

Transport in the Heavy Fermion Superconductor UPt₃

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Abstract

We report new theoretical results and analysis for the transport properties of superconducting UPt₃ 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 UPt₃ 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; UPt₃

Much has been learned about the superconducting states of the heavy fermion compound UPt₃ 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 UPt₃ 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 UPt₃ 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 UPt₃ 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

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superconducting A and B phases in the long-wavelength hydrodynamic limit. The transverse viscosity η and the sound attenuation α with wavevector \mathbf{q} and polarization ε are related by

$$\alpha_{ij}(T) = \omega^2 / (\rho c_s^3) \eta_{ij,kl}(\mathbf{q}, \omega) \hat{\varepsilon}_i \hat{q}_j \hat{\varepsilon}_k \hat{q}_l, \quad (1)$$

where ρ 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 $\varepsilon \parallel \hat{x}$ propagating along $\mathbf{q} \parallel \hat{y}$, 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 $\eta_{xy,xy}(0,0) \simeq v_f^2 p_f^2 N_f / |8 d\Delta(\theta)/d\theta|_{\text{node}}$. For other propagation directions the transverse viscosity has a nonuniversal but finite value for $\omega, T \rightarrow 0$ [9].

The anomaly in the attenuation at the A-B transition (Fig. 1) is largest for α_{xy} , and only weakly visible in α_{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 α_{xy} and α_{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-

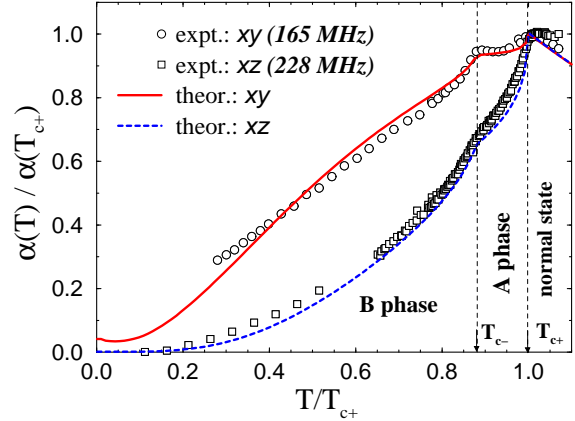


Fig. 1. Calculations of the transverse sound attenuation for an E_{2u} OP in the limit $\omega \rightarrow 0$ with a phenomenological scattering rate $\Gamma(T) = 0.01\pi T_{c+}(1 + T^2/T_{c+}^2)$. The splitting of $T_{c+} - T_{c-}$ in the specific heat determines the bare transition temperatures $T_{c2}/T_{c1} = 0.92$. The experimental data are from Ellman *et al.* [8].

temperature B-phase is described by a $(1, i)$ orbital state.

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