Pressure-induced magnetic quantum critical point and unconventional superconductivity in CrAs and MnP

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OUTLINE

1. QCP and unconventional SC
2. P-induced SC in CrAs
3. P-induced SC in MnP
4. Conclusion and outlooks
Quantum critical point (QCP)

- Ordered phase
- Fermi liquid

\[ m^*/m_0 \]

- Quantum fluctuations
- \( T_N \)

\[ \Delta \rho \propto T^n (1 \leq n < 2) \]

- Non Fermi liquid
- \( C_e/T \propto \ln T \)

Si & Steglich, Science (2010)
Sachdev & Keimer, Phys. Today (2011)
QCP and unconventional SC

Advantages
✓ clean
✓ fine and precise
Cr- and Mn-based superconductor?
OUTLINE

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$1^{st}$ order AF transition of CrAs

**Orthorhombic MnP-type crystal structure**

Pnma (62)
- $a = 5.6680$ Å
- $b = 3.4670$ Å
- $c = 6.2210$ Å

Helimagnetic structure

$Q = 0.353 \cdot 2\pi c^*$

$\alpha_{1,2} = \alpha_{3,4} = -120^\circ$

$\alpha_{2,3} = \alpha_{4,1} = +183^\circ$

$T_N = 265$ K

Acta. Chem. Scan. 25, 1703 (1971); JPSJ 30, 1319 (1971)
Earlier high pressure studies and motivation

What will happen at the magnetic critical point? Superconductivity??


G. I. Plots of $R(T)/R_0$ at various pressures $P$, kbar: 1--0.75; 3--1.4; 4--2.2; 5--3.2; 6--4.3; 7--4.9; 8--9.0.
High-quality CrAs single crystals are important.
HP measurements on the CrAs crystals

- Piston-cylinder cell
- Pressure manometer: Pb
  \[ P(\text{kbar}) = \frac{(7.2 - T_c)}{0.0365} \]
- Pressure medium: Glycerol

Pb CrAs

Pb+CrAs
Discovery of P-induced SC in CrAs

#6 RRR = 240

![Graph showing the relationship between temperature and resistivity for different pressures.](chart)

(a) 

(b) 

(c)
Bulk SC evidenced from ac susceptibility
T-P phase diagram of CrAs

- #6, #7, #9, $T_N^{\text{cool}}$ from $\rho$
- #9, $T_N^{\text{warm}}$ from $\rho$
- $T_N^{\text{warm}}$ from dc-$\chi$
- #6, #7, #9, $T_c^0$ from $\rho$
- #6, $T_c^0$ from ac-$\chi$
- #7a, $T_c^0$ from $\rho$ in PCAC

(a)

RRR

$#6 \ 240$
$#7 \ 327$
$#9 \ 250$

(b)

$|4\pi\chi|_{T=0.4K}$

0 1.0

0.0 0.5 1.0

Pressure (kbar)

0 10 20 30 40 50 60 70

0 1 2 3 4

$\Delta T$ (K)

0.1 0.2 0.3 0.4
$A_2Cr_3As_3$
(A=K, Rb, Cs)
(G. Cao, Zhejiang Univ.)

PRX (2015)
PRB (2015)
SCM (2015)

SC sensitive to disorder

#3  RRR = 45

![Graph showing resistivity (ρ) vs. temperature (T) at different pressures (P) and one bar (1 bar). The graph includes several curves for different pressures, with specific points marked for each curve. The graph also shows the transition temperature (TN) and the critical temperature (Tc) at 30 times the value of TN. The diagram includes lines and symbols representing different materials or samples (#3 and #4).]
Coherent length vs Mean free path

\[ R_H \approx 2.6 \times 10^{-10} \text{ m}^3/\text{C at 5 K} \]
\[ \rightarrow n = 2.4 \times 10^{28} \text{ m}^{-3} \]

\[ L_{\text{mfp}} = \frac{\hbar}{e^2 \rho_0} (3\pi^2)^{\frac{1}{3}} n^{-\frac{2}{3}} \]

\[ \text{RRR} \sim 250 \]
\[ \rho_0 = 2 \times 10^{-8} \ \Omega \text{ m} \]
\[ L_{\text{mfp}} = 766 \ \text{Å} \]

\[ \text{RRR} \sim 50 \]
\[ \rho_0 = 10 \times 10^{-8} \ \Omega \text{ m} \]
\[ L_{\text{mfp}} = 153 \ \text{Å} \]

\[ \mu_0 H_{c2}(T) = \mu_0 H_{c2}(0) \{1 - [T_c/T_c(0)]^\alpha \} \]

\[ \mu_0 H_{c2}(0) = \Phi_0 / 2\pi \xi^2 \]
\[ \xi = 185 \ \text{Å} \]
Neutron scattering: Phys. vs Chem. P

**Physical pressure**

**Chemical pressure**

\[ \text{CrAs}_{1-x}P_x \]
Inelastic neutron scattering

Inelastic neutron scattering of CrAs at 300K and 100K shows NNN AFM correlations.
Evidence for quantum criticality: Enhanced $m^*$

Enhancement of $A$ coefficient near $P_c$; $A \propto (m^*/m_0)^2$
Evidence for quantum criticality: nFL

\[ \rho = \rho_0 + B T^n \]

\[ \rho \] (\(\mu\Omega \text{ cm}\))

\[ P \] (kbar)

\[ T \] (K)

\[ \rho \] vs. \[ T \]

\[ P_c \]

\[ P = 9.5 \text{ kbar} \]

\[ \rho \] (\(\mu\Omega \text{ cm}\)) vs. \[ T^{1.5} \]

\[ T^{1.5} \text{ (K}^{1.5}\) vs. \[ P \] (kbar)

\[ \text{Piston cylinder cell} \]

\[ \text{Palm cubic cell} \]

\[ #9 \]

\[ #6 \]

\[ #7 \]
Further evidences for quantum criticality

CrAs$_{1-x}$P$_x$

$\rho - \rho_0$ vs $T^2 (K^2)$

$C/T (mJ/molK^2)$

$\rho (\Omega \cdot cm)$ vs $T (K)$

$A (10^9 \Omega \cdot cm^2)$ vs $T (K)$

$\gamma (mJ/molK^2)$ vs $x$ in CrAs$_{1-x}$P$_x$
Mn-based superconductor?

Superconductivity in the vicinity of antiferromagnetic order in CrAs

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Nat. Comm. 5, 5508 (2014)
MnP would be the a good start point to approach a magnetic instability by the application of high pressure!!!
Physical properties of MnP at ambient pressure

$T_s \approx 50 \text{ K}$

$T_c = 291.5 \text{ K}$
Earlier high-pressure studies

J. Solid State Chem. 4, 391 (1972)

0-30 kbar: Liquid PTM

30-50 kbar: Solid PTM
HP techniques with extended pressure capacity

Cubic anvil cell

\[ P_{\text{max}} : 15 \text{ GPa} \]
\[ \text{P-medium : Glycerol} \]

Cheng JG, RSI (2014)

Opposed-Anvil Cell

\[ P_{\text{max}} : 12 \text{ GPa} \]
\[ \text{P-medium : Ar} \]

Kitagawa, JPSJ (2010)
P suppresses the magnetic transition;
Possible SC appears near the magnetic instability;
P may alter the nature of magnetic transition
Nearly perfect diamagnetic signal confirms the P-induced SC with a $T_{sc} \approx 1$K in MnP;

SC exists within a narrow pressure range where the magnetic transition just vanishes;
T-P phase diagram of MnP
Signatures of AFM QCP

![Graphs showing the behavior of various parameters with respect to pressure and temperature.](image)

- **non-Fermi-liquid behavior and dramatic enhancement of effective mass $m^*$ near $P_c$**

**Cheng et al. PRL (2015)**
Conclusion and outlooks

- P-induced magnetic QCP is an important approach to search for unconventional SC, e.g. CrAs and MnP.
- Expected to have more Cr- and Mn-based SCs.

Open questions: What is the specialty for the helimagnetic QCP? Can we also realize SC in other helimagnets: FeP, FeAs? Nature of the AFM order in MnP?

Viewpoint

Superconductivity with a Twist

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Published March 16, 2015

The discovery of superconductivity in a manganese-based “helical” magnet opens a new path to explore the relationship between superconductivity and magnetism.