Innovations in Strongly Correlated Electronic Systems: School and Workshop

6 - 17 August 2012

Incommensurate Correlations & Mesoscopic Spin Resonance in YbRh2Si2

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U.S.A.
Incommensurate correlations & mesoscopic spin resonance in YbRh$_2$Si$_2$*

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*Supported by U.S. DoE Basic Energy Sciences, Materials Sciences & Engineering DE-FG02-08ER46544
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)
Spin Density Wave Order

Bao et al. PRL (1993)

Wolenski et al., PRB (1998)

Experimental $Q_c$
Spin Fluctuations & Neutrons Scattering

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

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

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

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

\[ \frac{\epsilon_{k+q}}{\epsilon_k} \]

Bao et al. PRL (1993)
Field Driven QCP in YbRh$_2$Si$_2$

Gegenwart et al. PRL (2002)
Kondo Lattice quantum criticality

Steglich et al, J. Phys. Cond. Matter (2012)

Schroeder et al, Nature (2003)

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

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

Gegenwart et al PRL (2002)

No neutron yet

No neutron yet
Collaborators

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Four CF Kramer’s Doublets in YbRh$_2$Si$_2$

\[ |0\pm\rangle = (-0.77 \pm 0.05)|\frac{3}{2}\rangle + (-0.63 \pm 0.05)|-\frac{5}{2}\rangle, \]
\[ |0\mp\rangle = (0.63 \pm 0.05)|\frac{5}{2}\rangle + (0.77 \pm 0.05)|-\frac{3}{2}\rangle, \]
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?

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

(1-(a/c)^2, 0,2) 
(1-(a/c)^2, 1-(a/c)^2, 2) 

Norman PRB (2005)
Apparent FM correlations upon heating

\[ h\omega \ (\text{meV}) \]

\[ \eta \]  

\[ (\text{hh2}) \ [\text{rlu.}] \]

0.3 K

\[ \Gamma (\text{meV}) \]

a) \( Q=(0,0,2) \)
Finite $\Gamma(T \to 0)$ in non-critical HF systems

$\text{UPt}_3$  $\text{CeNi}_2\text{Ge}_2$

Aeppli et al. (1988)

Schroeder et al. (2009)
Quantum critical scaling for $Q \approx 0$

$$\chi''(\omega) = \frac{\chi_0 \Gamma \omega}{\Gamma^2 + \omega^2} \quad \Gamma = C_0 k_B T \quad \chi_0 = \mu_{\text{eff}}^2 / k_B T$$

$$k_B T \cdot \chi''(\omega) = \mu_{\text{eff}}^2 \frac{\hbar C_0 x}{(\hbar C_0)^2 + x^2} = \mu_{\text{eff}}^2 f(x) \quad x \equiv \left( \frac{\hbar \omega}{k_B T} \right)$$

(d) $\alpha = 1.05 \pm 0.03$
Critical Exponent \( \alpha = 1.05(3) \)

Trofarelli et al PRL (2010)
Magnetization SQUID & neutrons

Gegenwart et al., NJP (2006)

C. Stock et. al., (2009)

YbRh$_2$Si$_2$, $Q=(0,0,2)$,
$E=0$ meV, $T=100$ mK
$\mu_0 H \parallel [110]$
$I \propto M^2$
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

\[ \hbar \Omega = g \mu_B (\mu_0 H) \]
\[ g_\perp = 3.86 \text{ (neutron)} \]
\[ g_\perp = 3.56 \text{ (EPR)} \]

YbRh\(_2\)Si\(_2\), T=100 mK, Q=(002)

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

Tarvin et al., Phys. Rev. (1978).
YbRh$_2$Si$_2$ : A spot in Q-space

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

\[ Y_{2\text{BaNi}_{0.96}\text{Mg}_{0.04}\text{O}_{5}} \]
\[ \hbar \omega = 1.30 \text{meV} \]
\[ H = 11 \text{T} \parallel c \]
\[ T = 0.1 \text{K} \]

SPINS \[ E_r = 5.1 \text{meV} \]
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
  \[ \xi = 6(2) \hat{A} \]

• Similar to a Kondo length scale
  \[ \xi_K \sim \hbar \nu_f / k_B T_K \sim 15 \hat{A} \]

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

- Effective FM critical regime for $T > 1 \text{ K}$
  
  $$
  (k_B T)^\alpha \cdot \chi''(\omega) = \mu_{\text{eff}, f}^2 \cdot f\left(\frac{\hbar \omega}{k_B T}\right) \quad \alpha = 1.05(3)
  $$

- 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

Stock et al to appear in PRL (2012)
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