Transport in the Heavy Fermion Superconductor UPt$_3$

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Abstract

We report new theoretical results and analysis for the transport properties of superconducting UPt$_3$ based on the leading models for the pairing symmetry. We use Fermi surface data and the measured inelastic scattering rate to show that the low-temperature thermal conductivity and transverse sound attenuation in the A and B phase of UPt$_3$ are in excellent agreement with pairing states belonging to the two-dimensional orbital $E_{2u}$ representation.

Keywords: sound attenuation; thermal conductivity; unconventional superconductivity; heavy fermions; UPt$_3$

Much has been learned about the superconducting states of the heavy fermion compound UPt$_3$ from studies of the superconducting phase diagram [1]. Transport properties have played an important role in narrowing down the viable theoretical models for the pairing state. Low-temperature measurements of the thermal conductivity [2] have shown that the B-phase of UPt$_3$ is in quantitative agreement with an order parameter (OP) belonging to either the $E_{1g}$ $E_{2u}$, or $AE$ pairing states, but is not consistent with the models based on accidentally degenerate representations belonging to the $AB$ classes or with the 1D orbital models based on triplet pairing and no spin-orbit coupling [3,4]. However, Tou et al. [5] argue that measurements of the Knight shift in UPt$_3$ requires a non-unitary spin-triplet order parameter with no spin-orbit locking [6]. This interpretation conflicts with the observed anisotropic paramagnetic limiting as well as the low-temperature transport measurements for the thermal conductivity [7,3]. Further analysis of the magnetic and transport properties of the superconducting phases is required in order to resolve these apparent conflicts.

Recently Ellman and co-workers [8] measured the transverse ultrasonic absorption in both the A- and B-phases of superconducting UPt$_3$ on the same crystals used to measure the low-temperature thermal conductivity. The results of our analysis show that the pairing states belonging to the $E_{2u}$ representation are quantitatively consistent with the thermodynamic phase diagram, specific heat, anisotropic thermal conductivity and anisotropic sound attenuation. Pairing states based on the $E_{1g}$ and $AE$ representations fail to account for the anisotropy in the sound attenuation.

We report the results of our calculations and analysis of the ultrasonic attenuation for both
superconducting A and B phases in the long-wavelength hydrodynamic limit. The transverse viscosity $\eta$ and the sound attenuation $\alpha$ with wavevector $\mathbf{q}$ and polarization $\varepsilon$ are related by

$$\alpha_{ij}(T) = \omega^2/(\rho c_s^2) \eta_{ij,kl}(\mathbf{q}, \omega) \mathbf{\hat{e}}_i q_j \mathbf{\hat{e}}_k q_l,$$

where $\rho$ is the mass density, $c_s$ the speed of sound, and $\omega = c_s q$, and $\mathbf{q} \cdot \varepsilon = 0$. For transverse waves with polarization $\varepsilon || \mathbf{\hat{x}}$ propagating along $\mathbf{q} || \mathbf{\hat{y}}$, or vice versa, all relevant OP models possess a universal zero-temperature value, except for the AE-model. In the case of the E-models the viscosity is

$$\eta_{xy,xy}(0,0) \simeq c_f \nu_c N_f / [8 d \Delta(\theta)/d\theta]_{\text{node}}.$$  

For other propagation directions the transverse viscosity has a nonuniversal but finite value for $\omega, T \to 0$ [9].

The anomaly in the attenuation at the A-B transition (Fig. 1) is largest for $\alpha_{xy}$, and only weakly visible in $\alpha_{xz}$. The anomaly reflects a decrease in the number of thermally excited quasiparticles in the B-phase relative to the A-phase. As temperature decreases below the second superconducting transition, $T_{c-}$, the subdominant OP nucleates and closes off the additional nodes in the A-phase. The anisotropy of this anomaly provides new information on the nodal structure of the order parameter. Our calculations show that the reported enhancement of the sound attenuation in the A-phase is in excellent agreement with the $(1, 0)$ state of an $E_{2u}$ OP model in the resonant impurity scattering limit; see Fig. 1. The order parameter and the scattering parameters are exactly those obtained from the analysis of the thermal conductivity on the same crystal [3]. Thus, there are no adjustable parameters in the calculation of the sound attenuation. The $E_{1g}$ and $AE$ models also provide an excellent fit to the thermal conductivity data, but fail to account for the transverse sound attenuation anomaly. This difference reflects the differences in the nodal structure for the A-phase in the two different E-rep models and the AE model.

In conclusion, measurements of $\alpha_{xy}$ and $\alpha_{xz}$ are in excellent agreement with the $(1, 0)$ orbital state in the high-temperature A-phase with $E_{2u}$ symmetry and a $k_z(k_x^2 - k_y^2)$ nodal structure. The low-temperature B-phase is described by a $(1, i)$ orbital state.

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