theta) - cos(2\theta)E(\sin\theta)\Big)\Big] \end{aligned} \tag{5}$$

and the thermal Hall coefficient κ_{xy} by

$$\begin{aligned} \frac{\kappa_{xy}}{\kappa_n} &= -\frac{v_a^2(eH)}{3\Delta^2}I_B(\theta)F_B^{xy}(\theta,\phi) \\ F_B^{xy}(\theta,\phi) &= \frac{2}{\pi}\frac{\sin(2\phi)}{3\sin^2\theta} \\ &\quad \cdot\Big[(2-\sin^2\theta)E(\sin\theta) - 2\cos^2\theta K(\sin\theta)\Big] \end{aligned} \tag{6}$$

The θ- dependence of κ_{ij} (ij=xx,zz,xy) is again shown in Fig. 2. As in YNi_2B_2C[9] the cusp in C_s and κ_{zz} indicates the presence of point nodes in the $\Delta(\mathbf{k})$ of UPt_3. Furthermore ϕ is the angle between the heat current and the magnetic field projected on the a-b plane and $K(\sin\theta)$ is again a complete elliptic integral. In the limit $\theta = \frac{\pi}{2}$, $I_B(\frac{\pi}{2})=\alpha + \frac{2}{\pi}$ and then

$$\kappa_{xx} \sim \frac{1}{\pi}\Big(1 - \frac{1}{3}\cos(2\phi)\Big); \quad \kappa_{xy} \sim \frac{2}{3\pi}\sin(2\phi) \tag{7}$$

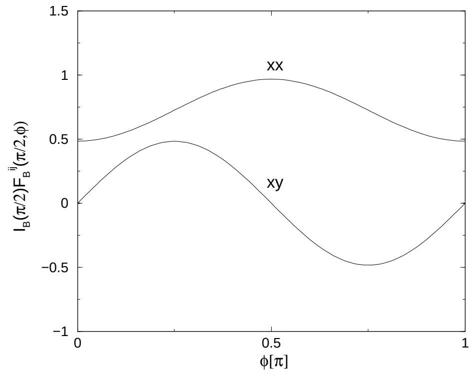

Fig. 3. ϕ- dependence of $I_B(\frac{\pi}{2})F_B^{ij}(\frac{\pi}{2}, \phi)$ (ij=xx,xy). The zz-component has no ϕ- dependence.

In Fig. 3 we show the ab- plane ϕ- dependences of κ_{xx} and κ_{xy}. The maximum in κ_{xx} occurs for heat current $\perp \mathbf{H}$ 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_2RuO_4, it is concluded that the nodes are horizontal and lie around $k_z = \pm\frac{\pi}{2c}$[10,11]. This indicates that the interlayer coupling plays the crucial role in Sr_2RuO_4[12]. 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.

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