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# Penetration depth study in the heavy-fermion superconductor $PrOs_4Sb_{12}$

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## Abstract

The penetration depth $\lambda$ in the filled-skutterudite heavy-fermion superconductor $PrOs_4Sb_{12}$ has been measured using transverse-field muon spin rotation (TF-μSR). It is found to be temperature-independent at low temperatures, consistent with a nonzero gap for quasiparticle excitations. In contrast, radiofrequency (RF) measurements yield a stronger temperature dependence of $\lambda(T)$, indicative of point nodes in the gap. A ~10% discrepancy is found at low temperatures. This may be due to mechanisms that modify the vortex-state field distribution, or to the surface scattering which breaks pairs in an odd-parity superconductor. Alternatively, it may be a matter of field orientation of nodal gap structure in the μSR measurements.

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## 1. Introduction

The heavy-fermion-(HF) filled-skutterudite superconductor (SC) $PrOs_4Sb_{12}$ has attracted much interest because of its unconventional order parameter and pairing mechanism. It is the first Pr-based HFSC, with a superconducting transition temperature $T_c = 1.85\,K$ and an effective mass $m^* \approx 50m_e$, where $m_e$ is the free-electron mass [1,2]. It is distinguished from other unconventional SC in that it has a nonmagnetic ground state of the localized *f* electrons in the crystalline electric field (CEF). Magnetic susceptibility, specific heat and inelastic neutron scattering experiments suggested that the CEF ground state of the $Pr^{3+}$ ions is a nonmagnetic $\Gamma_1$ singlet (cubic notation), separated from a $\Gamma_5$ triplet excited state by ~10 K [1–3]. The mechanism for the superconductivity of $PrOs_4Sb_{12}$ has been attributed to quadrupolar fluctuations [1,4] or, alternatively, to "rattling" of Pr ions in the icosahedral Sb cages of the filled-skutterudite structure [5].

A recent zero-field μSR experiment on $PrOs_4Sb_{12}$ reveals the spontaneous appearance of static internal magnetic fields below $T_c$, providing evidence that the superconducting state is a time-reversal-symmetry-breaking (TRSB) state [6]. Our previous transverse-field muon spin relaxation (TF-μSR) [7] and antimony nuclear quadrupole resonance measurements (Sb-NQR) [8] indicate a strong-coupling-based isotropic nodeless energy gap. However,

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several recent experiments indicate the presence of point nodes in the energy gap [9,10], most notably thermal conductivity measurements on $PrOs_4Sb_{12}$ in a magnetic field, which have been interpreted as evidence for two distinct superconducting phases, a low-field phase with two point nodes and a high-field phase with four or six point nodes.

## 2. Experimental results and discussion

We have carried out new time-differential TF-μSR experiments at the M15 channel at TRIUMF, Vancouver, Canada, on a mosaic of oriented $PrOs_4Sb_{12}$ crystals. The crystals were mounted on a thin GaAs backing, which rapidly depolarizes muons in transverse field and minimizes any spurious signal from muons that do not stop in the sample. μSR asymmetry data were taken for temperatures in the range 0.02–2.5 K and $\mu_0 H$ between 10 and 100 mT applied parallel to the $\langle 1\,0\,0\rangle$ axes of the crystals. Representative TF-μSR muon-spin precession signals at an applied field of 10 mT are shown in Fig. 1 in the normal and superconducting states. A small nonrelaxing background signal is visible at long times in Fig. 1(b). The μSR data were fit to an analytical Ginzburg–Landau model for the spatial field profile of the vortex lattice for $H \ll H_{c2}$ [11]:

$$\mathbf{B}(\mathbf{r}) = B_0(1-b^4)\sum_{K}\frac{e^{-i\mathbf{K}\cdot\mathbf{r}}uK_1(u)}{\lambda^2K^2}\,\hat{z}, \tag{1}$$

where $\lambda$ is the magnetic penetration depth, the $\mathbf{K}$ are the reciprocal-lattice vectors of the unit cell, $K_1(u)$ is a modified Bessel function, $b = B/B_{c2}$ is the reduced field, and

$$u^2 = 2\xi^2K^2(1+b^4)[1-2b(1-b)^2], \tag{2}$$

where $\xi$ is the Ginzburg–Landau coherence length. The fits are insensitive to the vortex core region for $H \ll H_{c2}$. This is due to the large Ginzburg–Landau parameter $\kappa = \lambda/\xi$ and the low field, which means the vortex core region only occupies a very small region of the sample. In addition, the line shapes in frequency space are not very asymmetric, and the high-field tail due to the field near the vortex cores is not easily distinguished. By fixing $\xi$ at different values it is found that the value of $\lambda$ returned by the fits is not very sensitive to the choice of $\xi$. Hence by fixing $\kappa = 30$ [1,7], the fit is statistically satisfactory.

The temperature dependence of $\lambda$ is shown in Fig. 2 for an applied field of 10 mT. It can be seen that $\lambda(T)$ is constant below ~1 K, indicative of a gapped quasiparticle excitation spectrum. The curve $\lambda(T) = \lambda(0)(1+\sqrt{(\pi\Delta/2T)}\,e^{-\Delta/T})$ [7] gives a good fit to the data for $T \leqslant 0.5T_c$ (inset of Fig. 2), suggesting that the energy gap is isotropic. However, radiofrequency (RF) measurements of the surface penetration depth in the Meissner state [10] suggest point nodes in the energy gap. In Fig. 3 we compare the change $\Delta\lambda = \lambda(T) - \lambda(0)$ obtained from μSR and surface measurements. Although the effect is small, in the inset it can be seen that at low temperature the increase of the TF-μSR data with increasing temperature is significantly less rapid than for the surface measurements.

The difference between μSR and surface results at low temperatures is similar to that found in the TRSB transition-metal oxide superconductor $Sr_2RuO_4$ [12,13], but such a discrepancy is not found in a number of non-TRSB superconductors. Figs. 4(a) and (b) show the difference $\Delta\lambda_{surf}(T) - \Delta\lambda_{\mu SR}(T)$ for TRSB superconductors $PrOs_4Sb_{12}$ and $Sr_2RuO_4$. Clearly the difference increases with increasing temperature; this is the discrepancy between the measurements noted above. Figs. 4(c)–(f) give $\Delta\lambda_{surf}(T) - \Delta\lambda_{\mu SR}(T)$ from literature data for the HF compound $CeCoIn_5$ [14,15], the borocarbide $YNi_2B_2C$ [16,17], and the high-$T_c$ cuprates $YBa_2Cu_3O_{6.95}$ [18,19] and

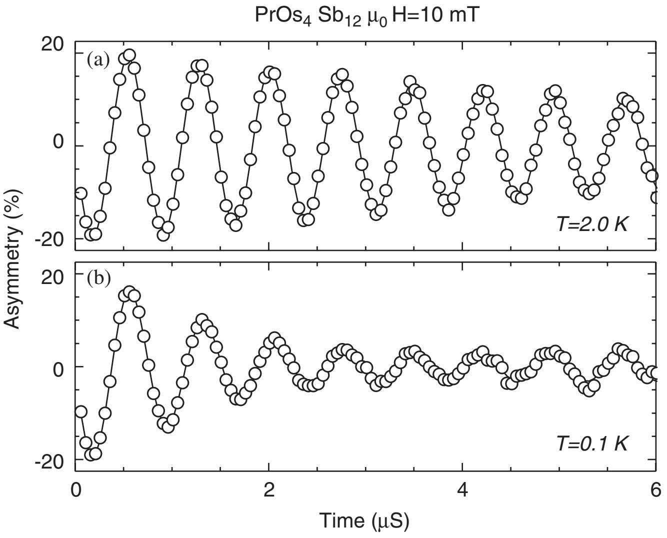

Fig. 1. TF-μSR spin precession signals in $PrOs_4Sb_{12}$, applied field 10 mT. (a) Normal state ($T = 2.0$ K). (b) Superconducting state ($T = 0.1$ K). The weak nonrelaxing signal in (b) is due to muons that do not stop in the sample.

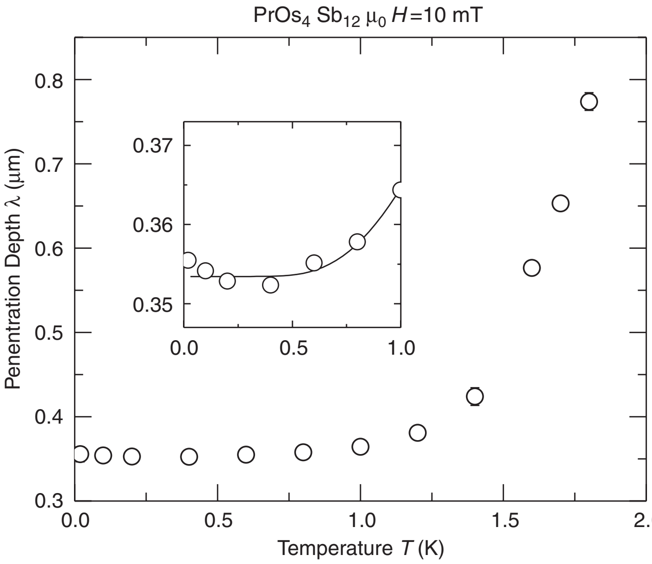

Fig. 2. Temperature dependence of vortex state penetration depth of $PrOs_4Sb_{12}$. Inset: low-temperature dependence. curve: $\lambda(T) = \lambda(0)[1+\sqrt{(\pi\Delta/2T)}e^{-\Delta/T}]$, $\lambda(0) = 0.3534(4)(\mu m)$, $2\Delta/k_BT_c = 4.9(1)$.

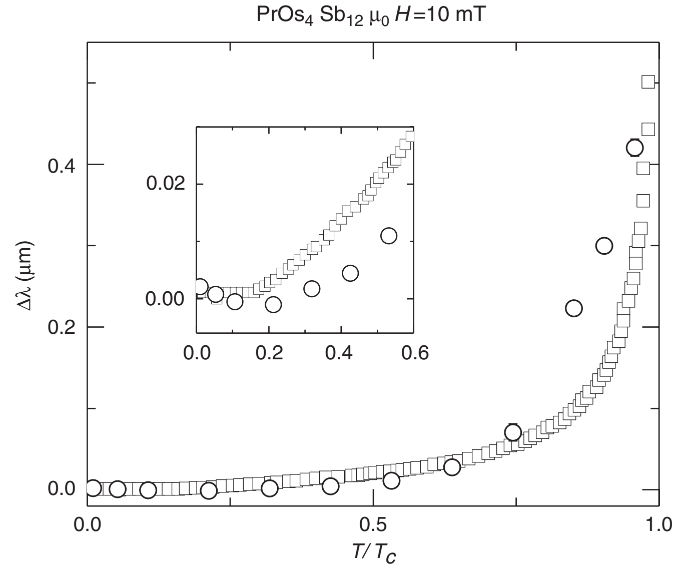

Fig. 3. Dependence of $\Delta\lambda = \lambda - \lambda(0)$ on reduced temperature $T/T_c$. Circles: μSR measurements. Squares: RF measurements of the surface penetration depth in the Meissner state [10]. Inset: low-temperature dependence.

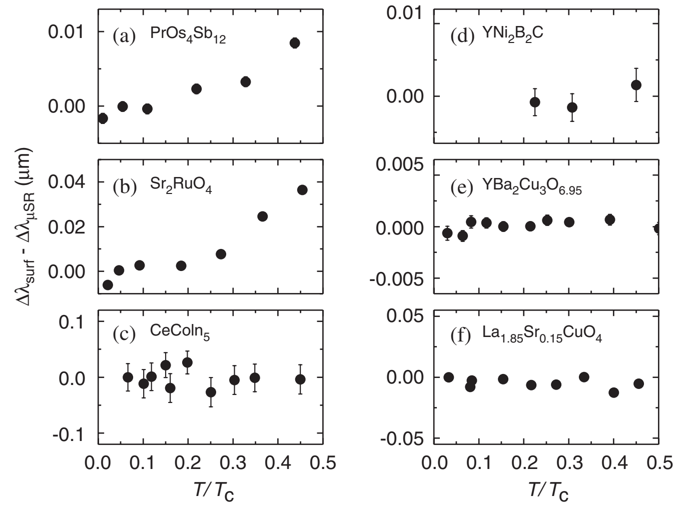

Fig. 4. Dependence of difference $\Delta\lambda_{\mathrm{surf}}(T) - \Delta\lambda_{\mu\mathrm{SR}}(T)$ on reduced temperature $T/T_c$ in six superconductors. (a) $PrOs_4Sb_{12}$, (b) $Sr_2RuO_4$, (c) $CeCoIn_5$, (d) $YNi_2B_2C$, (e) $YBa_2Cu_3O_{6.95}$, (f) $La_{1.85}Sr_{0.15}CuO_4$.

$La_{1.85}Sr_{0.15}CuO_4$ [20,21]. None of these superconductors exhibit TRSB, and none exhibit the temperature dependence of $\Delta\lambda_{\mathrm{surf}}(T) - \Delta\lambda_{\mu\mathrm{SR}}(T)$ seen in Figs. 4(a) and (b).

The origin of this discrepancy between μSR and surface penetration-depth measurements is not well understood at the moment. Low-field low-temperature phase transitions between superconducting states have been reported in both $PrOs_4Sb_{12}$ [22] and $Sr_2RuO_4$ [23], and may be involved in the discrepancy. Both $PrOs_4Sb_{12}$ and $Sr_2RuO_4$ are TRSB compounds, and the TRSB state may be coupled to RF or microwave fields, necessitating a revised interpretation of the surface measurements. It has also been noted that surface scattering breaks pairs in an odd-parity superconductor [24]. The edge currents in TRSB superconductors discussed by Braunecker et al. [25] might also contribute to the RF response. Alternatively, it is possible that the field in the μSR experiments reorients the gap structure so that the nodes are pointing along the field and do not affect vortex-state shielding supercurrents running perpendicular to the field.

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