Magnetic quantum critical point and superconductivity in U(Pt,Pd)$_3$

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Invited talk at SCES 2001, 6-10 August, Ann Arbor
1. Unconventional SC in UPt$_3$

- Multiple SC phases
- In SC state $c/T = \gamma_0 + bT$
  - line node in SC gap function
  - vector SC order parameter

Fisher et al., PRL 1989; Vorenkamp et al., PRB1993

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SC phase diagram UPt$_3$ in $B$-$T$ plane

Huxley et al., Nature 2000
Superconducting gap function

<table>
<thead>
<tr>
<th>Even parity</th>
<th>Odd parity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{1g}$</td>
<td>1</td>
</tr>
<tr>
<td>$A_{1u}$</td>
<td>$z k_z$</td>
</tr>
<tr>
<td>$A_{2g}$</td>
<td>$i m(k_x + i k_y)^6$</td>
</tr>
<tr>
<td>$A_{2u}$</td>
<td>$z k_z i m(k_x + i k_y)^6$</td>
</tr>
<tr>
<td>$B_{1g}$</td>
<td>$k_z i m(k_x + i k_y)^3$</td>
</tr>
<tr>
<td>$B_{1u}$</td>
<td>$z i m(k_x + i k_y)^3$</td>
</tr>
<tr>
<td>$E_{1g}$</td>
<td>$k_z \begin{pmatrix} k_x \ k_y \end{pmatrix}$</td>
</tr>
<tr>
<td>$E_{1u}$</td>
<td>$z \begin{pmatrix} k_x \ k_y \end{pmatrix}$</td>
</tr>
<tr>
<td>$E_{2g}$</td>
<td>$\begin{pmatrix} k_x^2 - k_y^2 \ 2k_x k_y \end{pmatrix}$</td>
</tr>
<tr>
<td>$E_{2u}$</td>
<td>$z k_z \begin{pmatrix} k_x^2 - k_y^2 \ 2k_x k_y \end{pmatrix}$</td>
</tr>
</tbody>
</table>

Basis functions for $D_{6h}$ symmetry


E.g.: SC gap for $E_{1g}$

$$\Delta(k) = \eta_1 k_z k_x + \eta_2 k_z k_y$$

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Superconducting pairing mechanism

- SC instability in strongly renormalised FL
  → SC is mediated by spin fluctuations (not phonons)

- AF fluctuations → even-parity SC
  FM fluctuations → odd-parity SC
  Anderson, PRB 1984; Miyake et al., PRB 1986

- SC order parameter of UPt$_3$ has odd parity
  - NMR Tou et al., PRL 1996
  - Impurity studies Dalichaouch et al., PRL 1996; Duijn et al., Physica B 1996

Controversy: Odd-parity SC state, while dominant fluctuations are of AF nature
2. Evolution of SC and AFM in $U(Pt,Pd)_3$

- SC suppressed at $x_{sc} \approx 0.006$
- Small-moment AF "order" for $x \leq 0.01$
- Large-moment AF order for $0.01 \leq x \leq 0.08$

Keizer et al., PRB 1999
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Superconductivity in U(Pt,Pd)$_3$

- $\Delta T_c$ increases with pd content
- $\Delta T_c \sim m^2$ supports SBF model

Keizer et al., PRB 1999
SMAF in $U(\text{Pt},\text{Pd})_3$

- Quasi-linear increase of neutron intensity at $Q = (0.5,1,0)$
  - $T_N \approx 6$ K constant
  - moment grows

- SMAF is crossover effect (fluctuating moment)

Keizer et al., PRB 1999

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LMAF in \( \text{U(Pt,Pd)}_3 \)

- Spin density wave AF ordering at \( Q = (0.5,1,0) \)
- Optimum doping \( x = 0.05 \)
  \( T_N = 5.8 \text{ K} \)
  \( m = 0.63 \mu_B/U \)

Keizer et al., PRB 1999
3. Magnetic QCP probed by $\mu$SR

- Transverse field ($B = 0.01$ T) $\mu$SR
  - implanted $\mu^+$ precesses around the local field $\nu_{\mu}=\gamma_{\mu} B_{\text{loc}}$ ($\gamma_{\mu} = 135.5$ MHz/T is muon gyromagnetic ratio)
  - internal dipolar magnetic fields lead in general to dephasing and damping of $\nu_{\mu}$
  - variation of damping rate with $T$ may yield information about emerging sources of magnetism

- Experiments in LTF ($T > 0.05$ K) at $\pi$M3 beam line at PSI

- Polycrystalline samples U(Pt$_{1-x}$Pd$_x$)$_3$ with $0.007 \leq x \leq 0.009$
Muon depolarisation function

- $\mu^+$ depolarisation:

$$P_{DG}(t) = A_{DG} \cos(\omega t) \exp(-\lambda_E t - \Delta^2 t^2 / 2)$$

- $\Delta \approx 0.06 \mu s^{-1}$ due to Pt nuclear moments

- Fit exponential damping:

$$\lambda_E = \lambda_{BG} + \lambda_{LMAF}$$

- $\lambda_{LMAF} \sim -\ln(T/T_N)$ for $T<T_N$

- $\lambda_{LMAF} = 0$ for $T>T_N$
Magnetic QCP in $U$(Pt,Pd)$_3$

- $T_N$ drops with decreasing $x$
  
<table>
<thead>
<tr>
<th>$x$</th>
<th>$T_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>1.23 K</td>
</tr>
<tr>
<td>0.008</td>
<td>0.78 K</td>
</tr>
<tr>
<td>0.007</td>
<td>0.45 K</td>
</tr>
</tbody>
</table>

- AF QCP at $x_{c,af} \approx 0.006$

AdV et al., PRL 85, 3005 (2000)
Phase diagram for $x \leq 0.012$

- $x_{c,af} = x_{c,sc} \approx 0.006$

Magnetic and SC critical points coincide
4. SC pairing mechanism

- SC vanishes when static AF order emerges
- Since FM fluctuations cannot coexist with static AF order, we propose:

Pd doping leads to a shift of spectral weight from FM to AF fluctuations
→ Odd-parity SC state mediated by FM fluctuations
Ferromagnetic fluctuations?

- Evidence for FM fluctuations
  - $T^3 \ln(T/T_0)$ term in specific heat Stewart et al., PRL 1984
  - Inelastic neutron scattering Bernhoeft et al., J. Phys.: CM 1995

- Investigate magnetic fluctuations by
  - Neutron scattering
  - Transport around the QCP to probe NFL laws:
    \[
    \rho(T) = \rho_0 + aT^\alpha \\
    \text{AF QCP } \alpha = 3/2
    \]

Graf et al., Physica B 2000
Superconductivity at the magnetic QCP

Mathur et al., Nature 1998

Saxena et al., Nature 2000

- AFM CePd$_2$Si$_2$
- Ferromagnet UGe$_2$

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Summary

- $\mu$SR: $U(Pt_{1-x}Pd_x)_3$ AF QCP at $x \sim 0.006$
- LMAF (not SMAF) provides AF instability
- Critical points for SC and AF order coincide
- Doping Pd: FM fluctuations weaken and no longer exist beyond $x \sim 0.006$ where static AF order sets in
- FM fluctuations mediate odd-parity SC