AF-PM-PPM / FM-PM instability \((P, H)\)
Spin Fluctuation and/or FS instability
Ce heavy fermions view from TEP

Ising type systems: \(P, H\) effect – metamagnetism phenomena

AF
\(\text{CeRu}_2\text{Si}_2\): NAF – PPM, Rh decoupling between AF – PPM
\(\text{CeRh}_2\text{Si}_2\): PM - AF-PPM and AF-PM \(\text{UGe}_2\)

FM
\(\text{FM-TCP / FM Wing QCEP : UGe}_2\)
\(\text{H reentrant SC and TCP : URhGe}\)

D Aoki, D Braithwaite, G Knebel, A Pourret, T W Knafo CEA, CNRS (Grenoble-Toulouse)
MT Suzuki Riken
Metamagnetism  \rightarrow \text{Fermi surface}

\begin{align*}
\text{M} & \quad \text{PM} \\
\text{FM} & \\
\text{PPM} & \\
\text{AF} & \quad \text{PM} \\
\text{FM} & \quad \text{PPM} \\
\text{AF} & \quad \text{PPM} \\
\text{FM} & \quad \text{UCoAl / UGe2 wing} \\
\text{QCEP} : P_{QCEP} & \\
H_{QCEP} & \\
P_c &
\end{align*}
<table>
<thead>
<tr>
<th></th>
<th>CeRu$_2$Si$_2$</th>
<th>LaRu$_2$Si$_2$</th>
<th>CeRh$_2$Si$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>4.192 Å</td>
<td>4.215 Å</td>
<td>4.09 Å</td>
</tr>
<tr>
<td>$c$</td>
<td>9.78 Å</td>
<td>9.93 Å</td>
<td>10.18 Å</td>
</tr>
<tr>
<td>$c/a$</td>
<td>2.32</td>
<td>2.20</td>
<td>2.48</td>
</tr>
<tr>
<td>$V$</td>
<td>171 Å$^3$</td>
<td>176.4 Å$^3$</td>
<td>170.3 Å$^3$</td>
</tr>
</tbody>
</table>
Metamagnetic field (AFM: CeRu₂Si₂)

In the AF phase, Ising character of the magnetism leads to a clear first order MMT
At low field PM or AF
PM phase (CeRu2Si2) FS fully determined 4f are itinerant
AF phase close to Pc or Xc from Japan (H Aoki et al) 4f are itinerant

At high field (above Hm) drastic change of FS ....Lifshitz transition
Hot spot in CeRu$_2$Si$_2$ (Rossat Mignod et al / Kadowaki et al)

S Raymond / W Knafo
Mechanism towards low energy scale

Interplay between spin, valence fluctuation and FS topology

Decrease of velocity: via $m^* \text{ SF} - \text{ VF}$
via $k_F$
CeRu2Si2 P=0
Alreary PM phase

In PM phase
Rare case FS fully
Determined
4f itinerant

M Suzuki and H Harima
In field pseudometamagnetism with FS change: TEP response

Previous Exp: Amato (1985), R Daou (2011)
Quantum oscillations below and above the metamagnetic transition even inside the transition.
Quantum oscillations

Aoki H. et al.

\[ \delta \]

\[ \beta \]

\[ \beta' \]

\[ \gamma \]

\[ \gamma' \]

below \( H_m \) (5-7.5T)
above \( H_m \) (9.5-16T)

\[ T=400\text{mK} \]

\[ CeRu_2Si_2 \]

\[ J//a \ H//c \]

H scan on CeRu$_2$Si$_2$ above QCEP

- TEP powerful tool for continuous topological FS evolution at very low temperature
- Improving TEP performance leads to microscopic evidence
- Metamagnetism is driven by electronic instability

Decoupling of metamagnetism (Hc) and pseudometamagnetism (Hm) Rh doping
Hc and Hm two electronic singularities

D Aoki et al J Phys Soc Jpn
Two FS changes at $H_c$ and $H_m$
CeRh2Si2 in the PM regime almost like CeRu2Si2
FS Phase diagram
Density of States and Fermi surface

- 4f electron localized in AF state
- Itinerant in PM state similar to CeRu₂Si₂

As consequence:

- Metamagnetic transition implies strong feedback on the Fermi surface

Calculation: LDA + U, M.-T. Suzuki
Metamagnetism and magnetic anisotropy

The graph shows the magnetization $M$ in units of $\mu_B$/Ce as a function of the magnetic field for different temperatures $T$ in kelvin. The field is applied parallel to the $[001]$ direction of the crystal. The curves are labeled with $H/\mu_B$ values at temperatures of 4.2 K, 20 K, 24 K, 28 K, 32 K, and 40 K, respectively. The graph indicates the magnetic phase transitions and the influence of magnetic anisotropy on the magnetization behavior.
$M//a \ M//c$ Pauli susceptibility isotropic (Settai)
Anisotropy of TEP
H, P studies
P=0 results up to 28 T
Detections of many frequencies
4\(q\)-magnetic structure of CeRh\(_2\)Si\(_2\) (S. Kawarazaki et al. (2000))

Unit cell of AFM

\[ a_{\text{Normal}} = b_{\text{Normal}} = 4.0829 \text{ (Angstrom)} \]
\[ c_{\text{Normal}} = 10.1705 \text{ (Angstrom)} \]
\[ a_{\text{AFM}} = b_{\text{AFM}} = \sqrt{2} a_{\text{Normal}} \text{ (Angstrom)} \]
\[ c_{\text{AFM}} = 2 c_{\text{Normal}} \text{ (Angstrom)} \]

Magnetic Brillouin zone of 4\(q\)-AFM

\(\Gamma\): (0,0,0), \(X\): (1/2, 0, 0), \(M\):(1/2,1/2,0) \(Z\):(0,0,1/2)

\[ a_{\text{AFM}}^* = 2\pi / a_{\text{AFM}} = 1.0882 \text{ (Angstrom}^{-1}) \]
\[ c_{\text{AFM}}^* = 2\pi / c_{\text{AFM}} = 0.3089 \text{ (Angstrom}^{-1}) \]

Length:
- \(\Gamma-X\) \(a_{\text{AFM}}^*/2\)
- \(X-M\) \(a_{\text{AFM}}^*/2\)
- \(\Gamma-Z\) \(c_{\text{AFM}}^*/2\)
Calculated Fermi Surfaces

PM state
no order

AF state (magnetic Brillouin zone 8 x smaller than PM) $p = 0$, $H < H_c$

PPM
$p = 0$, $H > H_c$

⇒ good agreement of observed quantum oscillations frequencies in AF state
⇒ no oscillations in PPM observed in the thermoelectric power experiment
AF phase experiment versus band calculation

TABLE I. List of quantum oscillation frequencies in the AF2 phase for $H \parallel c$ obtained from dHvA measurements of and from $S(H)$ at $T = 468$ mK for the transverse configuration compared with calculated ones.

<table>
<thead>
<tr>
<th>Frequencies of the AF2 phase (T)</th>
<th>dHvA [13 – 16.9] T</th>
<th>S(H) [8 – 16] T</th>
<th>Frequencies calculated (masses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>branches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l</td>
<td>44 (0.43)</td>
<td>44.6 (1.01)</td>
<td>37.0 (0.517)</td>
</tr>
<tr>
<td>k</td>
<td>56 (0.41)</td>
<td></td>
<td>54.9 (0.260)</td>
</tr>
<tr>
<td>j</td>
<td>66 (0.39)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>77 (0.26)</td>
<td>78 (2.2)</td>
<td>72.1 (0.113)</td>
</tr>
<tr>
<td>$\alpha''$</td>
<td>81 (1.8)</td>
<td></td>
<td>89.2 (0.384)</td>
</tr>
<tr>
<td>$\gamma'$</td>
<td>137 (0.45)</td>
<td>123 (2.7)</td>
<td>146.9 (0.360)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>184 (1.4)</td>
<td>189 (1.7)</td>
<td>174.0 (0.251)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>327 (1.9)</td>
<td>311 (3.8)</td>
<td>356.2 (1.380)</td>
</tr>
<tr>
<td>$\varepsilon + d$</td>
<td>445 (5.6; 3.8+2.2)</td>
<td>448.4 (1.263)</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>804 (4.9)</td>
<td>885 (5.5)</td>
<td>881.2 (0.592)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>1160 (3.7)</td>
<td>1278 (6.4)</td>
<td>1173.8 (1.427)</td>
</tr>
<tr>
<td>$\nu-\varepsilon$</td>
<td>1448 (6.0; 3.8+2.4)</td>
<td>1530 (4.7)</td>
<td>1331.3 (1.793)</td>
</tr>
<tr>
<td>$\nu-d$</td>
<td>1603 (4.4; 2.2+2.4)</td>
<td>1594 (3.6)</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>1770 (2.4)</td>
<td>1778 (2.4)</td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>7560 (6.4)</td>
<td></td>
<td>7489.4 (2.259)</td>
</tr>
</tbody>
</table>
Pseudometamagnetism (CeRu₂Si₂)
Metamagnetism (CeRh₂Si₂)
P Studies at H=0
Hall effect : FS change

**Fig. 5.30** – Evolution du rapport $\frac{R_H\sqrt{A}}{\rho_0}$ avec la pression
Coupling with H, P resistivity

\[ S/T(P) \text{ or } S/T(H) \]
P, H Phase diagram

See D Braithwaite Poster
- Difficulty growth of high quality crystal?
- Neutron scattering : $k_B T_K$ versus $J_{ij}$, $C_{CF}$
- TEP longitudinal versus transverse
- Detailed comparison exp, band structure
- Revisit SC : ac calorimetry
- Open question : full determination of PPM FS.

  evidence of real quantum critical point ??????