QCP in strongly correlated superconductors

Hong Xiao

IOP
QCP

Workshop on "Heavy Fermions and Quantum Phase Transitions", Nov 10-12, 2012
Outline

• QCP in heavy fermion superconductor CeCoIn$_5$

• QC in mixed valence compound Ce$_{1-x}$YbCoIn$_5$

• First order QPT and possible QTCP in iron-based superconductor Ba(Fe$_{1-x}$Co$_x$)As$_2$
Outline

• QCP in heavy fermion superconductor CeCoIn$_5$

• Quantum criticality in mixed valence compound Ce$_{1-x}$YbCoIn$_5$

• First order QPT and possible QTCP in iron-based superconductor Ba(Fe$_{1-x}$Co$_x$)As$_2$
HFSC: Prototypical system to study QCP

Doping-tuned QCP

Field-tuned QCP

Pressure-tuned QCP

QCP in CeCoIn$_5$

PRL 89, 157004 (2002)

PRB 73, 064519 (2006)

PRL 91, 246405 (2003)

PRL 106, 087003 (2011)
A direct probe is needed ...
I-V measurements

\[ \rho_{ff} \equiv k \frac{dV}{dI} \]

\( \frac{dV}{dI} \) : the slope of the linear region of the I-V curve

\[ \rho_{ff} \approx \rho_n \]

PRL 108, 056401 (2012)
Abnormal vortex core resistivity

- $\rho_{ff} \uparrow$ sharply as $T, H \downarrow$
- $\rho_{ff} \approx \rho_n$
- Sharp $\uparrow$ in $\rho_{ff}$ reflects the $\uparrow$ in the scattering of the quasiparticles in the vortex core due to critical AF fluctuations near $T_N$

Free flux flow dissipation

Dissipation of the vortices in the presence of pinning

PNAS 107, 9537 (2010)
PRL 108, 056401 (2012)
Pressure suppress the abnormal behavior

The abnormal behavior is greatly suppressed with $P \uparrow$, due to the suppressed AF order inside the vortex core.

AF phase boundary moves deeper inside the SC dome with $P \uparrow$, diminishing the effect of critical fluctuations.

Linear scaling for same $P$, and different $H$ and $T$
Phase diagram

\[ \frac{P - P_c}{P^* - P_c} = \left(1 - \frac{T_N}{T_{c0}}\right) \left(1 - \frac{H_N}{H_{c2}(T_N)}\right) \]

PRL 108, 056401 (2012)
\[ \frac{P - P_c}{P^* - P_c} = \left(1 - \frac{T_N}{T_{c0}}\right) \left(1 - \frac{H_N}{H_{c2}(T_N)}\right) \]

- Give the actual QCP line
- For \( P < P_c \), the SC phase is inside the AF dome
- For \( P > P_c \), the AF phase coexists with SC only inside the vortex cores
- SC and QC are close related

PRL 108, 056401 (2012)
Outline

• QCP in heavy fermion superconductor CeCoIn$_5$

• Quantum criticality in mixed valence compound Ce$_{1-x}$YbCoIn$_5$

• First order QPT and possible QTCP in iron-based superconductor Ba(Fe$_{1-x}$Co$_x$)As$_2$
$\beta$-YbAlB$_4$ NFL behavior without an apparent QCP

Science 331, 316 (2011)

PRL 106, 156403 (2011)

Workshop on "Heavy Fermions and Quantum Phase Transitions", Nov 10-12, 2012
Whether QCP must be present in the material’s phase diagram to induce NFL behavior and trigger SC?
MR data in $\text{Ce}_{1-x}\text{Yb}_x\text{CoIn}_5$
$H_{QCP}$

- Low T behavior: field quenching of AFM spin fluctuations
- At the QCP, the g-factor jumps.

arXiv:1208.4308
Evolution of $H_{\text{QCP}}$

- SC is robust and survives over the whole Yb doping range
- Field-induced QCP is strongly suppressed with Yb doping and disappears for $x>0.20$
- SC and quantum criticality are likely to be decoupled in this system

arXiv:1208.4308
Origin of NFL behavior

\[ \frac{|A|}{|A| + |B|} \]

[Graph and data analysis related to quantum phase transitions and heavy fermions, with references to arXiv:1208.4308 by Dudy et al.]

Workshop on "Heavy Fermions and Quantum Phase Transitions", Nov 10-12, 2012
Outline

• QCP in heavy fermion superconductor CeCoIn$_5$

• Quantum criticality in mixed valence compound Ce$_{1-x}$YbCoIn$_5$

• First order QPT and possible QTCP in iron-based superconductor Ba(Fe$_{1-x}$Co$_x$)As$_2$
Iron-based SC

Science 336, 1554 (2012)
Evidence for QCP

Field tuned QCP coincident with $H_{c2}$

PRL 104, 087005 (2010)

Science 336, 1554 (2012)
Absence of QCP in $\text{BaFe}_{2-x}\text{Ni}_x\text{As}_2$

- The static AF order in changes abruptly from a commensurate wave vector for $x = 0.085$ to an incommensurate wave vector with short-range order for $x = 0.092, 0.096$.

- $T_N$ suddenly vanishes at $x = 0.1$ from $T_N \sim 35K$ for $x = 0.096$. The IC AF to SC phase transition appears to be first order.
Tricritical point in $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$

- A magnetic tricritical point at $x \approx 0.022$

Science **327**, 181 (2010)

$\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$
I-V measurements

Unpublished

Workshop on “Heavy Fermions and Quantum Phase Transitions”, Nov 10-12, 2012
$X = 0.06$, AFM inside SC
$X = 0.06$, AFM inside SC
Summary

The origin of unconventional SC could be much more profound and need to be further explored.