Thermal Conductivity of Superconducting UPt$_3$

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The thermal conductivity $\kappa$ of the heavy-fermion superconductor UPt$_3$ has been measured on two single crystals of different quality as a function of temperature and applied magnetic field for different orientations of the heat current relative to both the field and the crystalline axes. The temperature dependence of $\kappa$ is far from exponential and nearly the same for both crystals, in which the heat current is, respectively, parallel and perpendicular to the hexagonal $c$ axis, suggesting a gap structure with nodes in the basal plane and normal to it. The field dependence of $\kappa$ is strongly anisotropic. In the best sample at low fields, where the scattering of heat carriers by vortices is thought to be important, $\kappa(H)$ depends on the relative orientation of field and current. On the other hand, at high fields near $H_{c2}$ (in both samples), $\kappa(H)$ depends on the relative orientation of field and crystalline axes, reflecting an anisotropy in the gap structure and in the Fermi velocities.

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1. INTRODUCTION

The superconducting state of UPt₃ is considered to be one of the most promising candidates for an unconventional order parameter. The non-exponential behavior of a number of physical properties of this system at the lowest temperatures investigated, such as the ultrasonic attenuation,¹ specific heat,² thermal conductivity,³,⁴ and NMR relaxation rate⁵ has in the past been interpreted as strong evidence for the presence of zeros in the gap function. As in the case of superfluid ³He, an anisotropic gap can be associated with a nontrivial symmetry of the order parameter.

The speculation of a nontrivial order parameter in UPt₃ has been reinforced by recent experimental evidence for a field-temperature phase diagram with several distinct superconducting phases.⁶ In particular, specific-heat measurements⁷,⁸ have clearly resolved the existence of two transitions at low fields, occurring at $T = T_c^-$ and $T = T_c^+$, which gradually merge at a critical point when the magnetic field is increased.⁹ Furthermore, the low temperature phase below $T_c$ (which we call phase B) appears to undergo a field-induced transition (to “phase C”) at $H = 0.6 \, H_{c2}$, detected by measurements of the velocity⁹ and attenuation¹⁰ of ultrasound. It is perhaps too early to say whether this multiplicity is a consequence of the existence of several superconducting order parameters with different internal symmetries, corresponding to distinct representations such as the A and B phases of ³He or rather, as proposed recently,¹¹-¹³ the result of a degeneracy of superconducting phases within a single multidimensional representation, lifted by an external perturbation, in analogy with the A and A₁ phases of ³He in a magnetic field. Nevertheless, there are a number of observations that favor the latter scenario, perhaps the most convincing being the parallel disappearance of the “splitting” $\Delta T_c = (T_c^+ - T_c^-)$¹⁴ and the symmetry-breaking antiferromagnetic moment¹⁵ with applied pressure. In either case, the question of the internal symmetry of the order parameters is of crucial importance and its determination remains one of the main tasks of theoretical and experimental research in this field.

One way of exploring the structure of the gap function is to measure the transport properties of the superconducting state. Indeed, the anisotropy of the quasiparticle density of states can be accessed only if the experimental probe has a vectorial character. For example, the temperature dependence of the thermal conductivity in the case of an anisotropic gap would not in general be the same for heat currents applied parallel and perpendicular to the symmetry axis. In this paper, we report on the first study of the thermal conductivity tensor in a heavy fermion compound. The temperature and field dependence of the thermal conductivity of UPt₃ were measured on single crystals, in the normal and superconducting phases, for different