Multiband superconductivity and penetration depth in PrOs$_4$Sb$_{12}$

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Abstract

The effective superconducting penetration depth measured in the vortex state of PrOs$_4$Sb$_{12}$ using transverse-field muon spin rotation (TF-$\mu$SR) exhibits an activated temperature dependence at low temperatures, consistent with a nonzero gap for quasiparticle excitations. In contrast, Meissner-state radiofrequency (rf) inductive measurements of the penetration depth yield a $T^2$ temperature dependence, suggestive of point nodes in the gap. A scenario based on the recent discovery of extreme two-band superconductivity in PrOs$_4$Sb$_{12}$ is proposed to resolve this difference. In this picture a large difference between large- and small-gap coherence lengths renders the field distribution in the vortex state controlled mainly by supercurrents from a fully-gapped large-gap band. In zero field all bands contribute, yielding a stronger temperature dependence to the rf inductive measurements.

Key words: penetration depth, multiband superconductivity, muon spin rotation, PrOs$_4$Sb$_{12}$

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The superfluid density $\rho_s$, a fundamental property of the superconducting state, is related to the superconducting penetration depth $\lambda$: $\rho_s \propto \lambda^{-2}$. Thermal excitations reduce $\rho_s$ and increase $\lambda$, with the result that the temperature dependence of $\lambda$ is an important probe of elementary excitations in the superconducting state. A fully-gapped Fermi surface results in activated behavior of the difference $\Delta \rho_s = \rho_s(T) - \rho_s(0)$ at low temperatures. Nodes in the gap on the Fermi surface increase the density of low-lying excitations, which yields a more rapid power-law temperature dependence of $\Delta \rho_s$.

In contrast, radiofrequency (rf) inductive measurements in the Meissner state [5] found $\Delta \lambda = \lambda(T) - \lambda(0) \propto T^2$, suggesting point nodes of the energy gap. The present paper discusses a possible resolution of this discrepancy (see also Ref. [6]). TF-$\mu$SR experiments on PrOs$_8$Sb$_{12}$ were carried out at the M15 beam line at TRIUMF, Vancouver, Canada. Samples and experimental details have been described previously [12]. TF-$\mu$SR in the superconducting vortex state yields the inhomogeneous distribution of muon spin precession frequencies, i.e., the inhomogeneous field distribution, in the vortex lattice. This distribution depends on an effective penetration depth $\lambda_{\text{eff}}$ that can be estimated from rough measures of the distribution width, such as the Gaussian relaxation rate measured in the time domain, or obtained more accurately from fits to Ginzburg-Landau (GL) models of the distribution shape [7].

Figure 1 gives the temperature dependence of $\lambda_{\text{eff}}$. Values from GL model fits [2] and from Gaussian relaxation rates are in good agreement. Little temperature dependence is observed at low $T$, and the BCS form is a good fit to $\lambda(T)$ below $\sim T_c/2$ (inset to Fig. 1). A fully-gapped Fermi surface is found, with a zero-temperature gap $\Delta(0) \approx 2.2 k_B T_c$ [1]. Figure 2 from Ref. [2], shows a clear difference between the

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can be defined; typically $\xi_0$ where $\Phi_{FL,S}$

ent sheets of the Fermi surface. With band-specific Fermi

L are explained by large and small gaps $\Delta_s$ characterized by a crossover field $H_{c2}^\text{eff} \sim 100 \text{ Oe} \approx H_{c1}$ [6].

For $H \gtrsim H_{c2}^\text{eff}$ small-band vortex core states with size scale $\xi_S$ overlap. In PrOs$_4$Sb$_{12}$ this applies for essentially the entire vortex state, and the observed anomalous thermal conductivity [38] is mainly due to heat transfer by small-band excitations. Then the small-gap states and their contributions to screening supercurrents are nearly uniform, and the vortex-state field inhomogeneity is mainly due to large-gap supercurrents. The activated temperature dependence of $\lambda_{\text{eff}}$ (Fig. 1) is evidence that the large gap is nodeless, which is corroborated by thermal conductivity experiments in very clean single crystals [6]. In this picture TF-$\mu$SR measurements are insensitive to the nodal structure of the small gap.

In contrast, the Meissner-state penetration depth $\lambda$ contains contributions from both bands, and its temperature dependence is controlled by both small- and large-gap superfluid densities. At low temperatures the small-gap contribution dominates the temperature dependence, and $\lambda$ varies more rapidly than $\lambda_{\text{eff}}$ as observed (inset to Fig. 2). The behavior of the data at higher temperatures is more complicated and will not be discussed here. The similar discrepancy found in Sr$_2$RuO$_4$ [29] might also be explained by multiband superconductivity in that compound.

This picture is qualitative and somewhat speculative; its chief merit is that it accounts for a number of different experimental results in PrOs$_4$Sb$_{12}$. To our knowledge there is at present no theory for the temperature dependence of the vortex-state field distribution in an extreme two-band superconductor.

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