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Incommensurate Correlations & Mesoscopic Spin Resonance in YbRh2Si2

Collin BROHOLM

Johns Hopkins University, Dept of Physics & Astronomy, Baltimore, U.S.A.
Incommensurate correlations & mesoscopic spin resonance in YbRh$_2$Si$_2$*

C. Broholm

Johns Hopkins University

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Overview

❖ Introduction
  • SDW Quantum Criticality in metals
  • The case of YbRh$_2$Si$_2$

❖ Results & Discussion
  • Incommensurate spin correlations
  • Quasi-FM Quantum Critical Scaling
  • Unconventional spin resonance

❖ Conclusions
Phases of a correlated metal

McWhan et al. PRB (1973)
Phases of a correlated metal

McWhan et al. PRB (1973)

\[ \frac{V_{2-y}O_3}{0.03} \quad \frac{(V_{1-x}Cr_x)_2O_3}{0.04} \]

\[ \text{SDW} \quad \text{AF1} \quad \text{PI} \quad \text{PM} \]

\[ T(K) \quad P(\text{kbar}) \]
Spin Density Wave Order

Bao et al. PRL (1993)

Wolenski et al., PRB (1998)

Experimental \( Q_c \)
Spin Fluctuations & Neutrons Scattering

\[ \frac{d^2 \sigma}{d\Omega dE'} = \frac{k'}{k} \left( \gamma r_0 \right)^2 \left| \frac{g}{2} F(q) \right|^2 e^{-2W(\kappa)} \times \sum_{\alpha\beta} \left( \delta_{\alpha\beta} - \hat{q}_\alpha \hat{q}_\beta \right) S^{\alpha\beta}(q\omega) \]

\[ S^{\alpha\beta}(q\omega) = \frac{1}{1 - e^{-\beta\hbar\omega}} \frac{\chi''(q\omega)}{(g\mu_B)^2 \pi} \]

\[ \chi(q\omega) = \frac{\chi_0(q\omega)}{1 - \mathcal{J}(q)\chi_0(q\omega)} \]

\[ \chi_0(q) = \sum_k \frac{f(\epsilon_{k+q}) - f(\epsilon_k)}{\epsilon_{k+q} - \epsilon_k} \]

\[ (1 0 1) \]

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Field Driven QCP in YbRh$_2$Si$_2$

Kondo Lattice quantum criticality


\[ T_K \propto \exp\left(-\frac{1}{J g(E_F)}\right) \]

\[ T_{RKKY} \propto J^2 g(E_F) \]

Fermi-surface reconstruction at $T_N$?

Friedemann et al. PNAS (2010)
Can Kondo & SDW transition be “detached”?  

S. Friedeman et al., Nature Physics (2009)
YbRh$_2$Si$_2$: neutrons come lately

- 200 x 5 × 5 mm$^2$ crystals
- Mounted with H-free oil
- Total mass 3 g
- Mosaic FWHM 2°
- Penetration depth $\approx$ 2 mm
Field Driven QCP in YbRh$_2$Si$_2$

\[
\text{Gegenwart et al PRL (2002)}
\]

No neutron yet

\[
\text{Gegenwart et al PRL (2002)}
\]

No neutron yet
Collaborators

Chris Stock & F. Demmel
ISIS Facility, Rutherford Appleton Lab

C. Petrovic & R. Hu
Brookhaven National Laboratory

H. J. Kang & Y. Qiu
NIST Center for Neutron Research
Four CF Kramer’s Doublets in YbRh$_2$Si$_2$

\[ |0_+\rangle = (-0.77 \pm 0.05)|\frac{3}{2}\rangle + (-0.63 \pm 0.05)|-\frac{5}{2}\rangle, \]
\[ |0_-\rangle = (0.63 \pm 0.05)|\frac{5}{2}\rangle + (0.77 \pm 0.05)|-\frac{3}{2}\rangle, \]
Incommensurate critical fluctuations

\[ T = 0.1 \text{ K} \quad \hbar \omega = 0.5 \text{ meV} \]
Incommensurate correlations

\[ \vec{Q}_m = (\delta \delta 0) \]
\[ \delta = 0.14(4) \]
\[ \ell \sim 3.6 (\vec{a} + \vec{b}) \]
\[ \hbar \Omega \geq 1 \text{ meV} \]
SDW from nesting instability?

\[ Q_{\text{nest}} = (0.07, 0.07, 0) \]

Norman PRB (2005)

4f hole bands match
Apparent FM correlations upon heating
Finite $\Gamma(T \to 0)$ in non-critical HF systems

$\text{UPt}_3$  \hspace{2cm}  $\text{CeNi}_2\text{Ge}_2$
Quantum critical scaling for $Q \approx 0$

\[
\chi^\prime\prime(\omega) = \frac{\chi_0 \Gamma \omega}{\Gamma^2 + \omega^2} \quad \Gamma = C_0 k_B T \quad \chi_0 = \mu^2_{\text{eff}} / k_B T
\]

\[
k_B T \cdot \chi^\prime\prime(\omega) = \mu^2_{\text{eff}} \frac{\hbar C_0 x}{(\hbar C_0)^2 + x^2} = \mu^2_{\text{eff}} f(x) \quad x \equiv \left( \frac{\hbar \omega}{k_B T} \right)
\]

\[d) \quad \alpha = 1.05 \pm 0.03\]
Critical Exponent \( \alpha = 1.05(3) \)

Trofarelli et al PRL (2010)
Magnetization SQUID & neutrons

Gegenwart et al., NJP (2006)

\[ M(B/Yb) \] vs. \( B \) (T)

\[ M_0 H \parallel [110] \]

\[ I \propto M^2 \]

C. Stock et. al., (2009)

\[ YbRh_2Si_2, Q=(0,0,2), E=0 \text{ meV, } T=100 \text{ mK} \]

\[ \mu_0 H \]

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From SDW to FM correlations with field

\[ \mu_0 H = 5 \, \text{T} \]

Effects of field:
- Upward shift of spectral weight
- Sharp peak at FM position
- Field induced resonance
Field Induced Resonance

$YbRh_2Si_2, T=100 \text{ mK}, \mathbf{Q}=(002)$

\begin{align*}
\hbar \Omega_0 &= g \mu_B \left( \mu_0 H \right) \\
g_\perp &= 3.86 \text{ (neutron)} \\
g_\perp &= 3.56 \text{ (EPR)}
\end{align*}

C. Stock et. al., PRL (2012)
MnSi: Field induced “ferromagnons”

YbRh$_2$Si$_2$ : A spot in Q-space

C. Stock et. al., PRL (2012)
Form factor for chain-end spin

$Y_{2}BaNi_{0.96}Mg_{0.04}O_{5}$

$\hbar \omega = 1.30\text{meV}$

$H=11\text{T }\parallel c$

$T=0.1\text{K}$

SPINS $E_f=5.1\text{meV}$

guide-80'-43'-300'
focused analyzer

Kenzelmann et al. PRL (2003)
Interpretation of the spin resonance

- Coincident g-factors indicate this is Electron Spin Resonance

- Coherent precession of spin density

\[ \xi = 6(2)A \]

- Similar to a Kondo length scale

\[ \xi_K \sim \hbar v_f / k_B T_K \sim 15 \text{ Å} \]

- Kondo Screened spins for \( B > B_c \)
Conclusions

• Effective FM critical regime for \( T > 1 \) K

\[
\left( k_B T \right)^\alpha \cdot \chi''(\omega) = \mu_{\text{eff}}^2 f\left( \hbar \omega / k_B T \right) \quad \alpha = 1.05(3)
\]

• Lower \( T \): Incommensurate critical fluctuations

\[
Q_m = (0.14(4), 0.14(4), 0)
\]

• SDW instability may arise from nesting of hole fermi-surfaces

• \( B \) suppresses SDW favoring FM polarized metal

• Meso-scopic spin precession indicates Kondo screened 4f spin degree of freedom

• SDW correlations persist at lower energies in magnetized kondo lattice state

Outlook

• SDW phase
  – Can band-theory account for incommensurate $Q_c$
  – Detect SDW Bragg peak and measure critical exponents
  – Pressure or doping driven changes in $Q_c$

• QCP
  – Inelastic scattering at lower $T$ and $\hbar \omega$
  – Identify field driven QC metal with higher critical temperatures and/or less neutron absorption