Broken time-reversal symmetry in superconducting partially-filled skutterudite $Pr_{1-\delta}Pt_4Ge_{12}$

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Background

- **The superconducting gap structure in $PrPt_4Ge_{12}$ is controversial: Point node?[1]? BCS[2]? Multiband[3][4]?**
- **It is puzzling that time reversal symmetry (TRS) breaks at temperature $T_m < T_c$.**

Motivations

A study of an imperfectly filled skutterudite $Pr_{1-\delta}Pt_4Ge_{12}$ to investigate;

(i) whether the cage-forming structure and superconductivity survive with partially filled ^{141}Pr nuclei;

(ii) the effect of the insufficient filled ^{141}Pr nuclei on TRS breaking in $PrPt_4Ge_{12}$

(iii) the gap symmetry of $Pr_{1-\delta}Pt_4Ge_{12}$ and implications of the superconducting order parameter of $PrPt_4Ge_{12}$.

Results

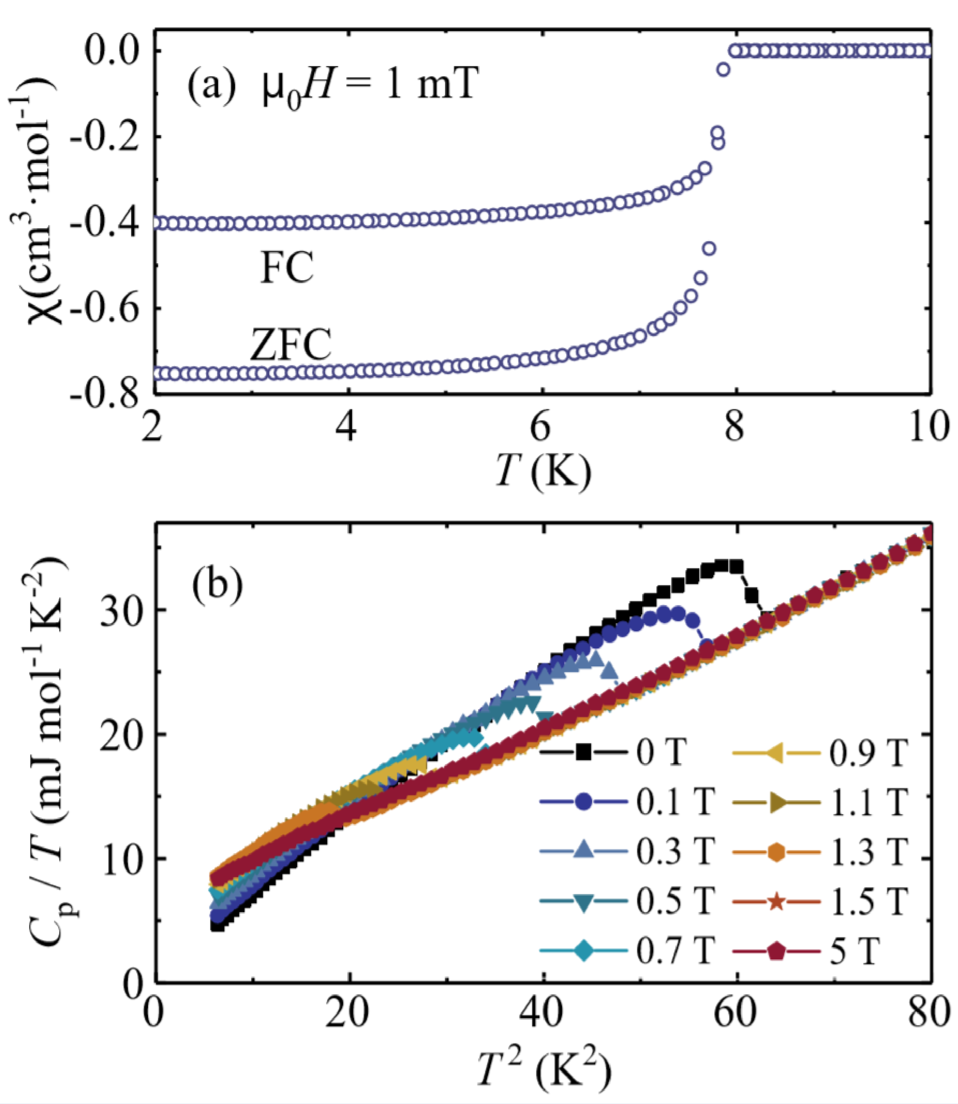

FIG. 1 (a) Magnetic susceptibility of the sample (b) Specific heat data of the sample displayed as C_p/T versus T^2.

- **Superconductivity is observed below T_c = 7.80 K, the same as $PrPt_4Ge_{12}$.**

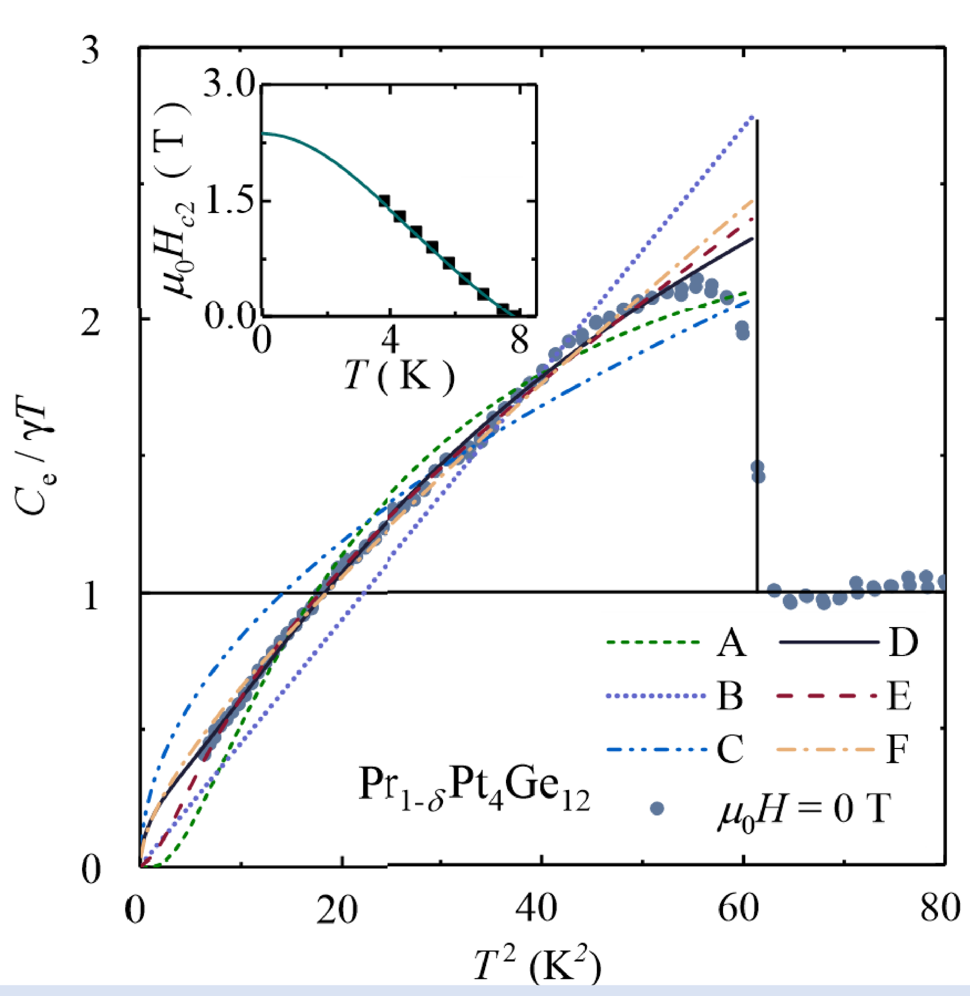

FIG. 2 Temperature dependence of the electronic specific heat coefficient of $Pr_{1-\delta}Pt_4Ge_{12}$ at zero field. The curves represent the fits using six different gap models. Inset: the critical fields H_{c2} derived from the midpoints of the jump in C_p/T. The green curve is the fit of Eq. (1) to data.

$$\mu_0 H_{c2}(\mathrm{T}) = \mu_0 H_{c2}(0)\frac{1-t^2}{1+t^2}, \qquad (1)$$

- **Temperature dependence of both the upper critical field and the electronic specific heat can be described in terms of a two-gap model: evidence of multi-band superconductivity.**

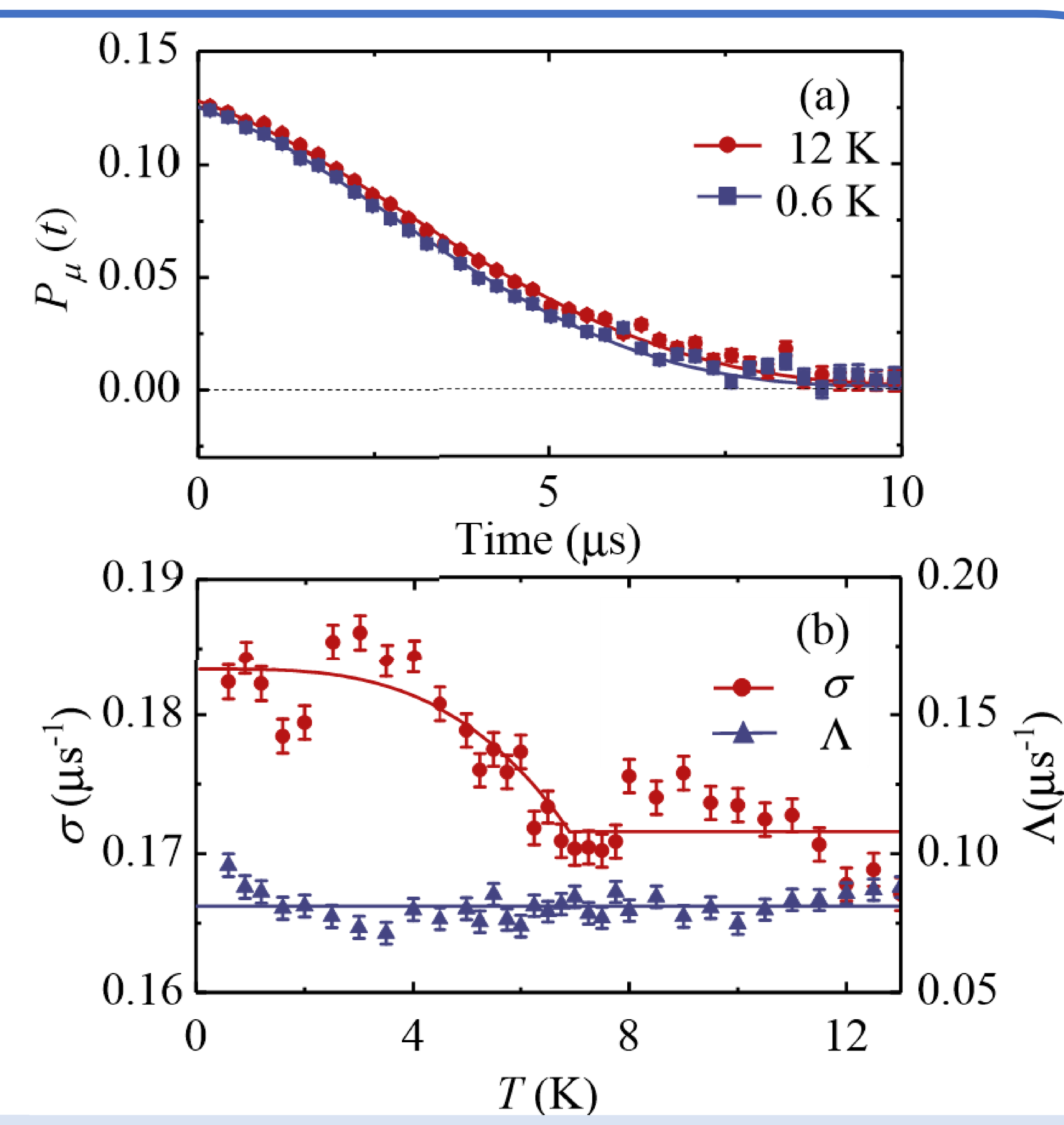

FIG. 3 (a) Zero-field μSR time spectra at 12 K (red circles) and 0.6 K (blue squares) for the sample. A background signal has been subtracted from the data. The corresponding solid lines are fits according to Eq. (3), where λ was fixed at 0 μs^{-1}. (b) Temperature dependence of the muon spin relaxation rates σ (red circles) and Λ (blue triangles). σ was derived from the fitting of Eq. (3) with Λ fixed at 0.08 μs^{-1}. The red curve is the fit of Eq. (5). The blue line denotes the average of Λ data from 0 to 13 K.

$$P_\mu(t) = G_z^{\mathrm{K-T}}(\sigma,\lambda,t)\exp(-\Lambda t). \qquad (3)$$

$$G_z^{\mathrm{K-T}}(\sigma,\lambda,t) = \frac{1}{3} + \frac{2}{3}(1-\sigma^2t^2-\lambda t)\exp(-\frac{1}{2}\sigma^2t^2-\lambda t) \qquad (4)$$

$$\sigma(T) = \begin{cases} \sigma_n & ,T > T_c \\ [\sigma_n{}^2 + \sigma_e(T)^2]^{1/2} & ,T < T_c \end{cases}, \qquad (5)$$

- **$\sigma_e(0)/\gamma_\mu$ in $Pr_{1-\delta}Pt_4Ge_{12}$ is 0.077(4) mT, nearly half of that (0.141 mT) in $PrPt_4Ge_{12}$.**

Conclusions

- **The $[Pt_4Ge_{12}]$ cage-forming structure survives and superconductivity is observed below T_c= 7.80 K.**
- **The temperature dependence of Hc_2 and the electronic specific heat are well described by the two-band model.**
- **The onset of broken TRS is observed at $T_m < T_c$, possibly due to the appearance of a second phase, while no obvious specific jump is observed around T_m.**
- **$\sigma_e(0)/\gamma_\mu$ in $Pr_{1-\delta}Pt_4Ge_{12}$ is half of that in $PrPt_4Ge_{12}$, indicating that the ^{141}Pr nuclei or Pr-Pr intersite interactions are responsible for broken TRS.**

Reference [1] A. Maisuradze, et al, Phys. Rev. Lett. 103, 147002 (2009). [2] F. Kanetake, et al. Physica C 470, S703 (2010). [3] L. S. Chandra, et al. Mag. 92, 3866 (2012). [4] Y. Nakamura, et al. Phys. Rev. B 86, 014521 (2012)