Magnetic Quantum Critical Point and Superconductivity in UPt_3 Doped with Pd

Presentation
by
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Magnetic Quantum Critical Point and Superconductivity in UPt_3 Doped with Pd

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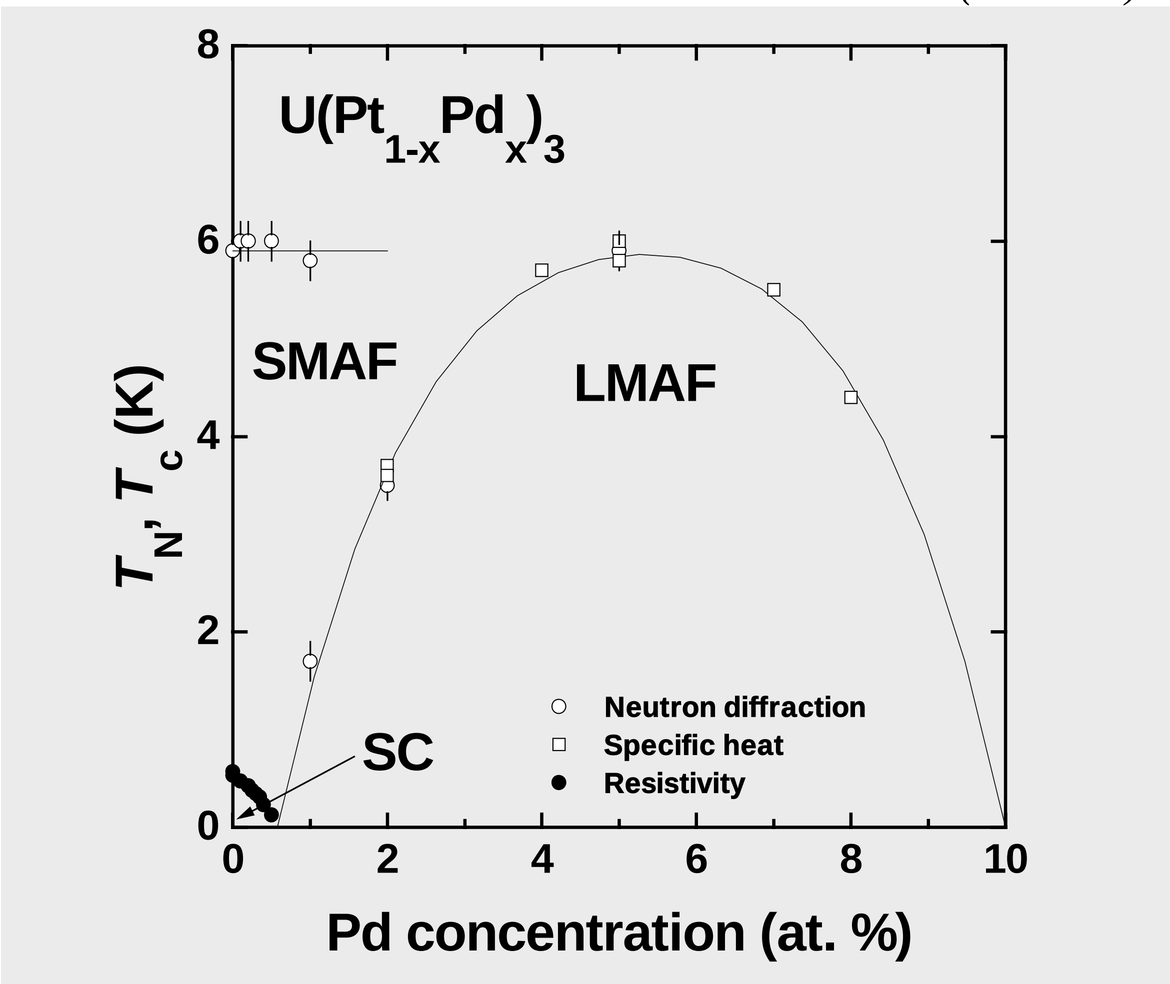
1. Introduction $U(Pt,Pd)_3$

Keizer et al. (PRB 1999)



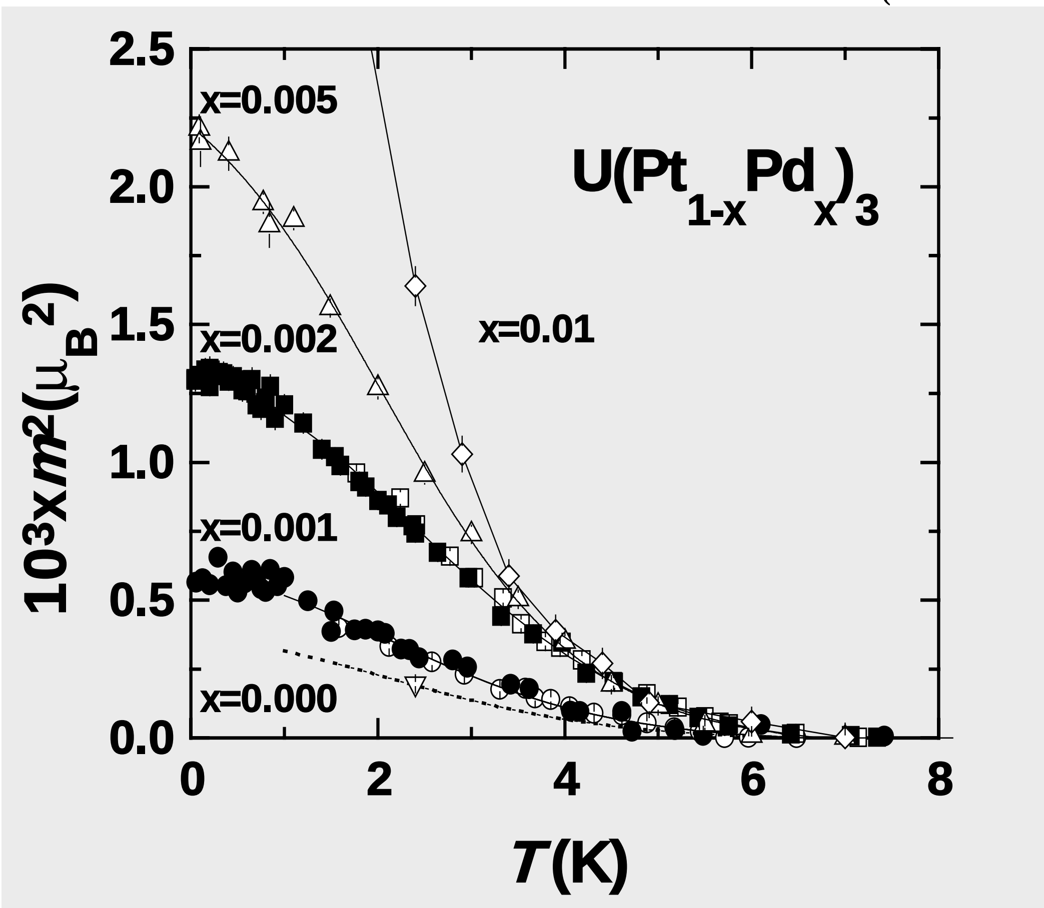
- Small-moment antiferromagnetism for $x \leq 0.01$
  m ~0.01-0.05 μ_B/U-atom and T_N~6 K

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

- Critical concentration for suppression of superconductivity
  $x_{c,sc} \cong 0.006$

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*

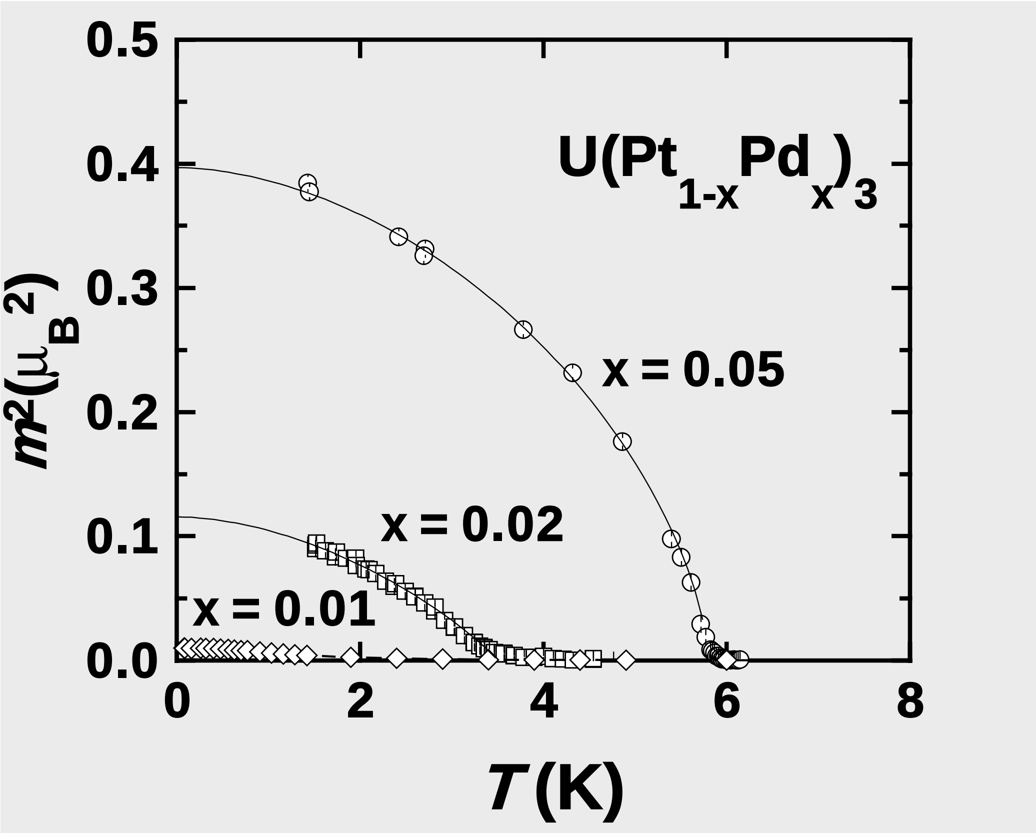
- For x= 0.000 $\rightarrow m$= 0.018±0.002 μ_B/Uatom
  For x= 0.005 $\rightarrow m$= 0.048±0.008 μ_B/Uatom

- 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 μSR $\rightarrow$ 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

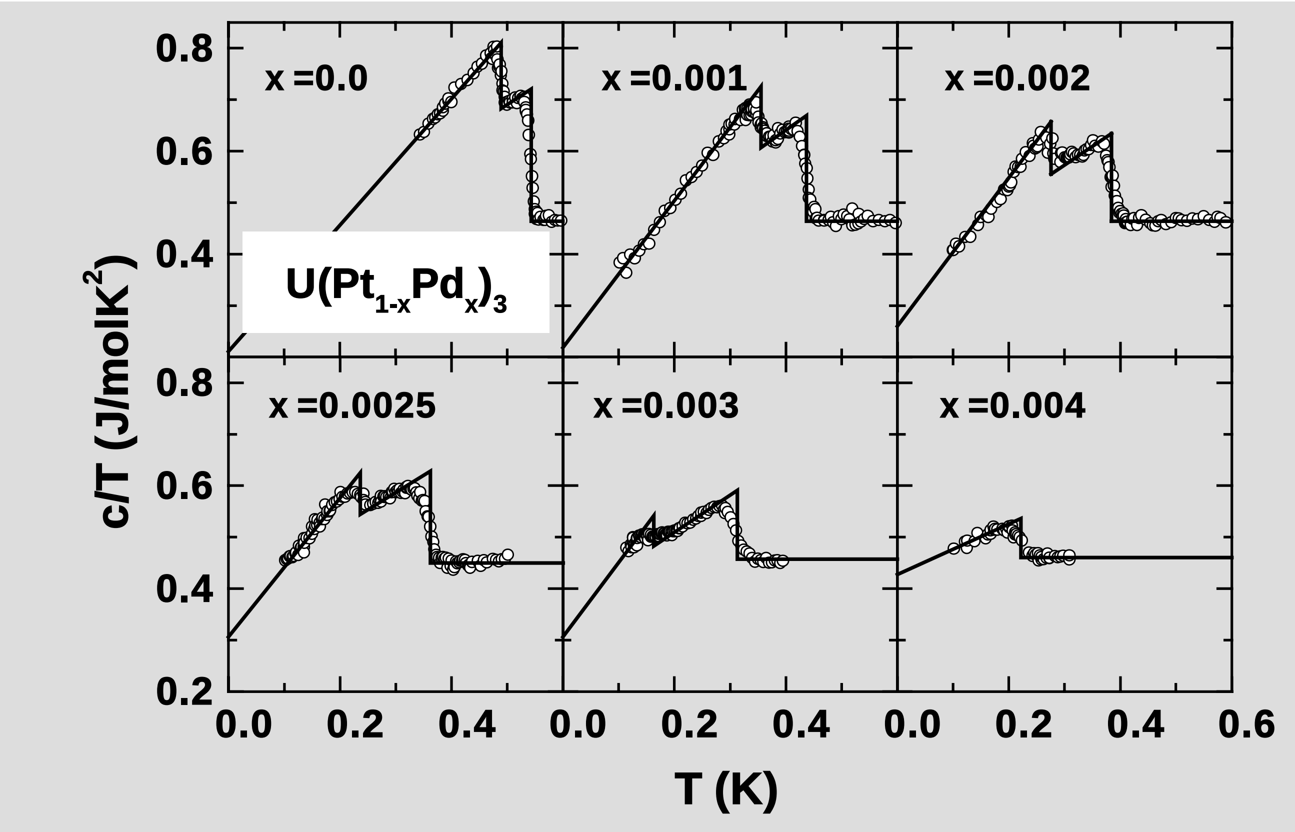
- T_N is maximum for x= 0.05, with m= 0.62±0.05 μ_B/U-atom

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

- Also observable in standard bulk probes NMR and μSR

Unconventional superconductivity

Keizer et al. (1999)



- Splitting ΔT_c increases with increasing Pd content
- "A phase" survives for x= 0.004
- From resistivity experiments $T_c^+ \to 0$ for $x_{c,sc}$~ 0.006
- ΔT_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 $0.007 \leq x \leq 0.009$
- When positive muons come to rest in the sample they start to precess around the local field, B_{loc}, with a precession frequency $\nu_\mu = \gamma_\mu B_{loc}$
  ($\gamma_\mu/2\pi = 135.5$ 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 ($\nu_\mu = 1.355$ 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, $\omega=2\pi\nu_\mu$, Δ= Gaussian damping rate
At the highest T: $\Delta \approx 0.06\ \mu s^{-1}$
$\rightarrow$ depolarization due to Pt nuclear moments

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

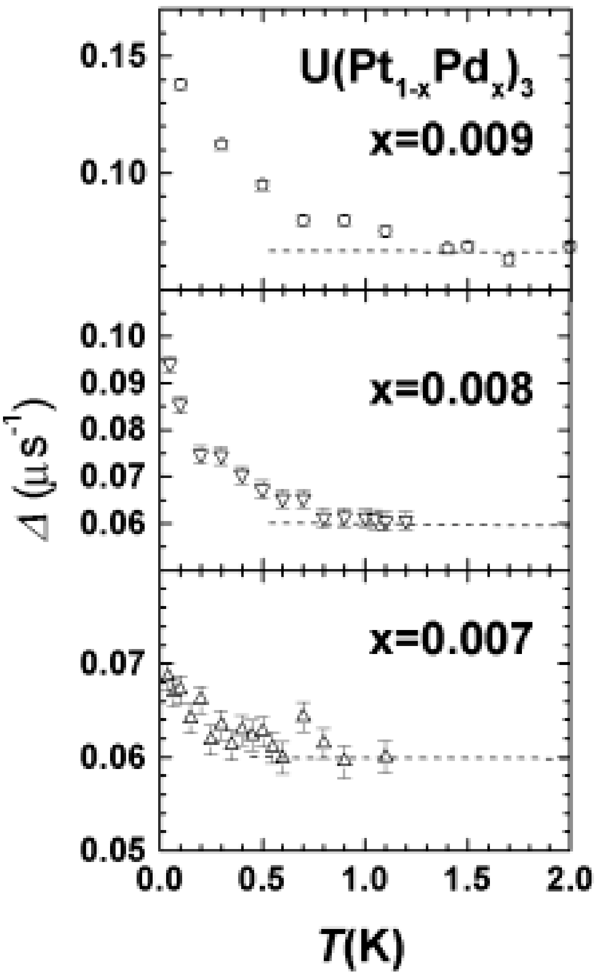
$$P_{DG}(t) = A_{DG}\cos(\omega t)\exp(-\lambda_E t-\Delta^2 t^2/2)$$

A_{DG}= asymmetry, λ_E= exponential damping rate

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

λ_{BG}= background signal
$\lambda_{LMAF} \sim -\ln(T/T_N)$ for $T<T_N$ is due to LMAF
λ_{LMAF}= 0 for $T>T_N$

Gaussian damped depolarization rate: $\Delta(T)$

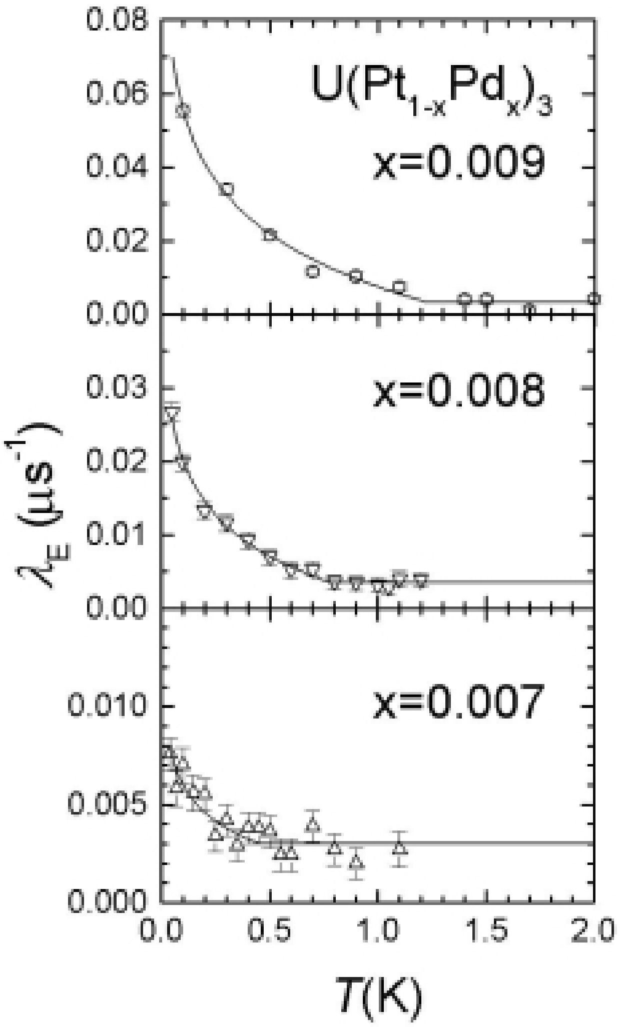


$P_G(t) = A_G\cos(\omega t)\exp(-\Delta^2 t^2/2)$

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

- T_N is determined by fitting $\lambda_E = \lambda_{BG} + \lambda_{LMAF}$

  λ_{BG}= background signal

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

  λ_{LMAF}= 0 for $T>T_N$

- T_N drops rapidly with decreasing x:

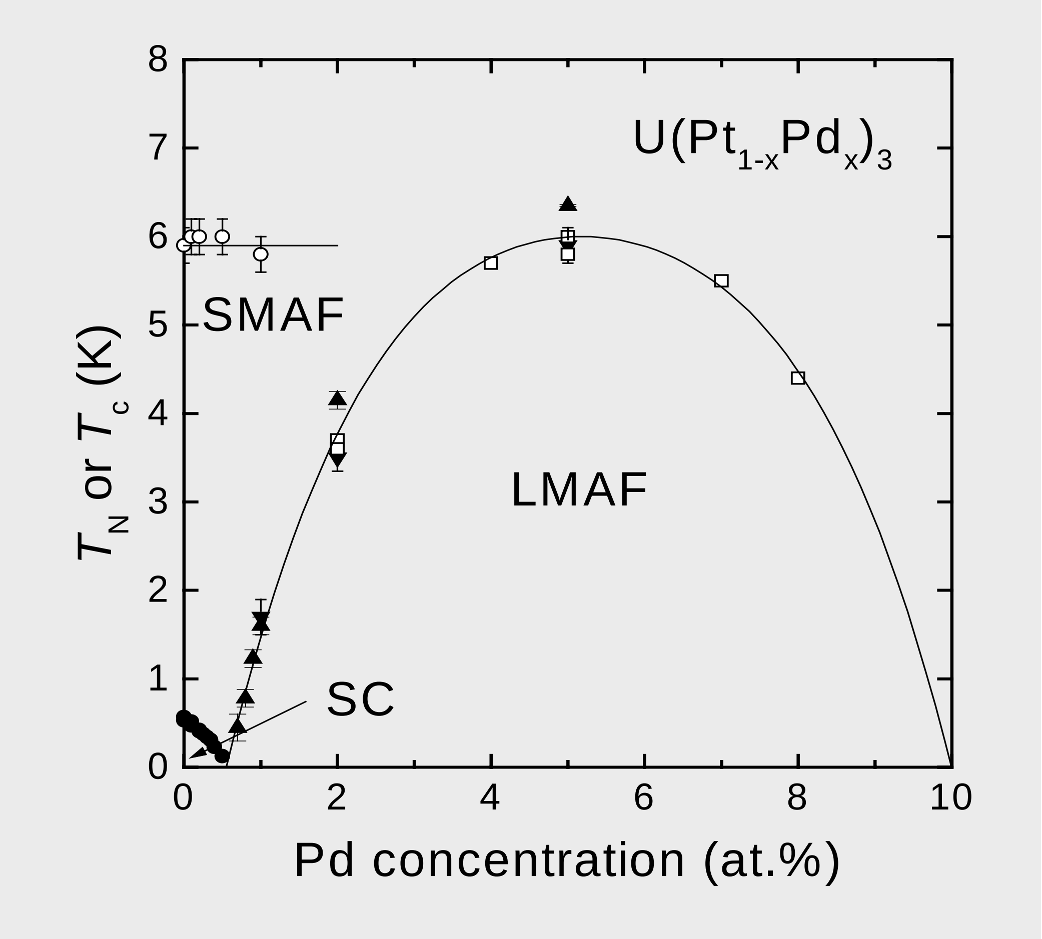
  For x= 0.009 T_N= 1.23±0.10 K

  For x= 0.008 T_N= 0.78±0.10 K

  For x= 0.007 T_N= 0.45±0.15 K

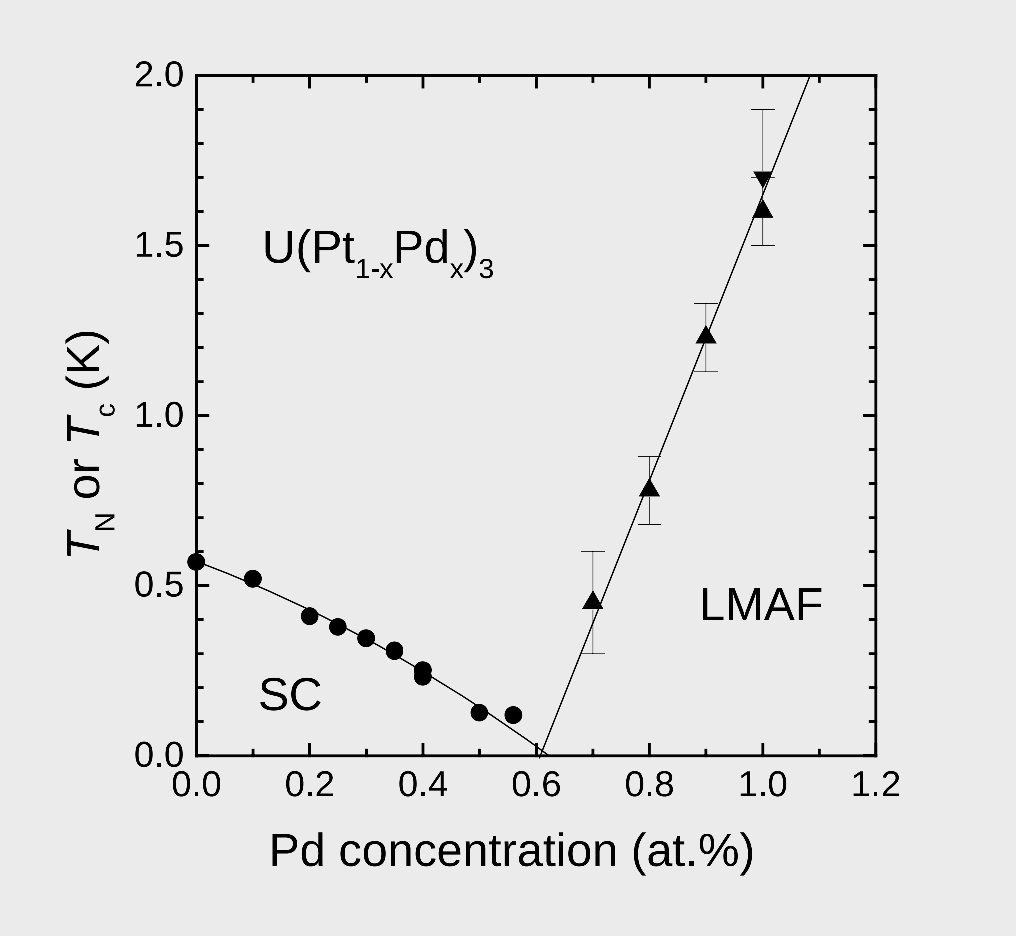
3. Magnetic quantum critical point

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



- In $U(Pt_{1-x}Pd_x)_3$ a magnetic quantum critical point is found at $x_{c,af}$~0.006
- LMAF rather than SMAF represents the antiferromagnetic instability

Phase diagram for $x \leq 0.012$



- 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 μSR 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".

  - Controversy: Anderson, PRB 30 (1984) 1549
    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
    alloying studies: de Visser *et al*., Phys. Lett. 113A (1986) 489
    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:

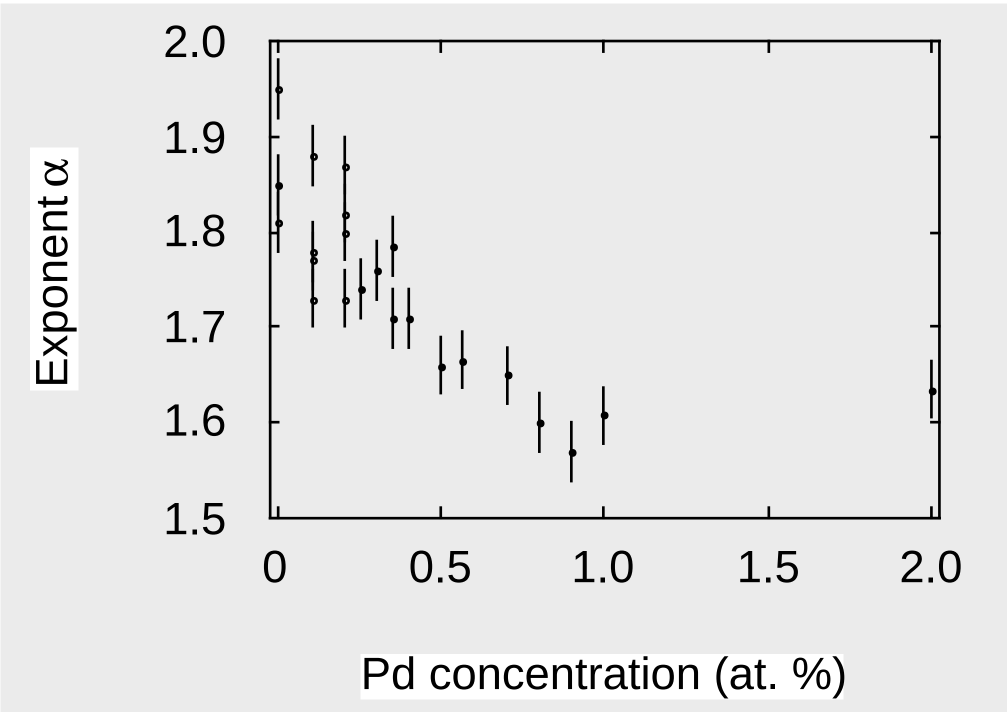
  "Pd doping leads to a shift of spectral weight from ferromagnetic to antiferromagnetic fluctuations"

  Ferromagnetic spin fluctuations mediate superconductivity rather than antiferromagnetic fluctuations

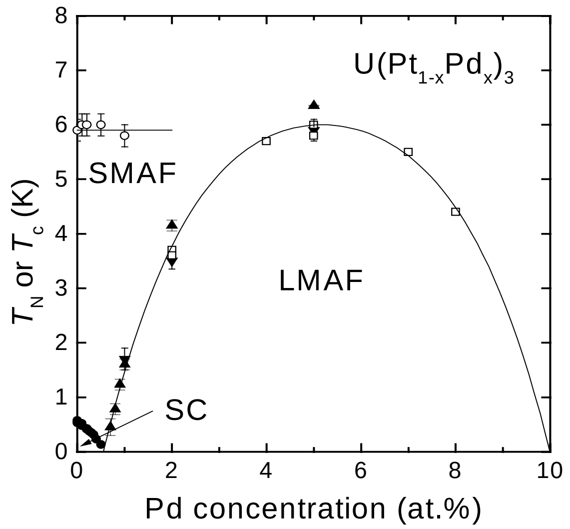
- Evidence for ferromagnetic fluctuations in pure UPt_3
  - $T^3 \ln T$ term in specific heat: Stewart *et al.*, PRL 52 (1984) 679
  - inelastic neutron-scattering: Goldman *et al.*, PRB 36 (1987) 8523

- 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 α=3/2; FM QCP α=5/3

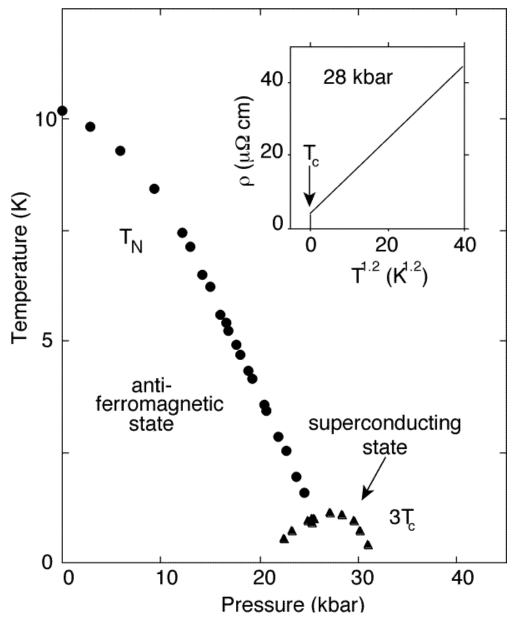
Graf et al. (Physica B 2000)



SC at magnetic QCP in related materials

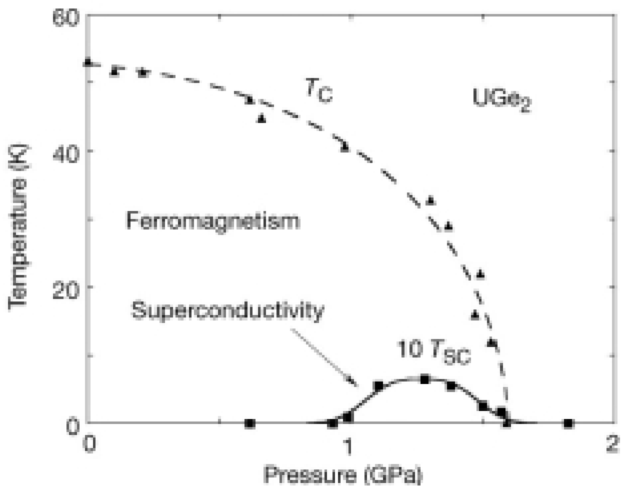


$U(Pt_{1-x}Pd_x)_3$
odd-parity superconductivity mediated by FM fluctuations suppressed at the AF QCP



Mathur et al. (Nature 1998)

$CePd_2Si_2$ (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 $x_{c,af}$~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