Single crystal growth and basic characterization of intermetallic compounds

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Beautiful single crystals! Then What?

We know how to make a noodle soup.

Is it delicious?

Is it interest? Magnetic, electronic, mechanical, thermal property, and so on…

If so, continue to make it, share the recipe with friends, and discuss how good it is.

Collaborations - open to community and try to understand the nature of the material.

If not, make another one!
Characterizations

Quantum mechanics, electrodynamics, statistical mechanics, and solid state physics

Structural!

Electronic!

Magnetic!

Thermal!

Thermodynamic and transport measurements “bulk”
Determination of crystal structure

- Identify crystal structure: powder and single crystal x-ray

- Determine crystallographic orientations: Laue back reflection

- Analyze elemental compositions: EDX, WDS, EPMA, etc
  \[
  \text{Ba Fe}^{1-x} \text{Co}_x \text{As}_2 : \text{nominal and actual } x
  \]
  Note: site-deficiency is a nature of some materials

- Synchrotron and elastic neutron
- Micro and surface structure: SEM, TEM, etc
Electronic properties - resistivity

Let’s categorize materials like metal, semiconductor, superconductor, and insulator.

We can get a lot of information from the temperature dependence of resistivity.
Electronic properties - resistivity

Resistivity / Resistance

In a simple way

Ohm’s law \( I = (1/R)\ V \)

\[ J = \sigma \ E \]

\[
\sigma = \frac{1}{\rho} = \frac{ne^2 \tau}{m}
\]

- \( n \): carrier density
- \( m \): effective mass
- \( \tau \): relaxation time

Electrical contact: silver/gold paste, soldering

Categorize materials from \( \rho(T) \)

For simple metal
- Temperature dependence
- Residual resistivity
- Residual resistivity ratio
- Spin disorder scattering
- Fermi surface
Electronic properties – Hall, TEP

Carrier density - electron and hole

Resistivity - even
\[ \rho(H) = \rho_{xx}(H) \sim H^2 \]

Hall resistivity - odd
\[ \rho_H(H) = \rho_{xy} \sim H \]

Hall coefficient
\[ R_H = \frac{\rho_{xy}}{H} \]

Thermoelectric power (thermocouple)
\[ S = - \frac{\Delta V}{\Delta T} \text{ (V/K)} \]

S is positive when the direction of electric current is the same as the direction of thermal current. Order of \( \sim \mu \text{V/K} \)

carrier type (electron, hole) – Hall coefficient and Thermoelectric power
Electronic properties - resistivity

Let's categorize materials like metal, semiconductor, superconductor, and insulator.

Metal: Cu, Ag, Au…

Semiconductor: Si, Ge, InSb…

Superconductor: Pb, Sn, In…

Insulator: wood, plastic, glass…

This is a simple picture.

In materials -
- Antiferromagnetic
- Ferromagnetic
- Superconductor
- Metal-to-Insulator
- CDW
- SDW
- Meta-magnetic
- Topologically non-trivial
- Nematic phase

There are more…
Residual resistivity and RRR

Metal at low temperatures

\[ \rho = \rho_0 + AT^2 \]

Residual resistivity \( \rho_0 \)

Residual resistivity ratio RRR

\[ \frac{R(300K)}{R(2K)} \] – geometric factors cancel out

NOTE: the measured electrical resistivity will contain an impurity scattering term, \( \rho_0 \) which appears additively. This is often associated with chemical impurities as well as a variety of structural defects.
Magnetic materials: spin disorder scattering

\[
\rho (\mu\Omega \text{cm}) = \rho_0 + \rho_{sd}
\]

Temperature (K)

- $T_N = 10.9$ K
- AFM order

\[
\rho_{sd}
\]

\[
\rho_0
\]

Resistivity

Temperature (K)

- $T_M$
- spin disorder scattering

- grain boundary, imperfection, dislocation, impurity

J. MMM 205 (1999) 27-52

TbAgSb$_2$

$H \parallel c$

$H \perp c$

$H = 0$

\[R_{RRR} = 53\]
Residual resistivity and RRR

\[ \rho_0 \]

- grain boundary, imperfection, dislocation, impurity

Extremely pure & fully ordered

\[ \rho_0 \approx 0.04 \ \mu\Omega \text{ cm} \]

RRR \approx 1000

Highly disordered:

- Ni site-deficiency
- LuNi\(_{0.81}\)Ge\(_3\)

\[ \rho_0 \approx 22 \ \mu\Omega \text{ cm} \]

RRR \approx 3

In general, high RRR means low \( \rho_0 \).
Residual resistivity and RRR

If the grown material is fully ordered, expected low $\rho_0$, high RRR, and

Quantum oscillations

dHvA

Very large MR
at low temperatures

Simple metal
(semimetal)

MR ~ $H^2$

Kohler rule

$$\frac{\Delta \rho}{\rho(0)} = F \left[ \frac{H}{\rho(0)} \right]^n$$

MR ~ $H^{1.8}$
Quantum oscillations

Quantum oscillations are phenomena observed in quantum systems, particularly in electron systems subject to an applied magnetic field. The frequency of these oscillations is related to the area of the extremal orbit, and is periodic in $1/H$. The amplitude of the oscillations increases as the magnetic field increases and decreases as the temperature increases.

L-K formula: effective (band, renormalize) mass

Dingle temperature, g-factor, and so on...

**Landau gauge:**

\[ H = H_k \]
\[ A = -Hy_i \]

**Landau level**

\[ \varepsilon_n = \frac{\hbar^2 k_z^2}{2m} + (n + \frac{1}{2})\hbar \omega_c \]

**Oscillation frequency:** related to area of extremal orbit, periodic in $1/H$, $p=1/F \sim 1/A$

**Oscillation amplitude:**
- increases as magnetic field increases
- decreases as temperature increases
- L-K formula: effective (band, renormalize) mass

**Dingle temperature, g-factor, and so on...**
Fermi surface of high $T_c$ cuprates

Quantum oscillations SdH

Nature 511, 61 (2014), samples come from UBC

Fourier Transform

Angle dependence – mapping Fermi surface

Multi-band system: PtSn$_4$

Complex and Difficult…

ARPES
CDW (and SDW) transitions, where nested parts of the Fermi surface become gapped below $T_{CDW}$. This leads to a decrease in conductivity $\sigma$ due to a decrease $S_F$. For a partial gapping of the F.S. the sample remains metallic and ultimately returns to $\rho(T)$ with positive slope.

E. Fawcett, Spin-density-wave antiferromagnetism in chromium, RMP 60, 209 (1988)
A. Arrott, Antiferromagnetism in Metals Vol. IIB, p.295


M. Maple, et al., PRL 56, 185 (1986)
Magnetism

- Magnetism
- Larmor diamagnetism (Langevin result)
- Pauli paramagnetism of conduction electrons
- Landau diamagnetism of free electrons
- Curie/Langevin paramagnetism (~ 1/T)
- Magnetic ordering: antiferromagnetic/Ferromagnetic
- NMR, Neutron scattering, ESR, etc.

Diagram:
- Magnetic susceptibility & Magnetization
- Larmor diamagnetism (Langevin result)
- Pauli paramagnetism of conduction electrons
- Landau diamagnetism of free electrons
- Curie/Langevin paramagnetism (~ 1/T)
- Magnetic ordering: antiferromagnetic/Ferromagnetic
- NMR, Neutron scattering, ESR, etc.

Questions:
- Atom or molecule: Na, NO, ...?
- Free atoms and ions with a partially filled shell?
- Exchange interactions?

Diagrams:
- Magnetic susceptibility vs. temperature
- Free spin paramagnetism
- Van Vleck paramagnetism
- Pauli paramagnetism (metals)
- Diamagnetism

Graphs:
- Magnetic susceptibility:
  - Free spin paramagnetism
  - Van Vleck paramagnetism
  - Pauli paramagnetism (metals)
  - Diamagnetism

Symbols:
- valence electron
- conduction electron
- nuclear
Hund Rules

The Hund rules as applied to electrons in a given shell of an atom affirm that electrons will occupy orbitals in such a way that the ground state is characterized by the following:

1. The maximum value of the total spin $S$ allowed by the exclusion principle
2. The maximum value of the orbital angular momentum $L$ consistent with this value of $S$
3. The value of the total angular momentum $J$ is equal to $|L-S|$ when the shell is less than half full and to $L+S$ when the shell is more than half full. When the shell is just half full, the application of the first rule gives $L = 0$, so that $J = S$

$$2S+1 \quad L_j$$

Fe$^{2+}$ 3$d^6$

$L_z = -2 \quad -1 \quad 0 \quad 1 \quad 2$

$L = -2+ -1+0+1+2+ -2 = 2$

$S = 1/2 * 4 = 2$

$J = L + S = 4$

$5D_4$
Hund Rules

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$\text{Ce}^{3+} \ M^{4f^1}$

\[
\begin{array}{cccccccc}
 & & & & & & & \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
\end{array}
\]

$L = 3$

$S = 1/2$

$J = L - S = 5/2$

$2F_{5/2}$

$\text{Gd}^{3+} \ M^{4f^7}$

\[
\begin{array}{cccccccc}
 & & & & & & & \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
\end{array}
\]

$L = 0$

$S = 7/2$

$J = S = 7/2$

$8S_{7/2}$
Hund Rules

The Hund rules as applied to electrons in a given shell of an atom affirm that electrons will occupy orbitals in such a way that the ground state is characterized by the following:
1. The maximum value of the total spin \( S \) allowed by the exclusion principle
2. The maximum value of the orbital angular momentum \( L \) consistent with this value of \( S \)
3. The value of the total angular momentum \( J \) is equal to \(|L-S|\) when the shell is less than half full and to \( L+S \) when the shell is more than half full. When the shell is just half full, the application of the first rule gives \( L = 0 \), so that \( J = S \)

Exercise

\[ \text{Dy}^{3+} \quad 4f^9 \]

\[
\begin{array}{ccccccc}
3 & 2 & 1 & 0 & -1 & -2 & -3 \\
\end{array}
\]

\[
\begin{align*}
L &= \\
S &= \quad 2S+1 \\
J &= L_J
\end{align*}
\]
Exercise

\[ \text{Dy}^{3+} \ 4f^9 \]

L = 5
S = 5/2
J = L+S = 15/2

\[ \frac{6}{15/2} H_{15/2} \]
3d and 4f electron basic level

**Table 2** Effective magneton numbers for iron group ions

| Ion       | Configuration | Basic level | \( p(\text{calc}) = \frac{g}{g[J(J + 1)]^{1/2}} \) | \( p(\text{calc}) = \frac{g}{2|S(S + 1)|^{1/2}} \) | \( p(\text{exp})^{a} \) |
|-----------|---------------|-------------|---------------------------------|---------------------------------|-----------------|
| Ti\(^{3+}\), V\(^{4+}\) | 3d\(^1\)     | \(^{2}\!D_{3/2}\) | 1.55                           | 1.73                           | 1.8             |
| V\(^{3+}\) | 3d\(^2\)     | \(^{3}\!F_{2}\) | 1.63                           | 2.83                           | 2.8             |
| Cr\(^{3+}\), V\(^{2+}\) | 3d\(^3\)     | \(^{4}\!F_{3/2}\) | 0.77                           | 3.87                           | 3.8             |
| Mn\(^{3+}\), Cr\(^{2+}\) | 3d\(^4\)     | \(^{5}\!D_{0}\) | 0                              | 4.90                           | 4.9             |
| Fe\(^{3+}\), Mn\(^{2+}\) | 3d\(^5\)     | \(^{6}\!S_{5/2}\) | 5.92                           | 5.92                           | 5.9             |
| Fe\(^{2+}\) | 3d\(^6\)     | \(^{5}\!D_{4}\) | 6.70                           | 4.90                           | 5.4             |
| Co\(^{2+}\) | 3d\(^7\)     | \(^{4}\!F_{9/2}\) | 6.63                           | 3.87                           | 4.8             |
| Ni\(^{2+}\) | 3d\(^8\)     | \(^{3}\!F_{4}\) | 5.59                           | 2.83                           | 3.2             |
| Cu\(^{2+}\) | 3d\(^9\)     | \(^{2}\!D_{5/2}\) | 3.55                           | 1.73                           | 1.9             |

\(^{a}\text{Representative values.}\)

**Table 1** Effective magneton numbers \( p \) for trivalent lanthanide group ions

(Near room temperature)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Configuration</th>
<th>Basic level</th>
<th>( p(\text{calc}) = \frac{g}{g[J(J + 1)]^{1/2}} )</th>
<th>( p(\text{exp}), \text{approximate} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce(^{3+})</td>
<td>4f(^{6}!5!f)</td>
<td>(^{2}!F_{5/2})</td>
<td>2.54</td>
<td>2.4</td>
</tr>
<tr>
<td>Pr(^{3+})</td>
<td>4f(^{7}!6!f)</td>
<td>(^{3}!H_{4})</td>
<td>3.58</td>
<td>3.5</td>
</tr>
<tr>
<td>Nd(^{3+})</td>
<td>4f(^{8}!5!f)</td>
<td>(^{4}!I_{8})</td>
<td>3.62</td>
<td>3.5</td>
</tr>
<tr>
<td>Pm(^{3+})</td>
<td>4f(^{9}!6!f)</td>
<td>(^{5}!I_{4})</td>
<td>2.68</td>
<td>—</td>
</tr>
<tr>
<td>Sm(^{3+})</td>
<td>4f(^{10}!5!f)</td>
<td>(^{6}!H_{15/2})</td>
<td>0.84</td>
<td>1.5</td>
</tr>
<tr>
<td>Eu(^{3+})</td>
<td>4f(^{11}!6!f)</td>
<td>(^{7}!F_{0})</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>Gd(^{3+})</td>
<td>4f(^{12}!5!f)</td>
<td>(^{7}!F_{4})</td>
<td>7.94</td>
<td>8.0</td>
</tr>
<tr>
<td>Tb(^{3+})</td>
<td>4f(^{13}!6!f)</td>
<td>(^{7}!F_{4})</td>
<td>9.72</td>
<td>9.5</td>
</tr>
<tr>
<td>Dy(^{3+})</td>
<td>4f(^{14}!5!f)</td>
<td>(^{6}!H_{13/2})</td>
<td>10.63</td>
<td>10.6</td>
</tr>
<tr>
<td>Ho(^{3+})</td>
<td>4f(^{15}!5!f)</td>
<td>(^{5}!I_{8})</td>
<td>10.60</td>
<td>10.4</td>
</tr>
<tr>
<td>Er(^{3+})</td>
<td>4f(^{16}!6!f)</td>
<td>(^{4}!I_{9/2})</td>
<td>9.59</td>
<td>9.5</td>
</tr>
<tr>
<td>Tm(^{3+})</td>
<td>4f(^{17}!5!f)</td>
<td>(^{3}!H_{6})</td>
<td>7.57</td>
<td>7.3</td>
</tr>
<tr>
<td>Yb(^{3+})</td>
<td>4f(^{18}!6!f)</td>
<td>(^{2}!F_{7/2})</td>
<td>4.54</td>
<td>4.5</td>
</tr>
</tbody>
</table>

\(d\)-electrons
Experiments close to \( S \)

\(f\)-electrons
Experiments close to \( J \)

Kittel Introduction to solid state physics
Itinerant and localized

- Crystalline Electric Field (CEF)
- Spin-orbit coupling

![Graph](image)

Figure 6-2. The relative outer radial extent of the atomic electrons in atomic Gd.

Magnetic properties of rare earth metals – R. J. Elliot

3d-electrons

\[ \Delta (CEF) > \Delta (L-S) \]

4f-electrons

\[ \Delta (CEF) < \Delta (L-S) \]

Note for d-electrons – most of the case considering \( t_{2g} \) and \( e_g \) energy level splitting due to the octahedron environment. But, in general we have to consider actual local point symmetry.
4f-electron magnetism

By controlling $S$, $L$, $J$ as well as point symmetry (CEF) we can get a wide variety of magnetic properties: $\mu_{\text{eff}}$, $\mu_{\text{sat}}$ and anisotropy.

| $f$-shell ($l = 3$) | $n$ | $l_z = 3$, 2, 1, 0, -1, -2, -3 | $S$ | $L = |\Sigma l_z|$ | $J$ |
|---------------------|-----|--------------------------------|-----|----------------|-----|
| 1                   | 1   | $\downarrow$                   | 1/2 | 3             | 5/2 |
| 2                   | 2   | $\downarrow \downarrow$        | 1   | 5             | 4   |
| 3                   | 3   | $\downarrow \downarrow \downarrow$ | 3/2 | 6             | 9/2 |
| 4                   | 4   | $\downarrow \downarrow \downarrow \downarrow$ | 2   | 6             | 4   |
| 5                   | 5   | $\downarrow \downarrow \downarrow \downarrow \downarrow$ | 5/2 | 5             | 5/2 |
| 6                   | 6   | $\downarrow \downarrow \downarrow \downarrow \downarrow \downarrow$ | 3   | 3             | 0   |
| 7                   | 7   | $\downarrow \downarrow \downarrow \downarrow \downarrow \downarrow \downarrow$ | 7/2 | 0             | 7/2 |
| 8                   | 8   | $\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$ | 3   | 3             | 6   |
| 9                   | 9   | $\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$ | 5/2 | 5             | 15/2|
| 10                  | 10  | $\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$ | 2   | 6             | 8   |
| 11                  | 11  | $\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$ | 3/2 | 6             | 15/2|
| 12                  | 12  | $\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$ | 1   | 5             | 6   |
| 13                  | 13  | $\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$ | 1/2 | 3             | 7/2 |
| 14                  | 14  | $\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$ | 0   | 0             | 0   |

$J = |L - S|$ and $J = L + S$.

$\begin{align*}
\text{Ground States:} \\
&{^2F_{5/2}} \\
&{^3H_4} \\
&{^4I_{9/2}} \\
&{^5I_4} \\
&{^6H_{5/2}} \\
&{^7F_0} \\
&{^8S_{7/2}} \\
&{^7F_6} \\
&{^6H_{15/2}} \\
&{^5I_8} \\
&{^4I_{15/2}} \\
&{^3H_6} \\
&{^2F_{7/2}} \\
&{^1S_0}
\end{align*}$
Effective moment and saturated magnetization

Magnetic susceptibility

\[ \chi = \frac{dM}{dH} \]

In the low field region, the magnetization of a paramagnetic system is linear in H. For such low field,

\[ \chi(T) \approx \frac{M(T)}{H} \]

Effective moment \( p = g[J(J+1)]^2 \)

\[ \chi(T) \approx \frac{M(T)}{H} = \frac{NP^2\mu_B^2}{3k_B T} = \frac{C}{T} \]
Effective moment and saturated magnetization

Magnetic susceptibility

Fit with Curie-Weiss Law: the temperature dependence of the magnetic susceptibility in the paramagnetic state is given by

$$\chi(T) = \frac{C}{T - \theta_P} + \chi_0$$

Plot inverse magnetic susceptibility

Determine $p$ from the slope and compare to the free ion value

$$C = \frac{Np^2\mu_B^2}{3k_B}$$

Gd$^{3+}$ free ion value $p = 7.94$

from the slope $7.9 \mu_B$/Gd$^{3+}$
Effective moment and saturated magnetization

Magnetic susceptibility

Fit with Curie-Weiss Law:

The temperature dependence of the magnetic susceptibility in the paramagnetic state is given by

$$\chi(T) = \frac{C}{T - \theta_P} + \chi_0$$

\(\chi_0\): basically temperature independent term that is the sum of core diamagnetism, Pauli paramagnetism, and Landau diamagnetism

Weiss temperature \(\theta_P\)
Effective moment and saturated magnetization

Magnetization isotherms - spin state of magnetic ions

Multiferroicity with coexisting isotropic and anisotropic spins in Ca$_3$Co$_{2-x}$Mn$_x$O$_6$

PRB 89, 060404(R) (2014)

Co$^{2+}$ spin state
S=3/2: M(T), x-ray absorption
S=1/2: M(H), low temp neutron studies

Mn$^{4+}$: 3$d^3$ S = 3/2

Co$^{2+}$: 3$d^7$ S = 3/2 or 1/2?

No evidence of low-spin to high-spin transition

Neutron – seeing ordered moment should be complementary
Anisotropy in magnetic susceptibility

The anisotropy can be clearly seen in $1/\chi$

CEF anisotropy

NO CEF anisotropy Gd$^{3+}$ or Eu$^{2+}$ (s-state, $L = 0$)

For rare-earth with finite $L$, there will be CEF splitting that can give rise to significant anisotropy, depending on local point symmetry.

Exchange interaction - anisotropy
Magnetism

Exchange interaction $J$

Magnetic ordering and quasi-particle
- Direct
- Indirect
- RKKY
- Kondo
Specific heat

Electron and phonon contribution

Specific heat of a metal at low temperatures

\[ c = \gamma T + \beta T^3 \]

\( \gamma \): \( n(E_F) \) density of state
\( \beta \): Debye temperature

Plot \( C/T \) vs \( T^2 \) – extract \( \gamma \) and \( \beta \)

Heavy fermion
- large \( \gamma \)!
- large effective mass \( m^* \)
- 1000 times bigger than Cu

Note: estimate \( \gamma \) value - carefully consider all possible contributions in specific heat, especially magnetic and Schottky contributions
Specific heat

Electron and phonon contribution

Heavy fermion superconductor

Specific heat jump at the $T_c$ - related to the $\gamma$

The $C_p$ jump - not related to any other contributions like electronic schottky, nuclear, magnetic fluctuations, and all strange stuffs…
Heavy fermion – Kondo effect

The electronic specific heat - measure of the electron effective mass

Relationship among thermodynamic and transport

Specific heat
Resistivity
Susceptibility
Thermal conductivity
Thermoelectric power
Thermal expansion

Fermi liquid: KW, Wilson number, and more...

Please make summary note just for yourself...

Anything deviates from conventional behavior?
Entropy

Specific heat is intimately related to entropy

\[ S = \int \frac{C_m}{T} \, dT \]

Tell us how much entropy is associated with a given state. For magnetic systems we need to use the magnetic specific heat.

Remove phonon contributions: often do this by subtracting a non-magnetic analogue.

\[ C_m = C_p(R) - C_p(Y, \text{La, Lu}) \]

Gd-compound, no CEF \( J(=S, L=0) = 7/2 \)

Entropy associated with magnetic ordering \( \text{Rln}(8) \)
Energy level splitting

CEF effect – Schottky anomaly

Consider a two-level system

\[ C = \left( \frac{\partial U}{\partial T} \right)_\Delta = k_B \frac{(\Delta / T)^2 e^{\Delta/T}}{(1 + e^{\Delta/T})^2} \]

Nuclear: 1 ~ 100 mK splitting, often observed below 1K

Estimate effective mass \( \gamma \)

Subtracting nuclear contribution by simply use \( \sim 1/T^2 \)
Energy level splitting

CEF effect – Schottky anomaly

Given the Hund’s rule, groundstate multiplet $J$ we would expect $R \ln(2J + 1)$ entropy associated with the magnetic state. For rare earths the spin-orbit coupling give rise to crystalline electric field (CEF) splitting.

Ce ($J = 5/2$) in cubic symmetry

$\Delta = \frac{k_B}{g_1 g_2} \left( \frac{\Delta}{T} \right)^2 \frac{e^{\Delta/T}}{1 + \frac{g_1}{g_2} e^{\Delta/T}}$

PrAgSb$_2$: no magnetic ordering at low temperatures – can be considered as a two level system

Specific heat at low temperatures and neutron at high temperatures
We have now seen how $\rho(T)$, $C_p(T)$, and $\chi(T)$ can be used to determine magnetic ordering temperatures (as well as many other useful parameters).

Phase transitions

We have now seen how $\rho(T)$, $C_p(T)$, and $\chi(T)$ can be used to determine magnetic ordering temperatures (as well as many other useful parameters).

Specific heat: good measure of bulk phase transition - superconductors

Poster: QMSS-18 Hyunsoo Kim (University of Maryland)
Crystal growth and annealing study of fragile, non-bulk superconductivity in YFe$_2$Ge$_2$

Jump in the specific heat!!!!
Guess from periodic table-tuning systems

PERIODIC TABLE OF THE ELEMENTS

Density of state
Exchange interaction

magnetic 4f metal
magnetic dense Kondo system
non-magnetic dense Kondo system
Valence Fluctuation

\( T \)

\( T_K \sim D \exp(-1/JN_0) \)

\( T_{\text{K}} < T_{\text{RKKY}} \)

\( T_{\text{K}} > T_{\text{RKKY}} \)

\( (JN_0)^2 \)

AFM
Fermi liquid
heavy quasi-particle

(\( JN_0 \))
Thank you!

Questions…