Hidden Order and Nexus between Quantum Criticality and Phase Formation: The Case of URu$_2$Si$_2$

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Outline

- Introduction to URu$_2$Si$_2$ and Hidden Order (HO)
- Pressure Tuning : Neutron Diffraction and NMR
- Theories, Models and Conjectures over HO
- Destruction of HO with Field : Magnetization and Transport Properties – Phase Diagram
- Effects of Rh-doping
- Simplified Phase Diagram – only Phase II
- Nexus between Quantum Criticality and Phase Formation
- Characterization of Phase II via C(T,H) and MCE
**Introduction**

**URu$_2$Si$_2$**

ThCr$_2$Si$_2$ bct - type (I4/mmm)

\[ a = 4.127 \text{ (Å)} \]

\[ c = 9.570 \text{ (Å)} \]

Coexistence of HO with SC

T$_{\text{o}} \sim 17.5$ K

T$_{\text{c}} \sim 1.2$ K

T.T.M. Palstra et al. (1985)

W. Schlabitz et al. (1986)

M.B. Maple et al. (1986)
Magnetic susceptibility

\( \chi (10^{-3} \text{ emu/mol}) \)

\( T \) (K)

URu\(_2\)Si\(_2\)

\( \mu_z^{\text{eff}} \approx 2.2 \mu_B \)

\( H \parallel c \)

\( H \parallel a \)

To
Specific heat vs. magnetic Bragg-peak intensity

\[ S_{\text{mag}} \sim 0.2 \, R \, \ln 2 \]

\[ \mu_{\text{ord}} \sim 0.01 - 0.04 \, \mu_B \]

Type-I AF \[ \xi_c \sim 100 \, \text{Å} \]

\[ \xi \sim 300 \, \text{Å} \]
Pseudo-gap in URu$_2$Si$_2$ measured through optical conductivity, D. A. Bonn et al. PRL (1988)

Similarity between optics and neutrons suggests magnetic excitations are strongly coupled to charge excitations
Magnetization as function of temperature, C. Pfleiderer et al. to be published (2005)
$R_H \left( 10^{-3} \text{ cm}^3 / \text{C} \right)$

$R_H \left( 10^{-3} \text{ cm}^3 / \text{C} \right)$

$T (K)$

$H = 8T$

URu$_2$Si$_2$

Experiment Data

Published Data
Neutron scattering under hydrostatic pressure

PRL 83 (1999) 5114
\[
\Gamma^2 (H, \theta, T) = \alpha^2 M^2 (H, \theta, T) + \lambda^2 (T)
\]
Orbital Antiferromagnet

Is the internal field also isotropic at Ru sites?

U-U Bond Current Direction

Resultant Magnetic Field
Hidden Order Unique Enough to Stimulate New Ideas:

Dipolar order with small $g$ values

- Crystal fields: Niewenhuys '86
- Quant. spin fluctuation: Sikkema et al. '96
- Duality: loc./itin.: Okuno, Miyake '98
- Spin-orbital cancellation: Yamagami '99
- Fragile AF order: Bernhoeft et al. '02

Non-dipolar order

- Quadrupole: Miyako et al. '91
- Triple spin: Barzykin, Gor'kov '93
- Quadrupole ($\Gamma_4$): Santini, Amoretti '94
- Quadrupole ($\Gamma_5$): H. A., Sakakibara '94
- Structural distortion: Barzykin, Gor'kov '95
- U dimer: Kasuya '97
- D-wave SDW: Ikeda, Ohhashi '98
- Quadrupole ($\Gamma_5$): Shimizu, Ohkawa '99
- Bond order - OAF: Chandra et al. '01
- Unconventional SDW: Virosztek, Maki, Dóra '02
Hidden Order Unique Enough to Stimulate New Ideas:

Non-translational-symmetry breaking

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Authors</th>
<th>Year</th>
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<tr>
<td>Landau-Pomeranchuk</td>
<td>Varma</td>
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<td>Valency transition</td>
<td>Gor'kov</td>
<td>'04</td>
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<td>Octupolar</td>
<td>Kiss &amp; Fazekas</td>
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<td>Falicov-Kimble</td>
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<td>Itinerant quadrupole</td>
<td>Harrison et al.</td>
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<td>Itinerancy &amp; HO</td>
<td>Tripathi &amp; (PC)^2</td>
<td>'05</td>
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Switching to the Metamagnetic Transition in URu$_2$Si$_2$

What happens as $T$ is lowered?

$\chi$ exhibits divergence for $T > 6$ K as for CeRu$_2$Si$_2$, Sr$_3$Ru$_2$O$_7$ and UPt$_3$.

**THEN SUDDENLY**

crossover splits for $T < 6$ K ($T$-stability crucial for discovery).

Transitions consistent with specific heat measurements [Jaime et al. PRL 89, 287201(2002)].

**CAN FIELD-INDUCED QCP INSTIGATE NEW PHASES?**
Hall Effect Results for URu$_2$Si$_2$ in Pulsed Magnet

\( \rho_{xx} \) for URu$_2$Si$_2$

\( \rho_{xy} \) for URu$_2$Si$_2$

Curvature change?

FS change

URu$_2$Si$_2$ H//c, I//ab

\( \mu_0 H \) (T)

URu$_2$Si$_2$ I//ab, H//c

\( \rho_{xx} \) (\( \mu \Omega \text{cm} \))

\( \rho_{xy} \) (V, arb. unit)

K. H. Kim
10/13/03

Fig. 1, Kim, Harrison, and Mydosh
Multiple phases nearby a QCP: H decreasing

Phase transitions observed as extremities in $d\rho/dB$ and $d\rho/dT$ confirmed in $M$, $C$ and sound velocity $\nu_s$. 
Multiple new phases result from (1) multiple competing interactions and/or (2) close proximity of $B_M$ to Hidden Order phase.
Summary of Transport Results for URu$_2$Si$_2$

**Metamagnetic transition**

$\rho = \rho_0 + AT^n$

$\sim 0.6K \leq T \leq 3 \text{ K}$

All the "smoking guns" indicate $H_{QCP} \sim 37 \text{ T} !$

**URu$_2$Si$_2$**

Another example of order created at quantum critical point??

K.H.Kim, N.Harrison, M.Jaime, G.S.Boebinger and JAM. PRL 91, '03
Effects of Rh-doping in URu$_2$Si$_2$

Phase diagram simplified on doping with Rh, yielding single field-induced phase (II) [without phase I (Hidden Order)] and clearer evidence for quantum critical point.

Quantum criticality occurs in absence of hidden order: so hidden order not responsible for quantum criticality.

Nexus between quantum critical point, phase II and $B_M$ observed as a function of Rh, indicating causality link.
Evidence for quantum criticality occurs at low and high magnetic fields, pointing to a single quantum critical point concealed inside phase II, with scaling: $T^* \propto A^{-1/2} \propto \varepsilon_F$.

Fits of $A$ to $(B-B_M)^\alpha$ support divergence in $m^*$ at quantum critical point: formation of phase II leads to suppression of fluctuations.

Phase II likely holds key to understanding magnetism, because it has 1/3rd of full saturated moment (neutrons should be able to detect large moment that is absent in Hidden Order phase): Ising moments imply broken translational symmetry likely.
phase diagram determined from longitudinal resistance ($\rho_{xx}$)
Metamagnetism and Quantum Criticality

“Transition” from Fermi surface A to Fermi surface B

**Metamagnetism** expected to be first order (no symmetry change?)

**Experimentally** first order transition not seen in itinerant electron metamagnets CeRu$_2$Si$_2$ or UPt$_3$ [Sakakibara et al. PRB 51,12030(1995)].

**Existence** of Fermi liquid at $B_M$ nevertheless quite unthinkable?

**Understanding Fermi surface topology** holds the key to everything

**Issue of Fermi surface change** at antiferromagnetic QCP in antiferromagnetic heavy fermion systems
Fermi Liquids and Quantum Criticality

Quantum critical point between two Fermi liquids: one with polarized $f$-electrons

New phase forms so as to avoid quantum critical point

Phase with $1/3 \text{rd}$ saturated moment possibly analogous to to $Q = 2/3c^*$ ferrimagnetic phase in UPd$_2$Si$_2$? [Honma et al., J. Phys. Soc. Japan 67, 1017 (1998)]
Fig. 4 of Sihanek et al.
$\text{URu}_{2-2x}\text{Rh}_{2x}\text{Si}_2$

$x = 0.04$

mass = 3.2 mg

$C/T$ (J/molK$^2$)

$T$ (K)

Thermodynamic (reversible) anomaly

$S_m = 0.3$ Rln2

Irreversible
\( URu_{(1-x)2}Rh_{2x}Si_2 \)

\( H = 28 \, T \)

\( X = 0.04 \)

Diagram showing the behavior of \( C/T \) as a function of \( T^2 (K^2) \) with a peak at \( T^2 (K^2) \) near 28. The diagram also indicates a phase transition labeled as MCE and a phase labeled as phase II. The graph shows cooling and warming processes.
Magnetocaloric effect

\[ \delta S = \frac{(C \cdot \delta T + \kappa \cdot \Delta T \cdot \delta t)}{T} \]

\[ \delta T = \frac{(Q_{\text{in}} - Q_{\text{out}})}{C} \]

\[ \delta Q_{\text{in}} = -T \cdot \delta S \]

\[ \delta Q_{\text{out}} = \kappa \cdot \Delta T \cdot \delta t \]
$U(Ru_{1-x}Rh_x)_2Si_2$

Body Centered Tetragonal
$a = 4.124 \, \text{Å}, \ c = 9.582 \, \text{Å} \ (4.2 \, \text{K})$
Summary of Progress

1) URu$_2$Si$_2$ exhibits quantum critical behaviour associated with itinerant electron metamagnetism

2) Quantum criticality is involved in creation of new phase(s) at high magnetic fields

3) New phases may also help us to understand Hidden Order parameter

4) Rh doping greatly simplifies the phase diagram with a single phase II surrounded by two low temperature Fermi liquid phases

5) Phase II exhibits an enormous specific heat discontinuity indicative of a first order phase transition - tricritical points