The “115” Superconductors

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Outline:

• 115 heavy fermion primer
• Non-universality of dopants (Cd vs. Sn doping)
  • Influence on quantum criticality and superconductivity
• High Magnetic Field Study of CeRhIn5
  • Competing Density wave
  • Gigantic anisotropy
Superconductivity in Heavy Fermions

- Large entropy goes into the SC state
- Stoichiometric $\rightarrow$ high purity, large m.f.p. (> 1µm)

$C/T$ (J/mol-K$^2$)

- Dirac Materials
- Nodal QP’s
  - that are heavy

$T_c/T_F$ similar to cuprates

$\frac{C}{T} \propto m^*$

- Heavy Electrons
- small energy scale $\rightarrow$ highly tunable

CeCoIn$_5$ H=0 T
CeCoIn$_5$ H=9 T
LaCoIn$_5$
SC in proximity to Antiferromagnetism

- Phase diagram generic for Cerium heavy fermion SC’s
- Parent compound is an AF metal
- $T_c/T_F \sim 0.1$
- SC is unconventional (power laws/sign changing OP)
- Tunable with doping or pressure.
- Spin Fluctuations...
Reducing Dimensionality

Increasing Bandwidth

CeIn$_3\quad T_c = 0.2\ K$

Ce$_2$MIn$_8\quad T_c = 2.1\ K$

CeMIn$_5\quad T_c = 2.3\ K$

CeM$_2$In$_7$

13 compounds in this family are superconductors

NpPd$_5$Al$_2\quad T_c = 5\ K$

PuMGa$_5\quad T_c = 18.5\ K$
Cd vs Sn doping in the 115’s

A Tale of Two Dopants

Why doping?

Dopants provides a window into novel states of matter
How we identified the instability in CeCoIn₅

Cd doping ~ <decreases hybridization>
Sn doping ~ <increases hybridization>

CeRhIn₅
CeRh(In,Sn)₅
CeCo(In,Cd)₅

Cd versus Sn doping

CeRhIn$_5$

T. Park, et al. Nature '08

CeRh(In,Sn)$_5$

S. Seo, et al. Nat. Comm. '15

CeCo(In,Cd)$_5$

Cd versus Sn doping

Cd doping:
- Decreased hybridization
- Small Tc suppression
- Signature of QCP disappears.

Sn doping:
- Increased hybridization
- Larger Tc suppression
- Signature of QCP remains.
Cd = “AFM droplets”
Sn ≈ homogeneous

H. Sakai, et al. unpublished
Little doubt that this system is $d_{x^2-y^2}$. Robustness likely due to strong coupling and extreme multiband.

Are inhomogeneous dopants less pair-breaking than homogeneous ones?

Are filled shells less pair breaking (ie. Cd and Zn)?

Inhomogeneity can obscure signatures of criticality!
QC not always so apparent in pnictides
(QC scaling removed by disorder?)

SC still robust.
Accessing the AFM QCP with magnetic field
A field induced density wave in CeRhIn$_5$


Microstructured CeRhIn$_5$

- Enables magnetoresistance at high fields
- High current densities possible
- Transport anisotropy of small crystals

$\text{RRR} \sim 260$
A field induced density wave in CeRhIn$_5$

- Field induced transition within the AFM state
- Hysteresis vanishes in pulsed fields.

A field induced density wave in CeRhIn$_5$

- Not clearly observed in $M(H)$ or $R_c(H)$
- Small fraction of the Fermi surface participates
A field induced density wave in CeRhIn$_5$

The $I$-$V$ curves resemble CDW systems.

$dV/dl$ ($\mu$V cm) vs. dc current bias (mA)

Field (T)

$\rho_a$

Lower branch

Upper branch

$H_c$

DW

$j_c \sim 190 \mu A$
Angular dependence of the density wave state

- Pushing field into the ab-plane makes the density wave formation energetically unfavorable.
Similarity with cuprates

Competing Phases

A field induced density wave

B. Keimer, et al.
ArXiv: 1409.4673
Anomalous transport with H//ab
Spin Waves in CeRhIn$_5$

The existence of a spin gap, $\Delta_{sg} = 0.25$ meV, is unexpected for the ordered moments $Q = (\frac{1}{2}, \frac{1}{2}, 0.297)$. The Hamiltonian for the system is given by:

$$\mathcal{H} = \sum_{ij} \left[ J_{ij} \left( n_i^x n_j^x + n_i^y n_j^y \right) + \Delta J_{ij} n_i^z n_j^z \right]$$

CeRhIn$_5$ is a frustrated system along the c-axis.

$J_0 = 0.37$ meV, $J_1 = 0.05$ meV, $J_2 = 0.809 J_1$, $\Delta = 0.82$

Spin-Orbit Coupling
How does Spin-Orbit coupling influence $T_c$?

$$Z^4/n^3 \sim \lambda_{SO}$$

Y. Chen, et al. (unpublished)
two non-magnetic dopants (Cd and Sn) produce dramatically different responses.

- Inhomogeneity can have weaker pair breaking effects
- Can also disguise signatures of quantum criticality

Field Induced Density Wave in CeRhIn5 under applied magnetic field

How does spin-orbit coupling influence Tc?