Magnetic Quantum Critical Point and Superconductivity in UPt$_3$ Doped with Pd

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Magnetic Quantum Critical Point and Superconductivity in UPt$_3$ Doped with Pd

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1. Introduction $U(Pt,Pd)_3$

Keizer et al. (PRB 1999)

- Small-moment antiferromagnetism for $x \leq 0.01$
  
  $m \sim 0.01 - 0.05 \mu_B/U$-atom and $T_N \sim 6$ K

- Large-moment antiferromagnetism for $0.01 \leq x \leq 0.08$
  
  Optimal doping for $x = 0.05$: $m \sim 0.6 \mu_B/U$-atom and $T_N \sim 6$ K

- Critical concentration for suppression of superconductivity
  
  $x_{c,sc} \approx 0.006$
Small-moment antiferromagnetism

Keizer et al. (PRB 1999)

- Quasi-linear increase of the neutron intensity measured at $Q = (0.5, 1, 0)$; doubling of the nuclear unit cell along $a^*$

- For $x = 0.000 \rightarrow m = 0.018 \pm 0.002 \mu B/U_{\text{atom}}$
  For $x = 0.005 \rightarrow m = 0.048 \pm 0.008 \mu B/U_{\text{atom}}$

- $T_N$ does not change with Pd content!

- Only observed by neutron-diffraction and magnetic x-ray scattering, not by standard bulk probes, NMR and $\mu$SR → moment fluctuates at a rate >10 MHz
Large-moment antiferromagnetism

Keizer et al. (PRB 1999)

- Rather conventional increase of the neutron intensity measured at \( Q=(0.5, 1, 0) \);
  identical magnetic structure as SMAF

- \( T_N \) is maximum for \( x = 0.05 \), with \( m = 0.62 \pm 0.05 \, \mu_B/\text{U-atom} \)

- \( T_N(x) \) represents a Doniach-like phase diagram

- Also observable in standard bulk probes NMR and \( \mu \text{SR} \)
Unconventional superconductivity

Keizer et al. (1999)

- Splitting $\Delta T_c$ increases with increasing Pd content
- "A phase" survives for $x = 0.004$
- From resistivity experiments $T_c \rightarrow 0$ for $x_{c,sc} \approx 0.006$
- $\Delta T_c$ correlates with $m^2$ which yields support for SMAF as symmetry breaking field
2. Transverse-field μSR experiments

- Experiments carried out at the LTF at the πM3 beam line at the Paul Scherrer Institute
- Polycrystalline samples with 0.007 ≤ x ≲ 0.009
- When positive muons come to rest in the sample they start to precess around the local field, $B_{\text{loc}}$, with a precession frequency
  \[ \nu_{\mu} = \gamma_{\mu} B_{\text{loc}} \]
  \( \gamma_{\mu}/2\pi = 135.5 \text{ MHz/T} \) is the muon gyromagnetic ratio
- The internal dipolar magnetic field distribution in general leads to de-phasing of the precession frequency and consequently the signal is damped
- At each temperature we measure the damping rate in an applied field of 100 G \( \nu_{\mu} = 1.355 \text{ MHz} \) by fitting the depolarization of the muon as function of time \( P(t) \)
- The variation of the damping rate with temperature may yield information about emerging sources of magnetism
Fitting procedure

1. Fit to Gaussian damped depolarization function:

\[ P_G(t) = A_G \cos(\omega t) \exp(-\Delta^2 t^2/2) \]

\( A_G = \) asymmetry, \( \omega = 2\pi \nu \mu \), \( \Delta = \) Gaussian damping rate
At the highest \( T \): \( \Delta \approx 0.06 \mu s^{-1} \)
→ depolarization due to Pt nuclear moments

2. Fit to damped-Gauss function with \( \Delta \approx 0.06 \mu s^{-1} \)

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

\( A_{DG} = \) asymmetry, \( \lambda_E = \) exponential damping rate

3. We determine \( T_N \) by fitting \( \lambda_E = \lambda_{BG} + \lambda_{LMAF} \)

\( \lambda_{BG} = \) background signal
\( \lambda_{LMAF} \sim -\ln(T/T_N) \) for \( T<T_N \) is due to LMAF
\( \lambda_{LMAF} = 0 \) for \( T>T_N \)
Gaussian damped depolarization rate: $\Delta(T)$

$P_G(t) = A_G \cos(\omega t) \exp(-\Delta^2 t^2/2)$

- At highest $T$ depolarization due to Pt nuclear moments: $\Delta = \sim 0.06$ $\mu$s$^{-1}$

- At lower $T$ increase of $\Delta$ signals additional source of internal dipolar fields
**Exponential damping rate** $\lambda_E(T)$

from damped Gauss fit

*de Visser et al., PRL 85 (2000) 3005*

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

with $\Delta \approx 0.06 \, \mu s^{-1}$

• $T_N$ is determined by fitting $\lambda_E = \lambda_{BG} + \lambda_{LMAF}$
  
  $\lambda_{BG} = \text{background signal}$
  
  $\lambda_{LMAF} \sim -\ln(T/T_N)$ for $T<T_N$
  
  $\lambda_{LMAF} = 0$ for $T>T_N$

• $T_N$ drops rapidly with decreasing $x$:
  
  For $x=0.009$ $T_N = 1.23\pm0.10$ K
  
  For $x=0.008$ $T_N = 0.78\pm0.10$ K
  
  For $x=0.007$ $T_N = 0.45\pm0.15$ K
3. Magnetic quantum critical point

*de Visser et al., PRL 85 (2000) 3005*

- In $\text{U(Pt}_{1-x}\text{Pd}_x)\text{$_3$}$ a magnetic quantum critical point is found at $x_{c,\text{at}} \sim 0.006$

- LMAF rather than SMAF represents the antiferromagnetic instability
• The critical concentration for the emergence of LMAF coincides with the critical concentration for the suppression of SC

\[ x_{c,af} = x_{c,sc} \approx 0.006 \]

Notice: For \( x = 0.005 \) absence of LMAF has been demonstrated by zero-field \( \mu \)SR on a polycrystal (\( T > 0.04 \) K) and by neutron-diffraction on a single crystal (\( T > 0.1 \) K).
4. Superconductivity mediated by ferromagnetic spin fluctuations

- Long-standing controversy regarding the superconducting pairing mechanism in UPt$_3$:

"Superconducting order parameter has odd parity while the dominant spin fluctuations are of antiferromagnetic, rather than ferromagnetic, nature".

  Miyake et al., PRB 34 (1986) 6554

- Odd parity:
  polarised neutron diffraction: Stassis et al., PRB 34 (1986) 4382
  NMR: Tou et al., PRL 77 (1996) 1374
  impurity studies: Dalichaouch et al. PRL 75 (1996) 1374,
  Duijn et al., Physica B 223&224 (1996) 44

- AF fluctuations:
  susceptibility: Frings et al., JMMM 31-34 (1983) 240
  neutron scattering: Aeppli et al., PRL 60 (1988) 615

- Our new results show that upon Pd doping superconductivity is suppressed and static antiferromagnetic order emerges

"The antiferromagnetic QCP coincides with the critical point for superconductivity"
• In order to solve the controversy we propose:

"Pd doping leads to a shift of spectral weight from ferromagnetic to antiferromagnetic fluctuations"

Ferromagnetic spin fluctuations mediate superconductivity rather than antiferromagnetic fluctuations

• Evidence for ferromagnetic fluctuations in pure UPt$_3$
  - $T^3\ln T$ term in specific heat: Stewart et al., PRL 52 (1984) 679
  - inelastic neutron-scattering: Goldman et al., PRB 36 (1987) 8523

• In order to test the idea of shift of spectral weight:
  - inelastic neutron-scattering experiments
  - (magneto)transport experiments around the QCP to probe the non-Fermi liquid power laws:
    AF QCP $\alpha=3/2$; FM QCP $\alpha=5/3$

*Graf et al. (Physica B 2000)*

![Graph showing the relationship between Pd concentration and exponent $\alpha$](image)
SC at magnetic QCP in related materials

$U(Pt_{1-x}Pd_x)_3$
odd-parity superconductivity 
mediated by FM fluctuations
suppressed at the AF QCP

Mathur et al. (Nature 1998)

CePd$_2$Si$_2$ (and CeIn$_3$)
even-parity superconductivity
mediated by AF fluctuations at
the AF QCP

Saxena et al. (Nature 2000)

$UGe_2$
p-wave superconductivity
mediated by FM fluctuations
5. Conclusions

- The U(Pt$_{1-x}$Pd$_x$)$_3$ system has an antiferromagnetic quantum critical point at $x_{c,af} \approx 0.006$

- LMAF rather than SMAF represents the antiferromagnetic instability

- The antiferromagnetic QCP coincides with the critical point for superconductivity: $x_{c,af} = x_{c,sc} \approx 0.006$

- Upon doping UPt$_3$ with Pd ferromagnetic fluctuations weaken and no longer exist for $x > 0.006$, where AF order sets in

- Ferromagnetic spin fluctuations mediate odd-parity superconductivity rather than antiferromagnetic fluctuations