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Multiband model for $PrOs_4Sb_{12}$ in the superconducting state

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The gap symmetry has been extensively investigated in the heavy-fermion superconductor, $PrOs_4Sb_{12}$. The pairing appears to be unconventional because of (i) the presence of the double transition observed in the specific heat near the $H_{c2}(T)$ boundary [1], (ii) the appearance of the internal magnetic field in the μSR measurement [2], and (iii) the two- and four-fold oscillatory behaviors found in the thermal conductivity under the oriented magnetic fields [3].

A contrast between the relatively light mass observed in de Haas-van Alphen (dHvA) measurements [4] and the heavy quasiparticle in the specific heat, suggests a possibility of two-gap superconductivity, in which the density of states and the Fermi velocity differ considerably in relevant Fermi surfaces. Although the origin of the heavy quasiparticle is not known at the moment, possible canditates for the origin are the local electron-phonon coupling inherent in the large cage structure and/or the strong electron correlation. The latter favors anisotropic pairing in general, while the former may lead to an extended s-wave with the identity representation of the point group.

Motivated by these observations, we consider the multiband and the multicomponent gap model for $PrOs_4Sb_{12}$. Specifically, we consider $s + id$ wave state ($\Delta_\ell(\mathbf{k}) = \Delta_{s\ell}(\mathbf{k}) + i\Delta_{d\ell}(\mathbf{k})$) both in heavy and light bands ℓ. The single-band $s + id$ wave gap was discussed by Goryo [5], who tried to explain the "transition" between the two- and the four-fold symmetry in the thermal conductivity under the magnetic fields. We demonstrate that this "transition" is indeed a crossover of two gaps, and the real transition from the $s + id$ wave to the pure d wave state occurs near $H_{c2}(T)$. Using the approximate analytic solution in the quasiclassical formalism, we determine variationally the gap magnitudes, $\Delta_{s\ell}$ and $\Delta_{d\ell}$, and discuss the various physical quantities under magnetic fields within the single framework. Our main results are:

- When the attractive interactions in s- and d-wave channels are comparable in the heavy band, the double transition occurs along the $H_{c2}(T)$ boundary, as observed in the experiment. With decrease of T or H, the pure d-wave state first appears, then the $s+id$ wave continuously develops below the lower T_c, at which the specific heat jumps again.

- The nonlocal contribution from the smaller gap in the light band gives the T^2-like dependence of the penetration depth at low T, which is consistent with the zero-field radiofrequency measurement [6].

- The rapid rise of $\kappa(H)$ at low fields can be understood in terms of the weakness of the small gap with large coherence length against impurities, and of the large Fermi velocity.

- The crossover from the two- to the four-fold symmetry in $\kappa(H)$ with increasing fields can be explained in terms of decreasing contribution from the d-wave component of the small gap with the large velocity.

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