$\text{UPt}_3$: More data after all these years

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The UPt₃ Story Begins on a Friday Afternoon:

**Possibility of Coexistence of Bulk Superconductivity and Spin Fluctuations in UPt₃**

G. R. Stewart, Z. Fisk, J. O. Willis, and J. L. Smith

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(Received 24 October 1983)
$\text{UPt}_3$ exhibits Unconventional - SC ($T_c \sim 0.5K$):

Fisher et al., PRL 62,(89).

van Dijk, Physica B 186 (93)
**UPt$_3$ Spin Fluctuation Behavior**

1) Crystal Structure HCP

2) Thermodynamic Signature of Spin Fluctuations - Specific Heat: $T^3 \ln(T/T_{SF})$ at low $T$, AFM correlations in Magnetism, $T_{SF} \sim 18$ K, $B \parallel a$-$b$

3) Neutron scattering [Aeppli, G. et al. PRB32(85)] -

- AFM and FM spin fluctuations

![Crystal Structure Diagram](image)

- **Ferromagnetic Correlations**
  - In-plane, exist up to $T \sim 150$ K

- **Antiferromagnetic Correlations**
  - Between planes, appear at $T < 30$ K

- **Low $T$, $T^3 \ln(T/T_{SF})$ typical of SF systems**

- **HF $\gamma = 422$ mJ/K$^2$ mole**

![Graph](image)

- $T_{SF} \sim 18$ K

- $B \parallel a$, $b$ axis

- $B \parallel c$ axis

- Frings et al. PRB 31 (85)

- **Stabilization of AFM correlations starting at $\sim 30$ K along $c$ (Goldman, PRB,36 (1987))**

- Stewart et al. PRL 52 (84)
Using impurities to study the evolution of magnetism and superconductivity

Why not pressure?
Drives system away from magnetic instability, has minimal effect on superconductivity

Pd (or Au) for Pt, or Th for U strengthen AFM in UPt$_3$
Opposite effect compared to pressure, presumably because all these substitutions slightly reduce c/a ratio in this HCP system

U(Pt$_{1-x}$Pd$_x$)$_3$ is most studied
$x \leq 0.005$: size of ordered moment increases, but onset temperature is constant, and it is still only observable by neutron scattering
$x > 0.01$: onset of conventional AFM with same magnetic structure, much larger ordered moment, and detectable by bulk and local probes
Magnetic Phase Diagram of $U(Pt,Pd)_3$

- Small-moment AF “order” for $x \leq 0.01$
- Large-moment AF “order” for $0.007 \leq x \leq 0.08$
- Superconductivity suppressed at $x_{SC} \sim 0.006$

Keizer et al., PRB, 1999

de Visser et al., PRL, 2000
Phase diagram: detailed for $x < x_c$


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

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DC Magnetization

Magnetization shown to be linear up to $B = 9 \, \text{T}$
Hydrostatic pressure increases c/a
Pd, Th decrease c/a (Pd shrinks lattice, Th expands it)

Pd and Th provide “negative chemical pressure”

Qualitative agreement: Pd (and Th) doping,
Hydrostatic Pressure and the change in the c/a ratio

From Opeil et al., Physica B, June 2002
Normal State Resistivity of U(Pt$_{1-x}$Pd$_x$)$_3$ $0.3 \leq T \leq 300$ K

Resistivity ($\mu$Ohm-cm) vs Temperature (K)

$T_N$

$x = 0.020$

$x = 0.000$

$U(Pt_{1-x}Pd_x)_3$

$B = 0$ Tesla
Electronic Transport/Resistivity  Direct Evidence

$T_N$ vanishes abruptly between $x = 0.013 - 0.014$ in resistivity, but $\mu$SR says no!

Data scaled for comparison

$x=0.050$ data van Sprang
(Thesis UvA, unpublished)
Is there any evidence for quantum critical behavior near $x_c$?

FL $\alpha = 2$

NFL $\alpha \neq 2$, 3Dim - AFM $\rightarrow \alpha = 3/2$

Power law resistivity: $\rho = \rho_0 + AT^\alpha$

Exponent reaches minimum value near 1.5 at concentration near $x_c$

$\alpha_{\text{eff}} = \frac{d \ln(\rho - \rho_0)}{d \ln T}$ constant at low T -- true power law

NFL Behavior? Disorder & Impurity Effects

AFM 3D, $\alpha_{\text{EFF}} = 3/2$


Can we infer a QCP from resistivity data?

Evidence for QCP

1) Decrease of temperature dependent exponent $\alpha$ to near 1.5

2) $T_N \rightarrow 0$ K at $x_c = 0.006$

3) Power law behavior of $x_c = 0.006$ consistent with a strongly disordered NFL (Rosch). No bump upon entering the FL regime.

Evidence against QCP

1) Exponent for *pure* UPt$_3$ is only 1.75, varies from sample to sample

2) No perfect agreement with Temperature dependence in Rosch model

3) Disorder can cause loss of coherence of spin fluctuations $\alpha = 2$, $\alpha \rightarrow 3/2$
   Riseborough, PRB 29(84): SF scattering and disorder interplay...loss of SF coherence
   Lui et al., PRB 61(00): NFL arises from disorder...e.g. CeRhRuSi$_2$

Conclusion: Evidence is ambiguous from Electronic Transport!
U(Pt,Pd)$_3$ Polycrystal (6T)

SCM- Measurements

$T_N$ vanishes between $x = 0.014$ and 0.010
U(Pt,Pd)$_3$ Single Crystal

SCM- Measurements

Except by neutrons, No $T_N$ for $x = 0.010$ single crystal $B = 6$ T

NFL behavior in $x_c = 0.006$ ?

NFL behavior associated with a QCP manifests itself by an upturn in the magnetic susceptibility i.e. $\chi(T) \propto -\beta T^{1/2}$ (3D behavior) or $-\beta \ln T$ (2D behavior) as $T_N \to 0$ K.
Nothing special happens at $x = 0.006$
Specific Heat of $U(Pt_{1-x}Pd_x)_3$

Nothing special happens at $x = 0.006$

AF QCP (3D) Divergence as $T \to 0$ K $\gamma \sim -\ln(T/T_0)$ in Specific Heat
Based on the SCM and specific heat data, we believe the onset of LMAF is a crossover behavior not the result of a true phase transition.

Detection depends on the timescale of the probe

Very broad transition into conventional AFM

\[ G(t) = A_1 \left( \frac{2}{3} e^{-\lambda_1 t} \cos(\omega t) + \frac{1}{3} e^{-\lambda_1 t} \right) + A_2 G_{KL}(t) + A_3 G_{KT}(t) \]

Magnetic

Paramagnetic or weak AFM

Fractional magnetic signal = \( \frac{A_1+A_2}{A_1+A_2+A_3} \)

Why is the transition region so broad? Speculation: Th substitution slows down magnetic fluctuations of weak AFM Observable in $\mu$SR at 7 K

Conclusions:

1) The change in $T_{\text{SF}}$ quantitatively correlates to the change $c/a$ ratio.

2) Resistivity behavior is consistent with NFL, but not distinguishable from disorder effects.

3) No confirmation of NFL nor proposed QCP found by Cantilever Magnetometry or Specific Heat at $x = 0.006$. NFL behavior arises from magnetic instability and SF scattering.

4) AFM ordering (LMAF) at $T_N$ is not observed for $x = 0.010$ by bulk magnetization for $\text{U(Pt,Pd)}_3$ single and polycrystals.

5) We believe that the transition from SMAF to LMAF is a crossover behavior. Pd slows down the temporal fluctuations of the SMAF phase.

Future Work: (Graf Dilution Refrigerator: Boston College)

1) Specific Heat and Cantilever Magnetometry ($0.010 < T < 1 \text{ K}$) on $\text{U(Pt}_{1-x}\text{Pd}_x)_3$ $0 \leq x \leq 0.020$ to examine the affect of doping on the new AFM ordering reported at ($\sim$ 18 mK) by Schubeth et. al. ($c/T$ vs $T$) and Schöttl et al.($\tau$ vs $T$).

2) Hydrostatic Pressure studies on $\text{U(Pt}_{1-x}\text{Pd}_x)_3$ $0.005 \leq x \leq 0.010$ single crystals to examine the possibility of re-entrant (unconventional) SC and impurity effects about the AF magnetic instability.
With special thanks to J. L. Smith:

Happy
65th Birthday!