Magnetic Ordering in $Ce_{1-x}Yb_xRhIn_5$ Heavy Fermions as a Function of Doping

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NCNR SURF GROUP AT NIST

[1]ROCHESTER INSTITUTE OF TECHNOLOGY

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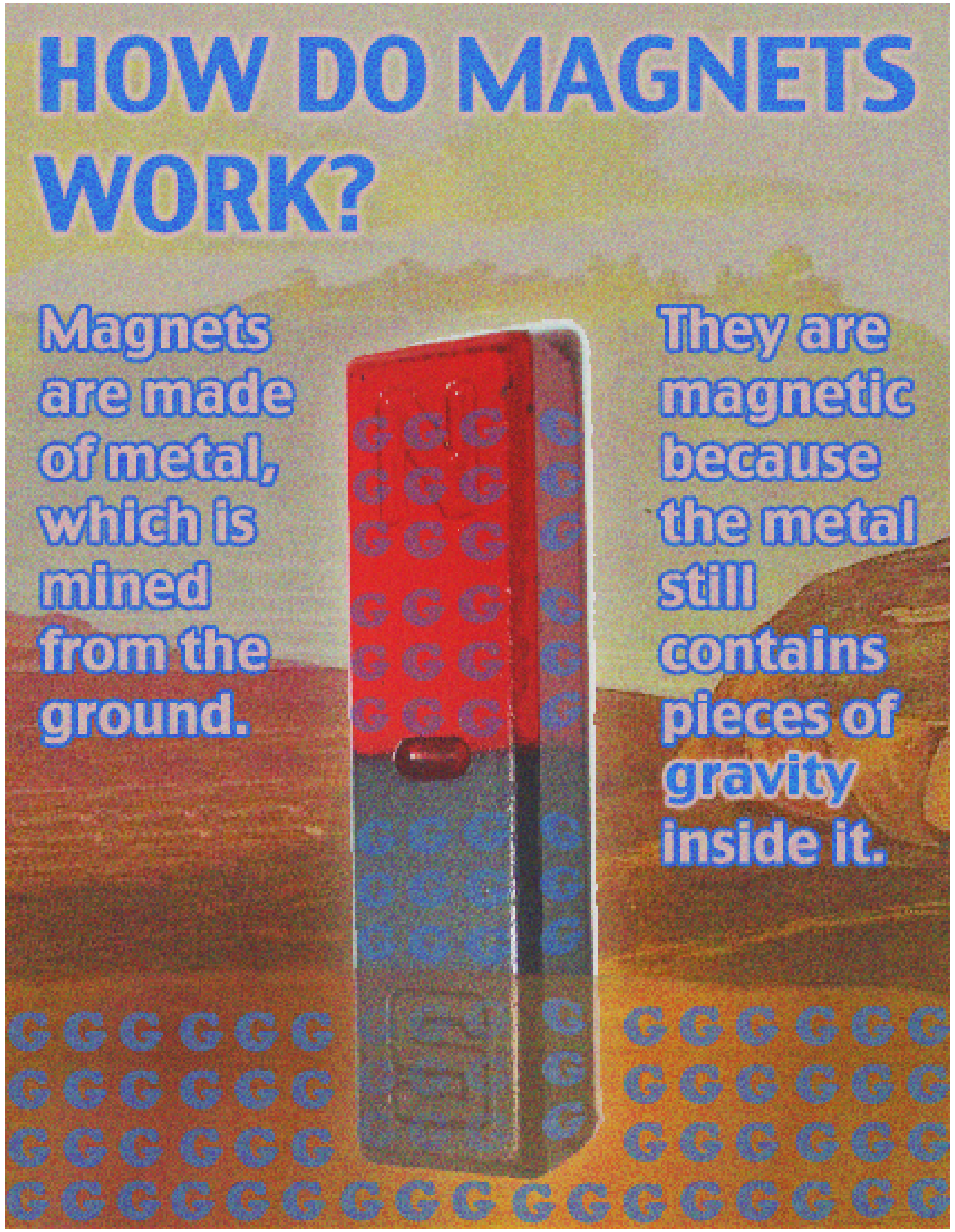
One Definition:



HOW DO MAGNETS WORK?

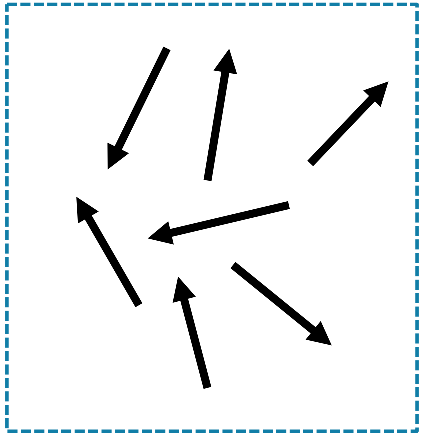
Magnets are made of metal, which is mined from the ground.

They are magnetic because the metal still contains pieces of gravity inside it.

Types of Magnetic States (only 3 shown)

$T > T_c$: DISORDERED

Paramagnetic

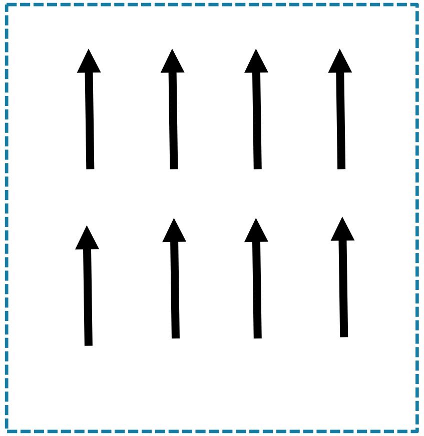


$$< \vec{M} > = 0$$

$$\vec{M} = \chi_m \vec{H}$$

$T < T_c$: ORDERED

Ferromagnetic



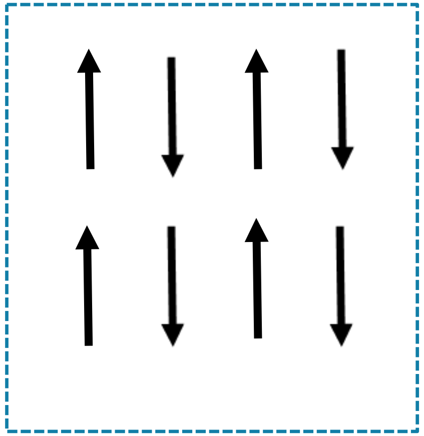
$$< \vec{M} > \neq 0$$

$$H = -J \sum_{i,j} \vec{s}_i \cdot \vec{s}_j$$

$$J > 0$$

Ex: Iron and Cobalt

Antiferromagnetic



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Ex: Common Metal-Oxides

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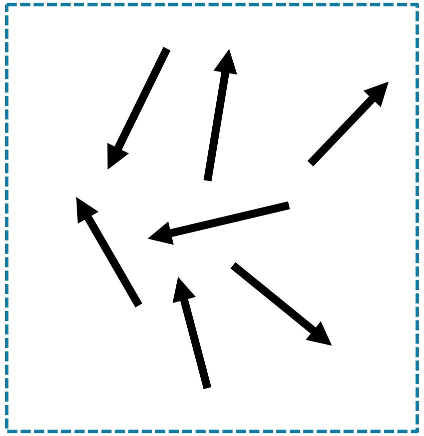

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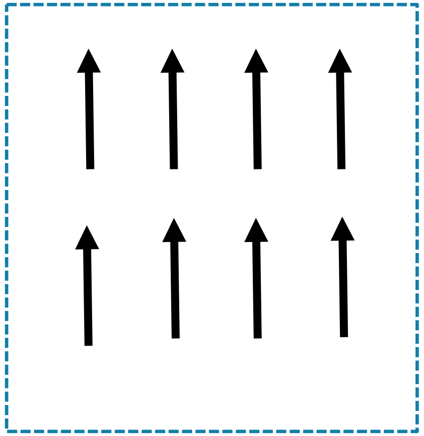

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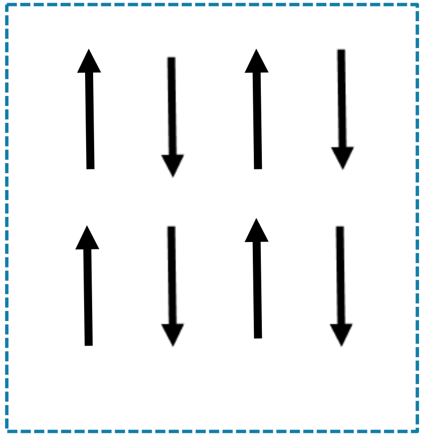

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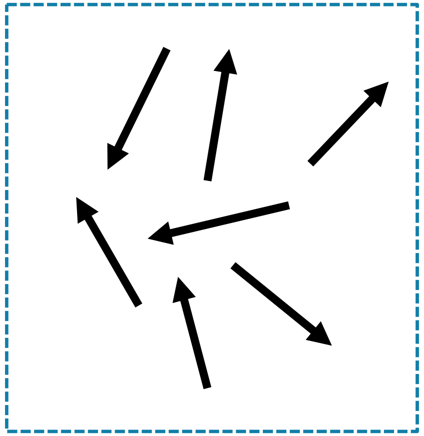

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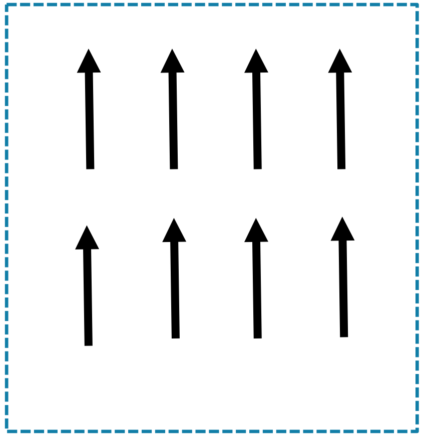

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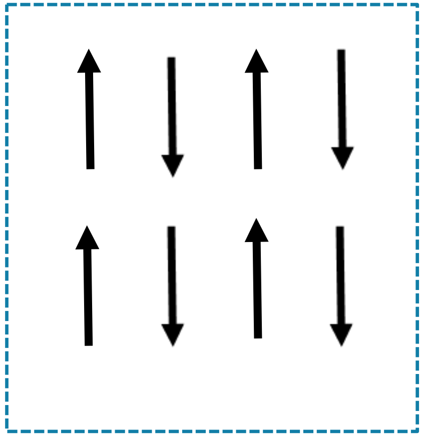

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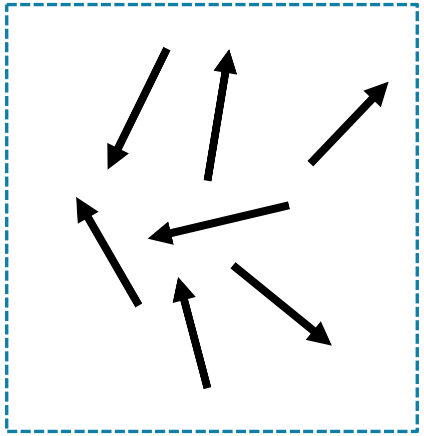

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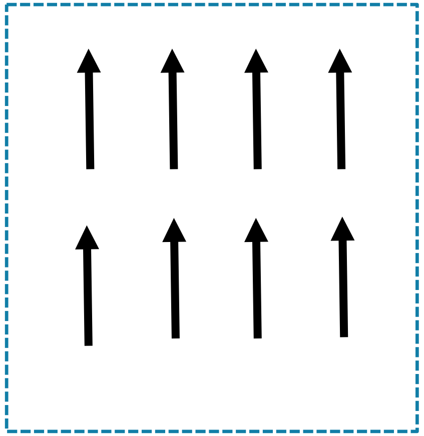

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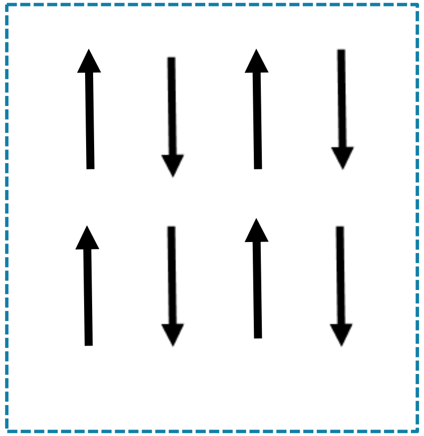

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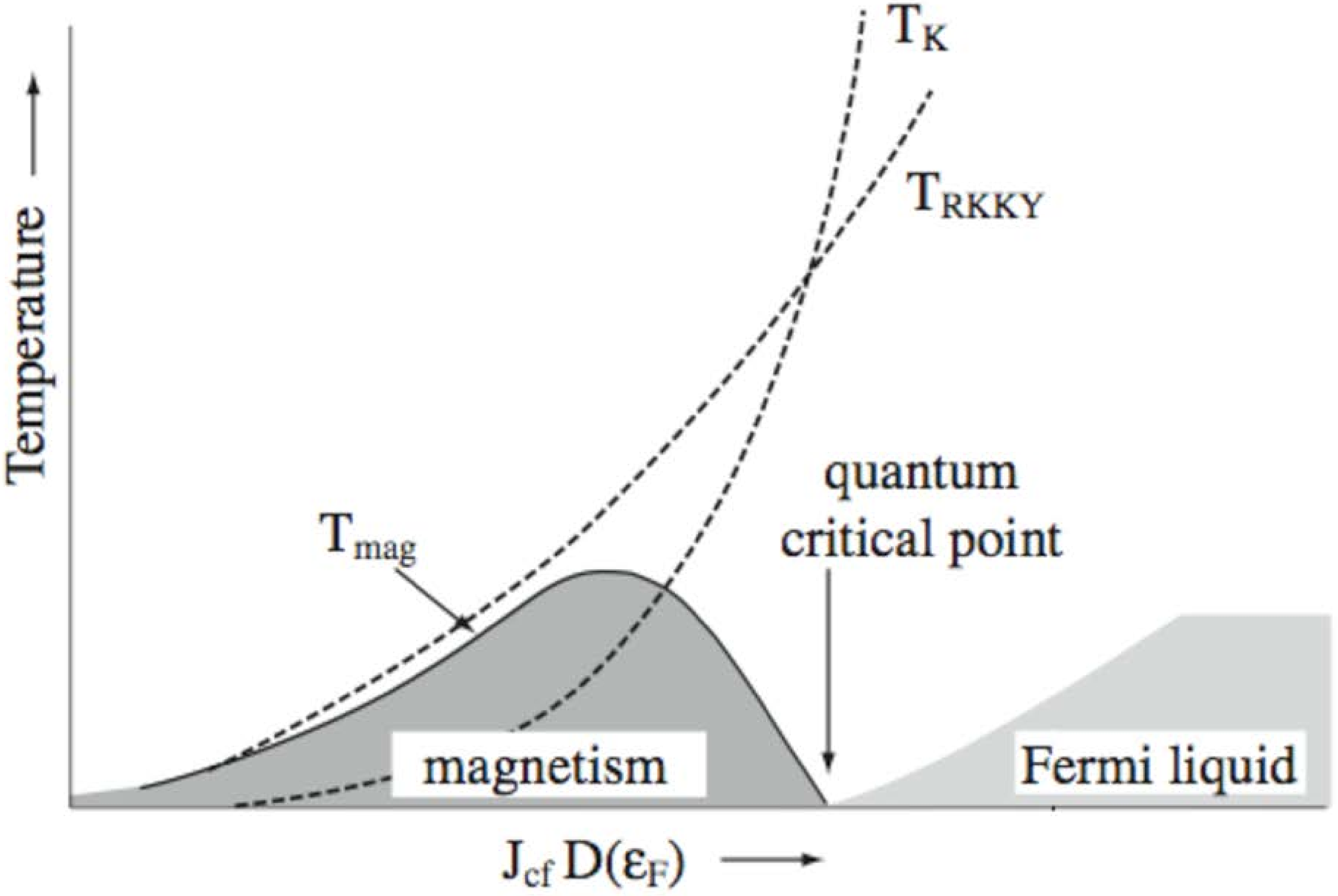
What are Heavy Fermions?

Kondo Interactions
-Conduction spin screening
-Suppresses magnetic ordering

RKKY Interactions
-Coupled moments dependent on distance
-Enhances magnetic ordering

Combining Both
-Huge increase in effective mass.
-Kondo and RRKY interactions co-exist
-Possible unconventional superconductivity near QCP



Also, increasing H, P, doping, ect.

from UNLP

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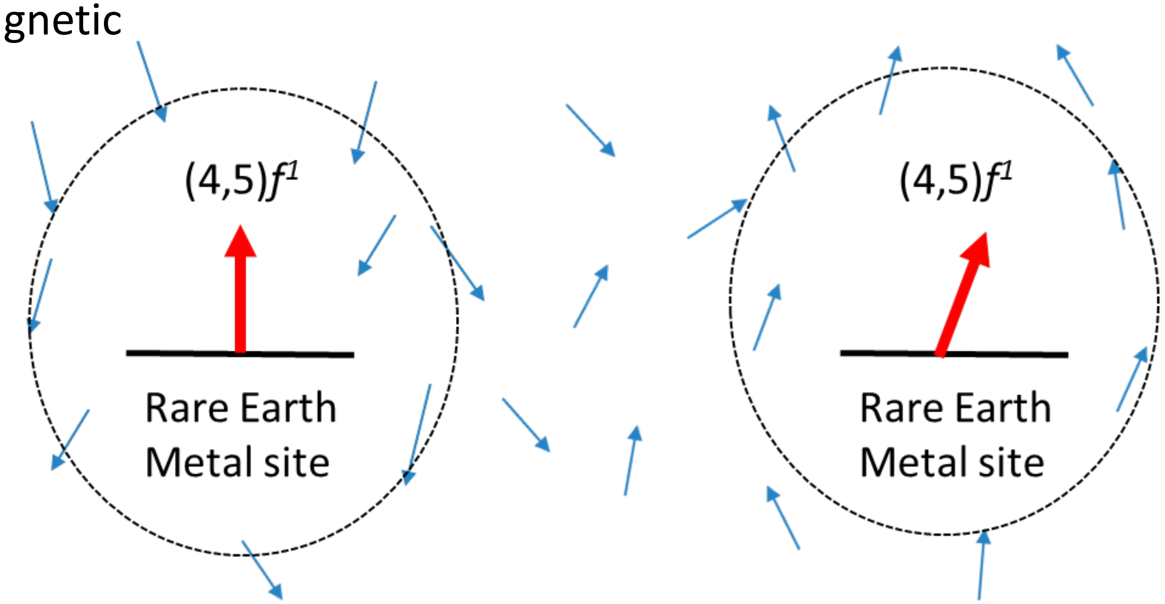

↙ - Conduction electron spins

↑ - "Heavy" electron. Localized to the Rare Earth site. High angular Momentum from *f* orbital

◌ - Effective shielding

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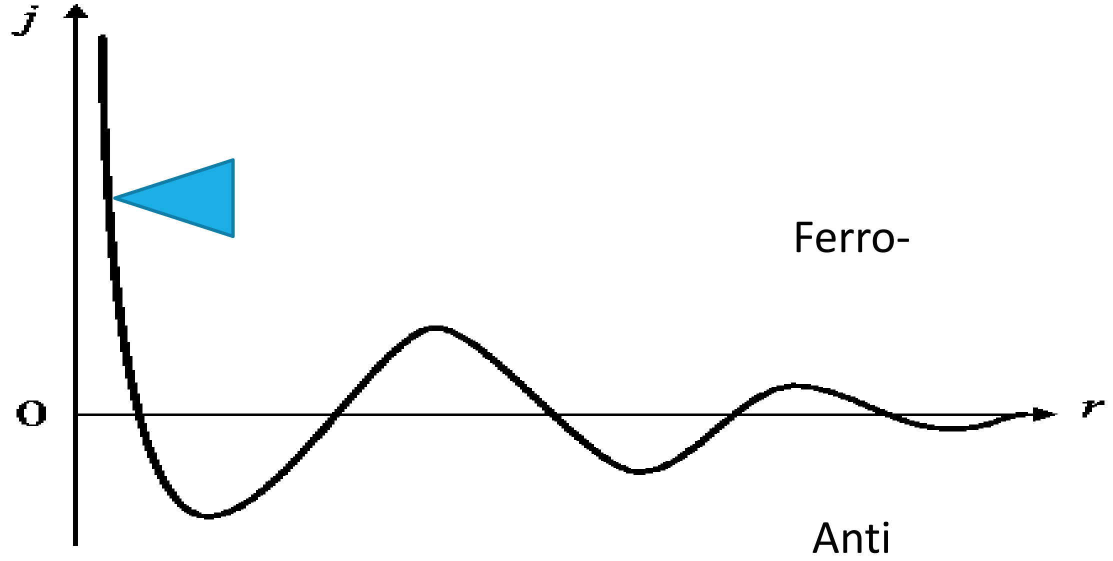

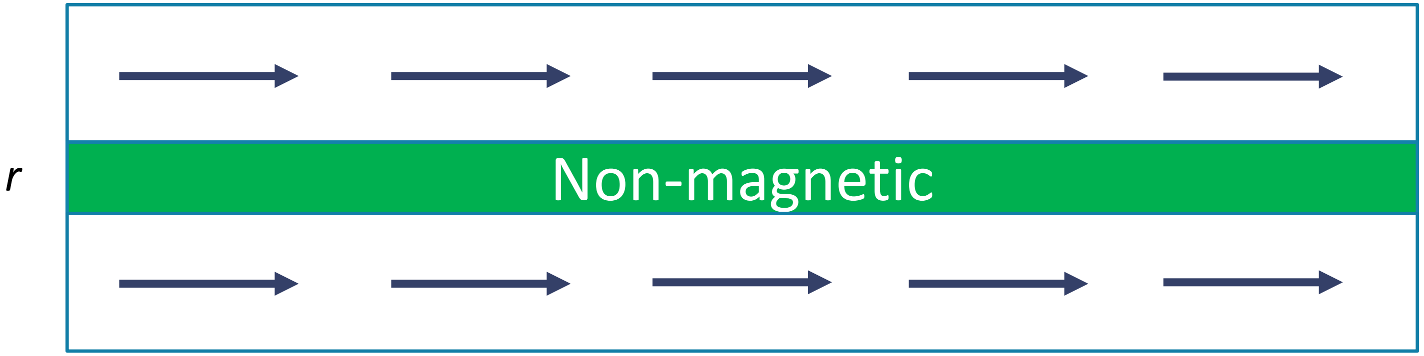

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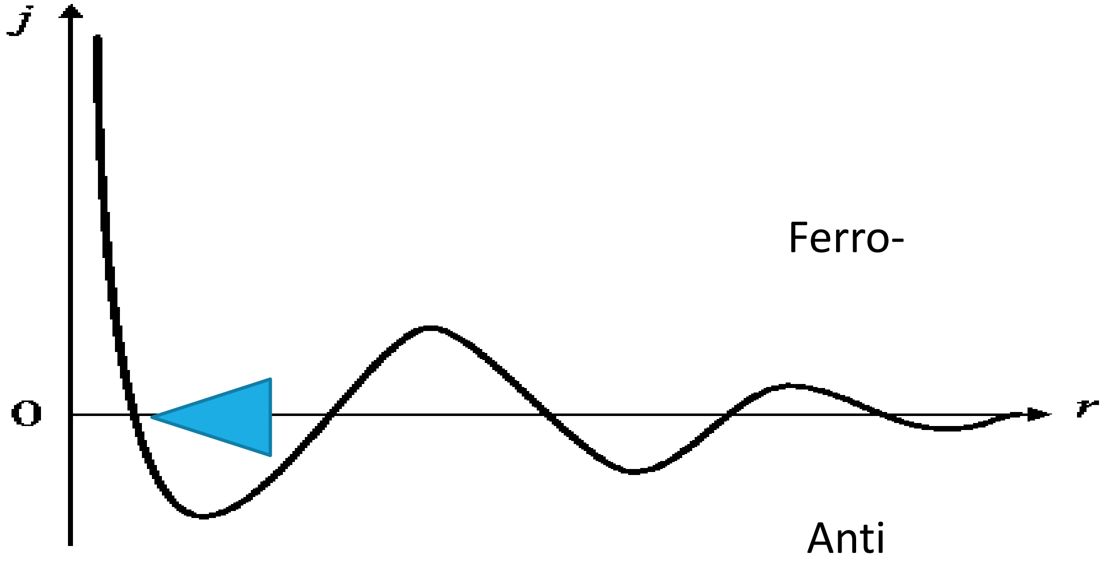

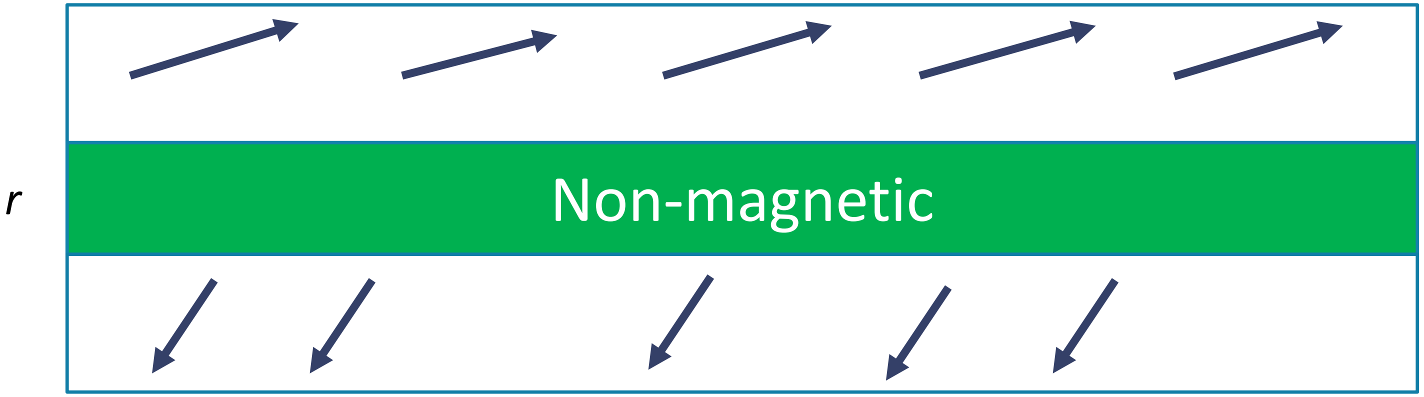

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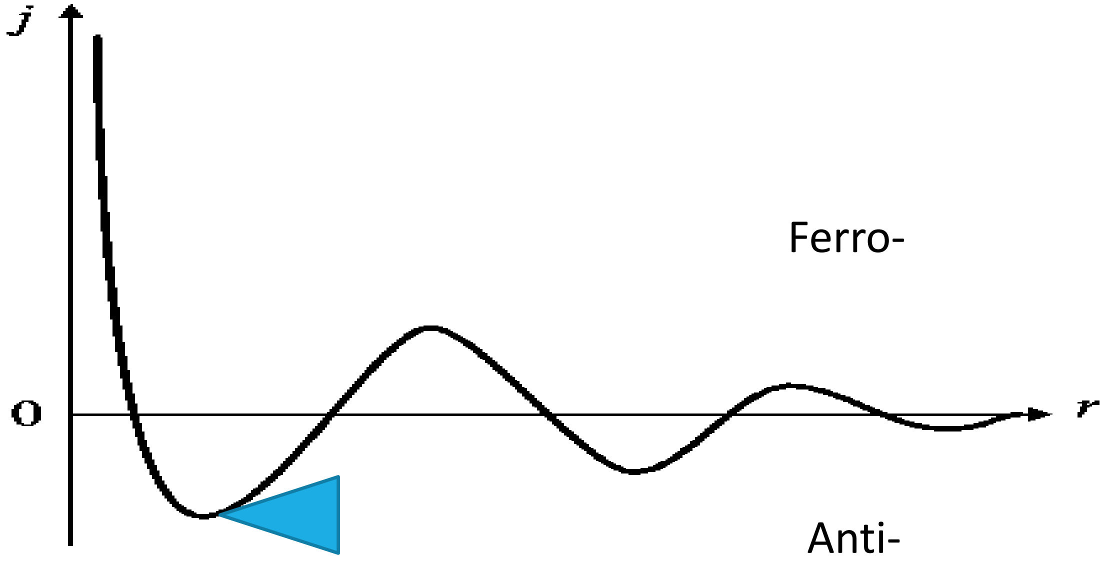

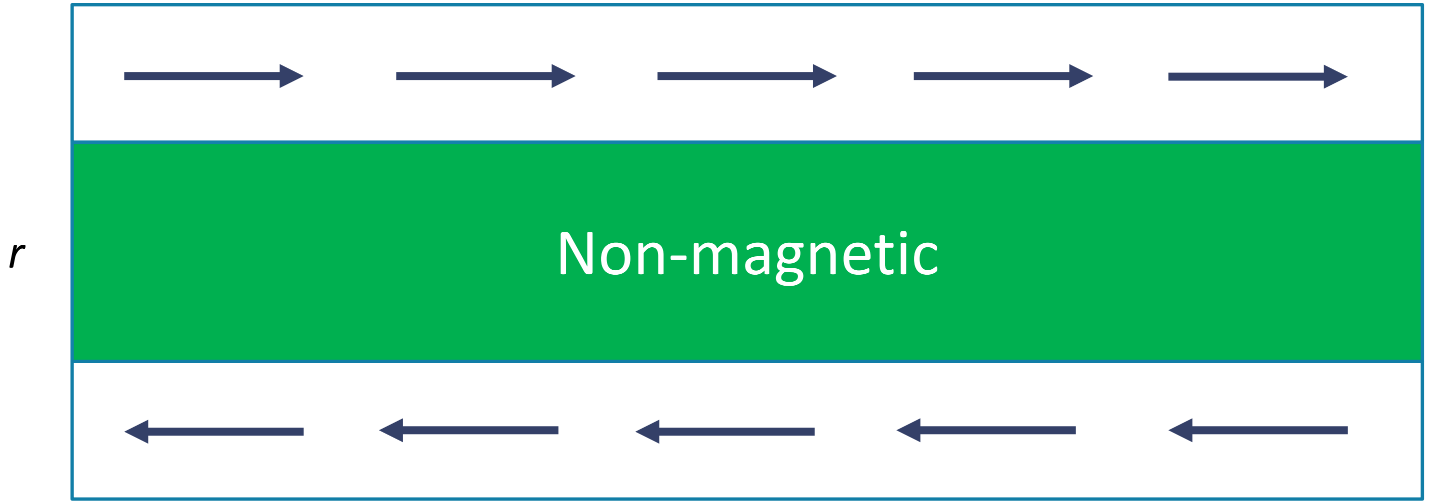

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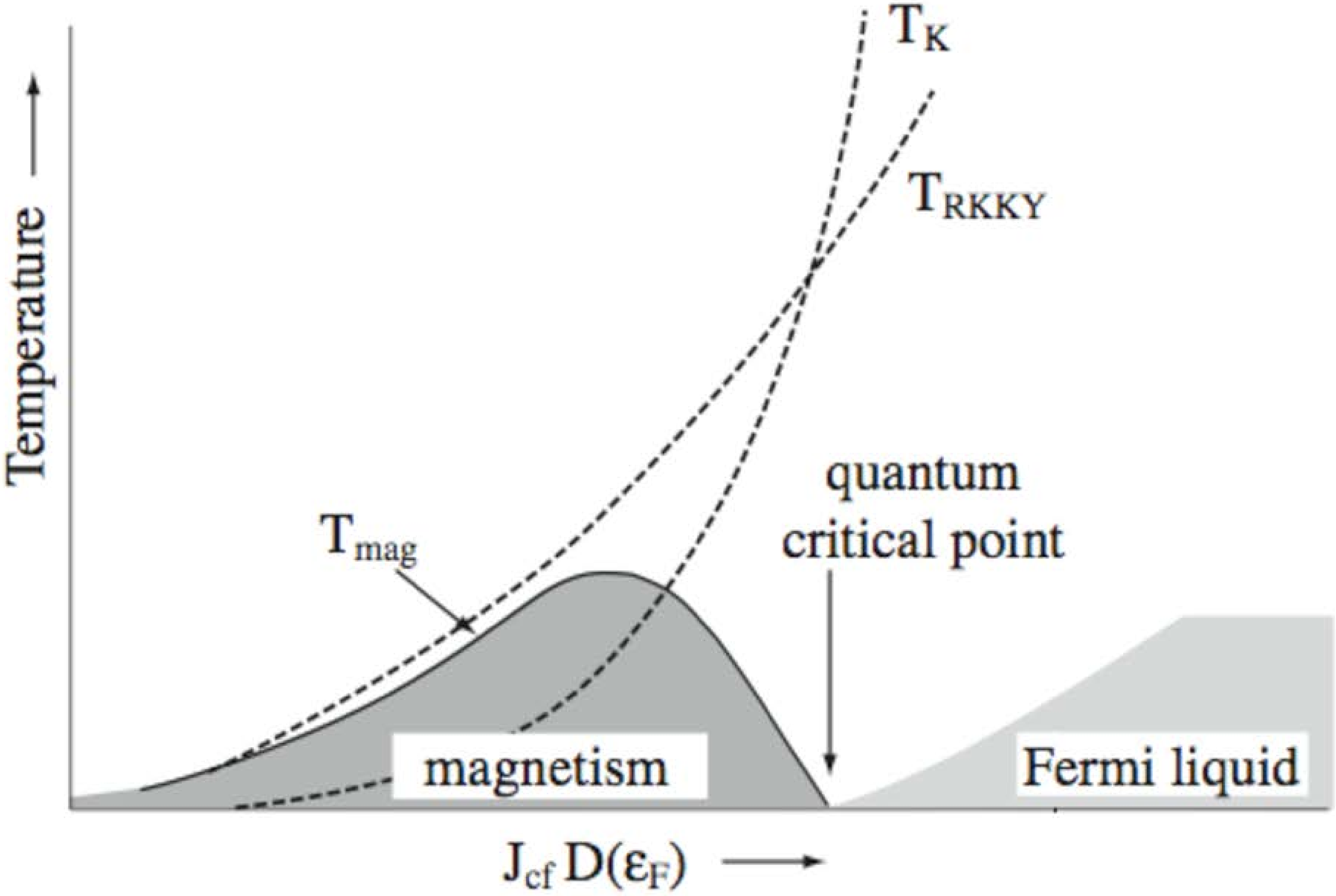

Also, increasing H, P, doping, ect.

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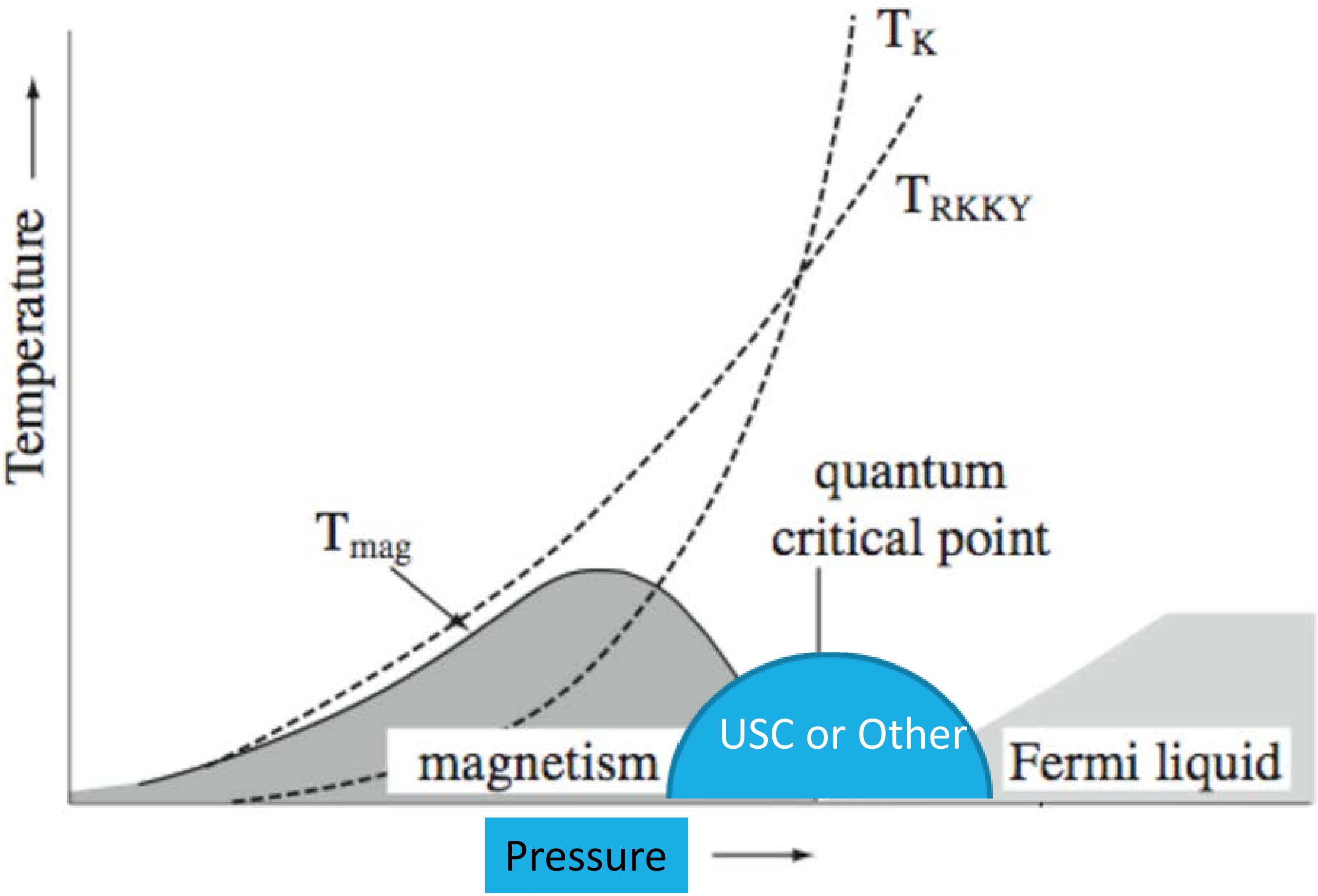
$\underline{Ce_{1-x}Yb_xRhIn_5}$

QCP

-Kondo and RKKY on equal footing.

-Material can go superconducting under pressure.

-USC is similar to High Temp SC in copperates.



$CeRhIn_5$ goes superconducting under applied pressure

$Ce_{(1-x)}Yb_xRhIn_5$ (Heavy Fermion Material)

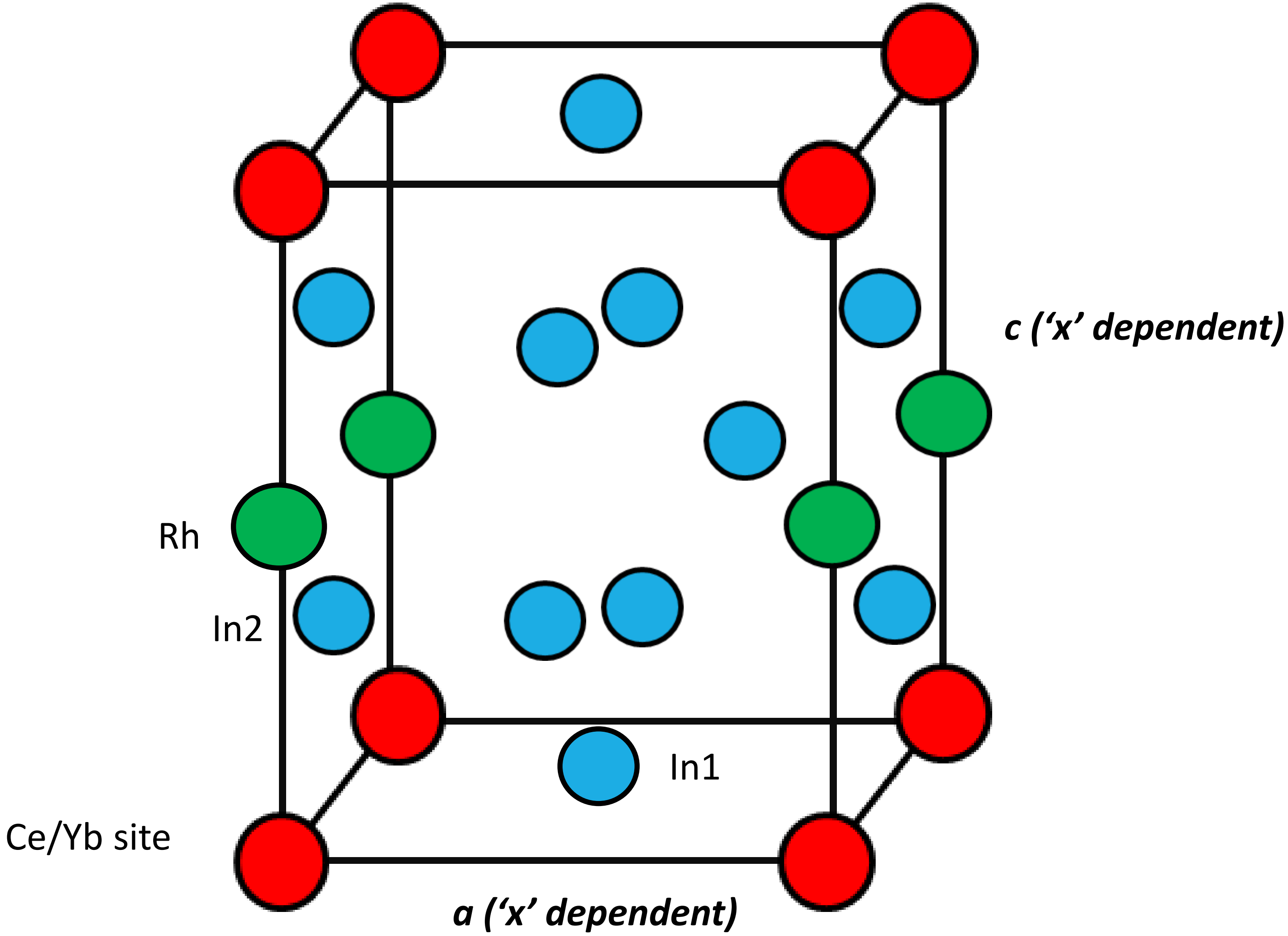
Tetragonal:

a=b≠c

α=β=γ=90°

Space group:

P 4/m m m



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Goal: $Ce_{1-x}Yb_xRhIn_5$ Magnetic Transitions

Finding the transition
(in terms of T and x)
For change to commensurate structure

$CeRhIn_5$

$YbRhIn_5$

Turns antiferromagnetic
k=(½,½,0.297) [3]
T=3.8 K
(incommensurate structure)

Finding
the transition
(in terms of T and x)
For magnetic ordering

Metallic Paramagnet [4]

[3] Wei Bao, P. G. Pagliuso, J. L. Sarrao, J. D. Thompson, Z. Fisk, J.W. Lynn, and R.W Erwin. ***Incommensurate magnetic structure of CeRhIn5.*** Phys. B 62-22

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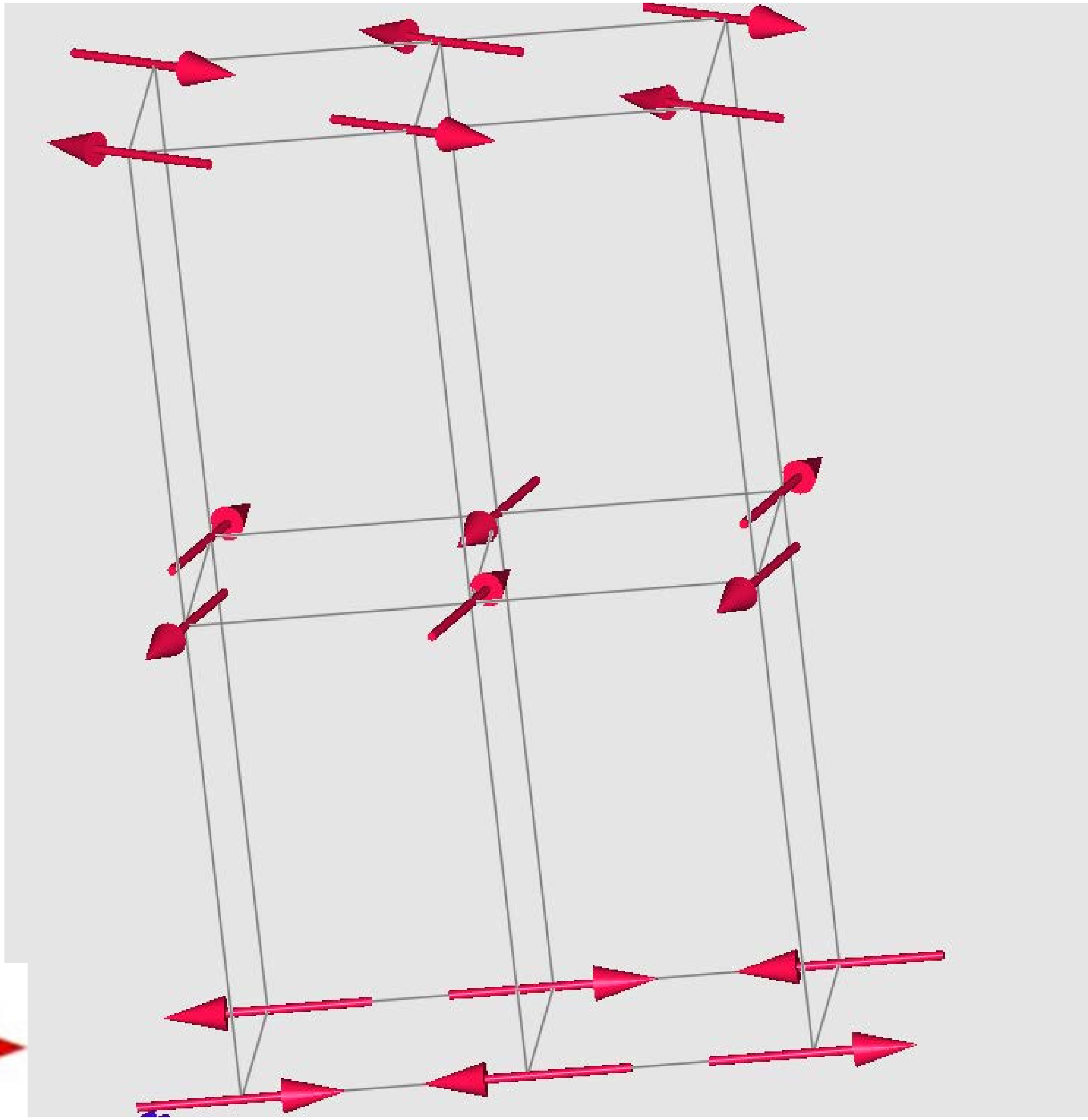
CeRhIn$_5$ [3]



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Finding the transition
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For change to commensurate structure

$CeRhIn_5$

Increasing x

$YbRhIn_5$

Turns antiferromagnetic
k=(½,½,0.297) [3]
T=3.8 K
(incommensurate structure)

Finding
the transition
(in terms of T and x)
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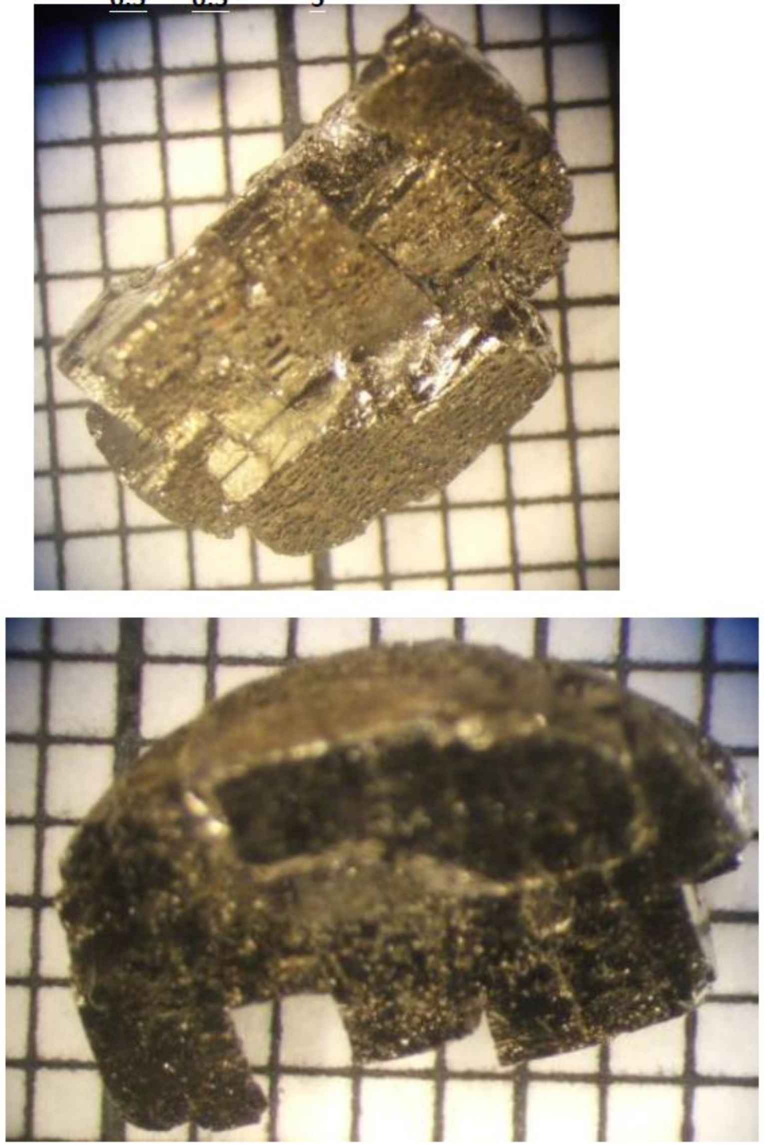
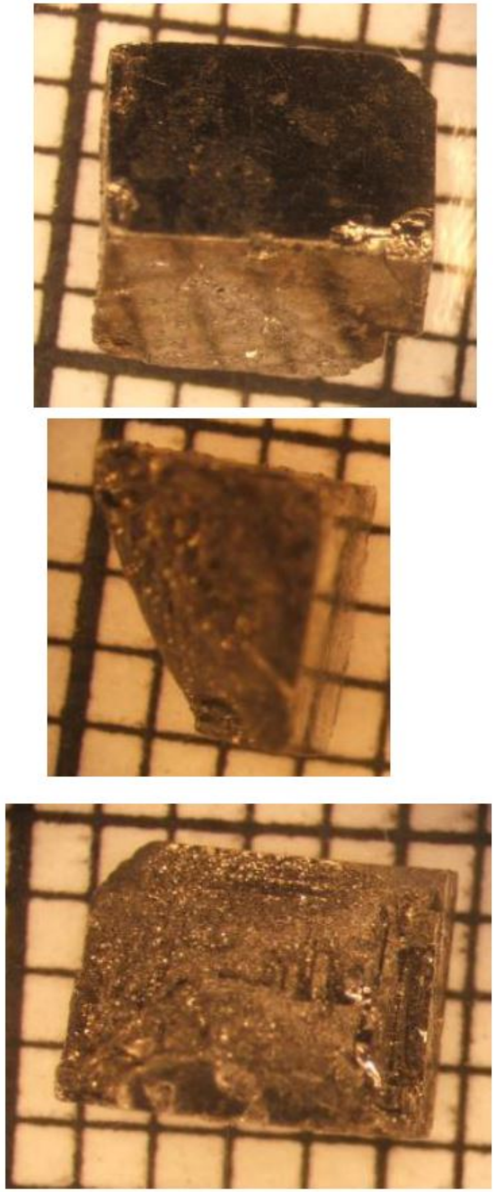
$Ce_{0.5}Yb_{0.5}RhIn_5$



$Ce_{0.4}Yb_{0.6}RhIn_5$



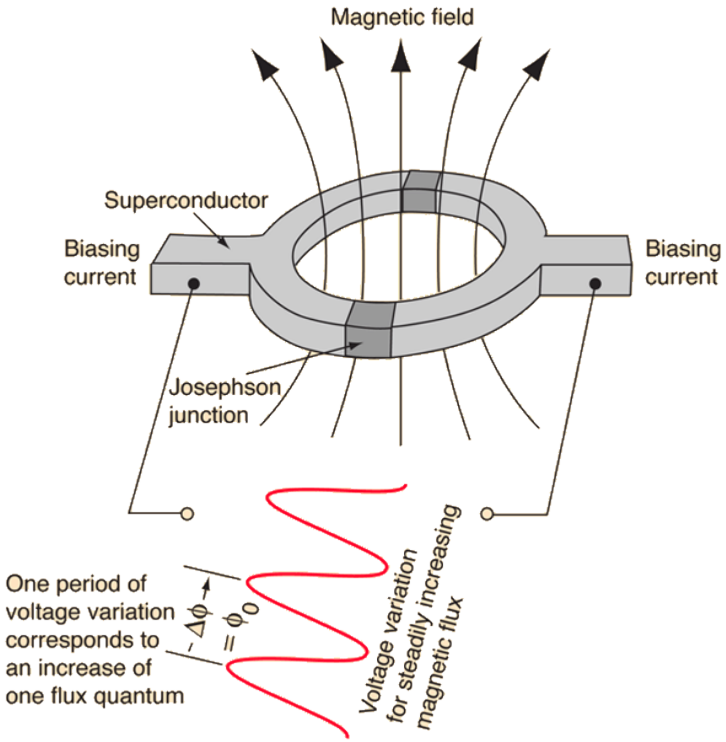
Actual sample concentration were not matching with the concentrations used to make these samples.

Needed a way to measure concentrations.

Made powders and headed to UMD for SQUID measurements.

SQUID Magnetometry for measuring μ_{eff} (superconducting quantum interference device)

SENSITIVE LOW TEMP MAGNETOMETER



SQUID AT U MARYLAND COLLEGE PARK

Our powder sample
x=‘.5’; 25 mg
x=‘.6’; 32.7 mg

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* Hyperphysics SQUID Magnetometer

Sample reported as x='.5'

C= 0.967 +/- 0.004 [(emu K)/or]
Curie Temp= -43.2 +/- 0.4 [K]
μ_{eff} = 2.7814 +/- 0.0009 μ_B
x= 0.090 +/- 0.001

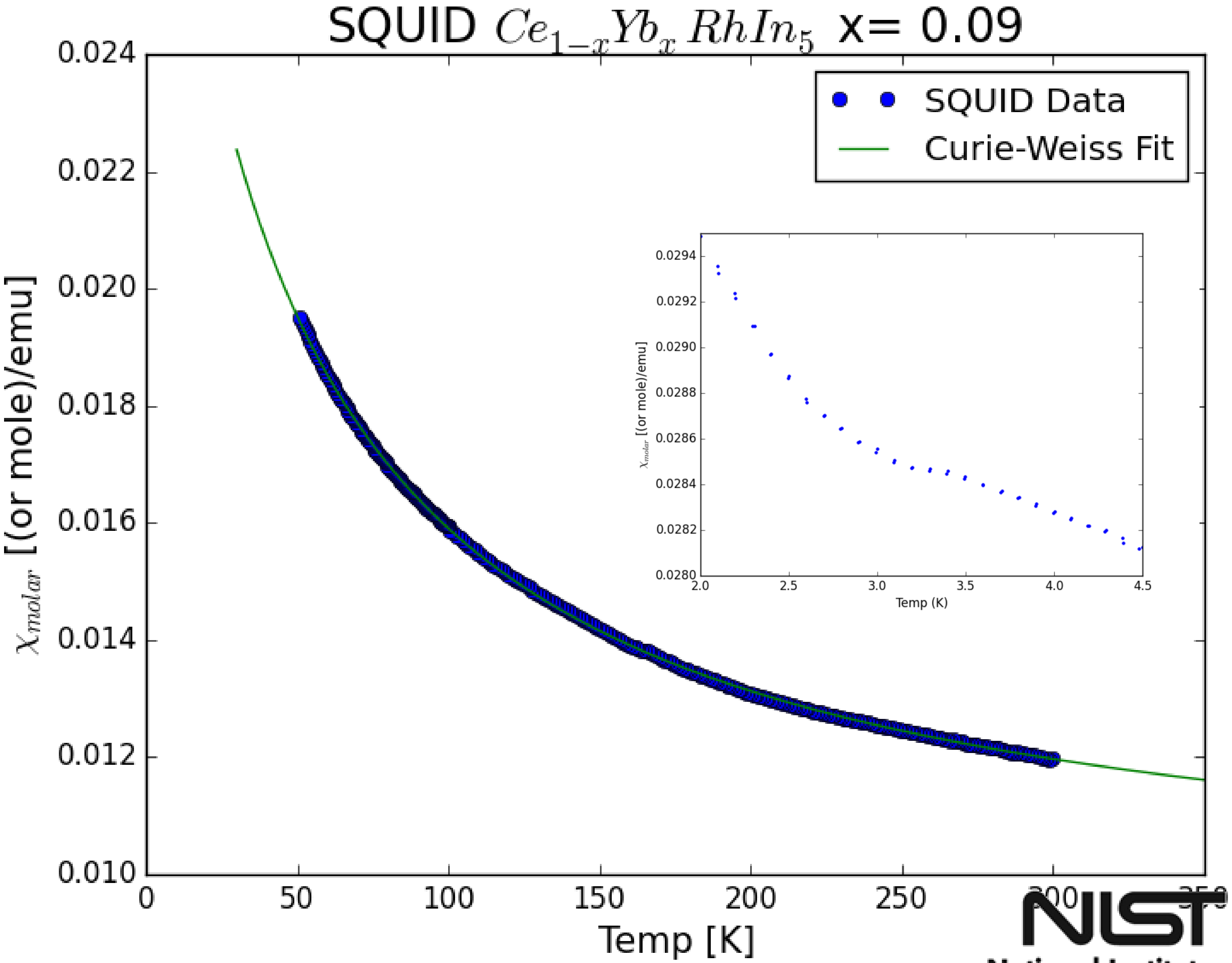
$$\chi(T) = \frac{\mu_{bulk}(T)}{H * moles} = \frac{C}{T-\theta_m} - \chi_0$$

T - Temperature [K]
C – Curie Number [(emu K)/or]
θ_m - Curie Temp. [K] (+ Ferro, - Anti)

$$C_{molar} = \frac{N_a \mu_{eff}^2(x)}{3k_B}$$

$$\mu_{eff}^2(x) = xP_{Yb^{+3}}^2 + (1-x)P_{Ce^{+2}}^2$$

$$P_{Ce^{+3}} = 2.54\,\mu_B$$
$$P_{Yb^{+3}} = 4.54\,\mu_B$$



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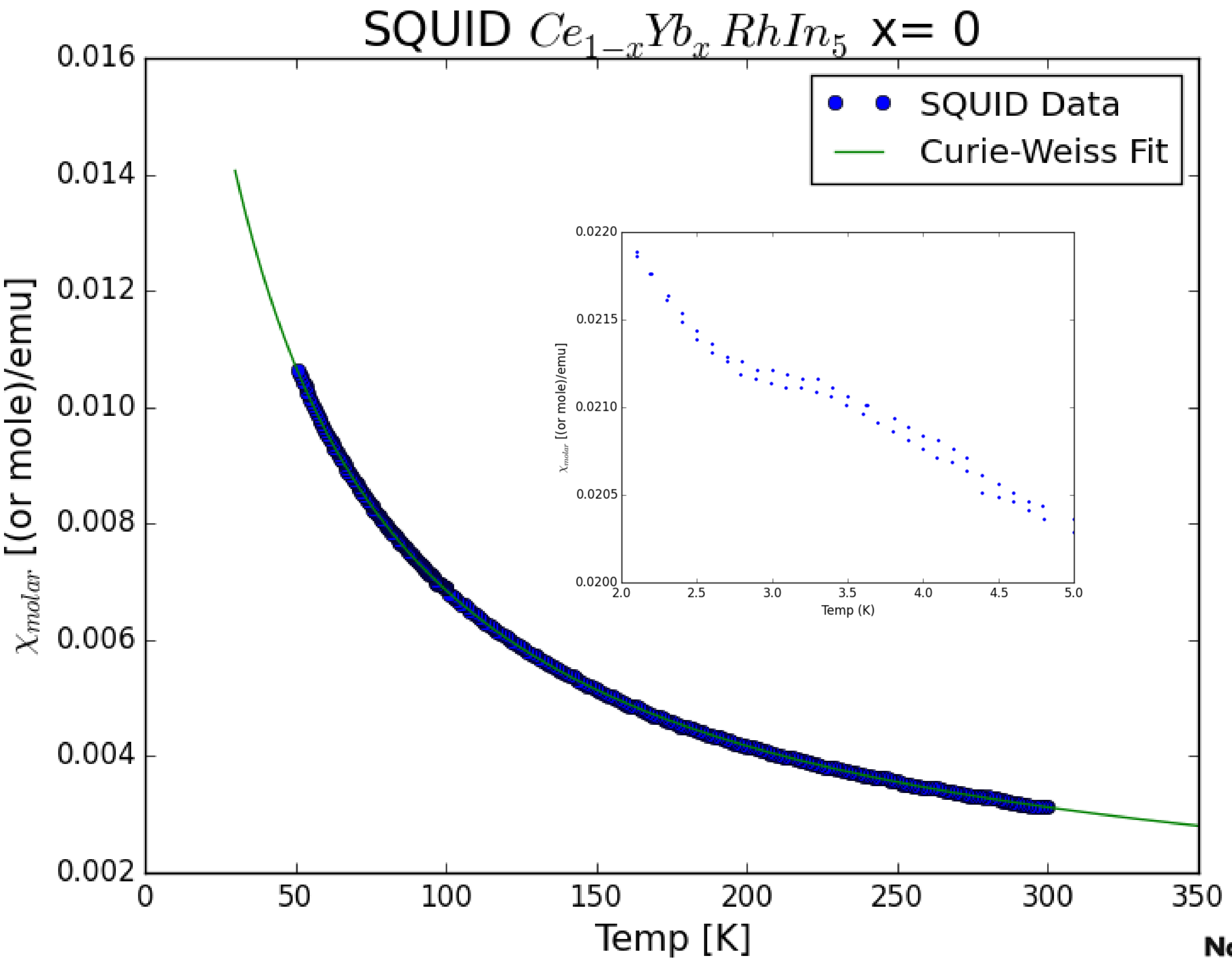
Sample reported as x='.6'

C= 0.799 +/- 0.002 [(emu K)/or]
Curie Temp= -29.8 +/- 0.4 [K]
μ_{eff} = 2.5280 +/- .0009 μ_B
x= -0.0043 +/- 0.0004

Effectively close to zero:
Only seems to be
Ce^{+3} moment contributing.
Very small doping on the order of <1%



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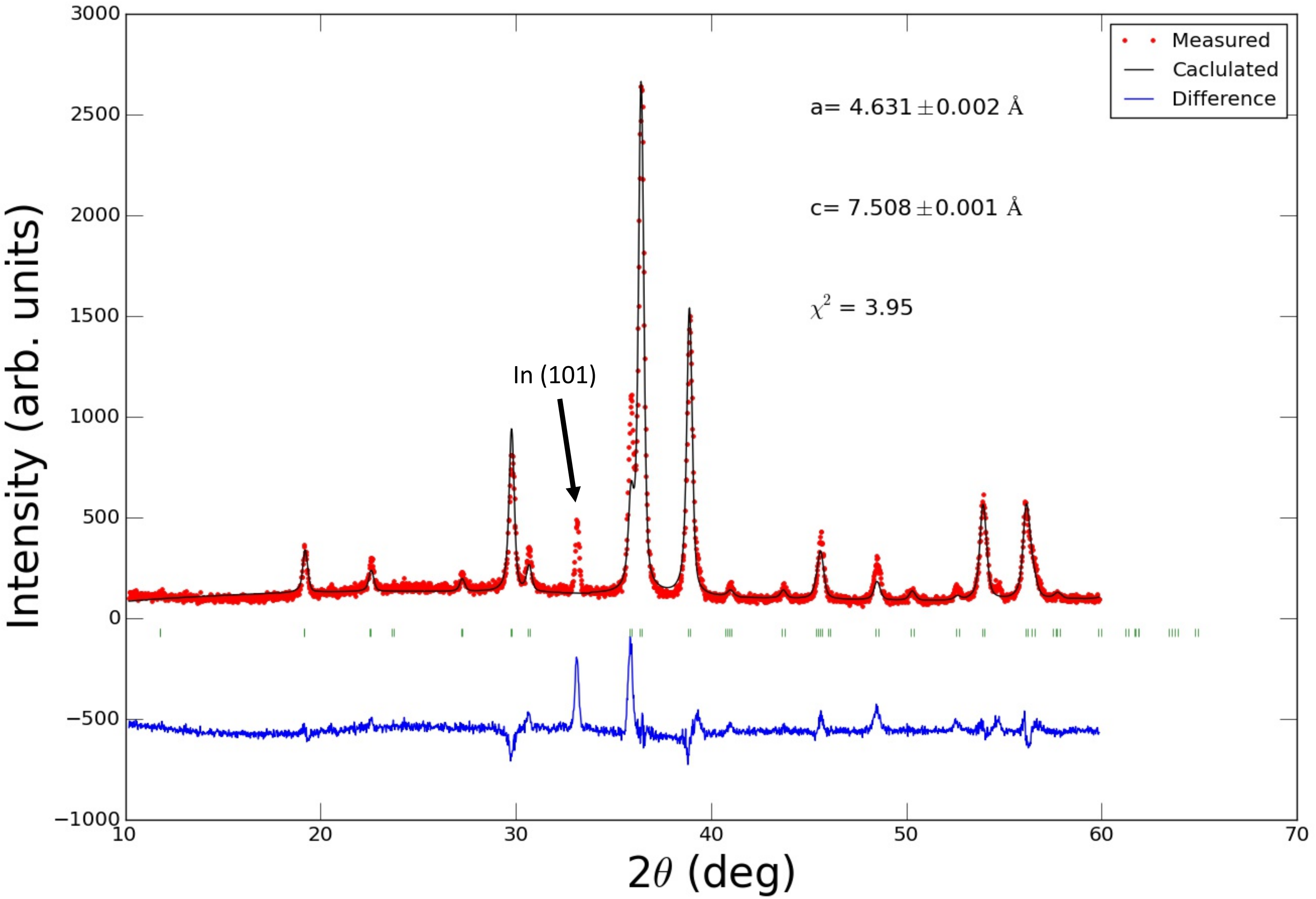
X-ray powder diffraction $Ce_1Yb_0RhIn_5$ (x<1%)

Rietveld refinement done with FullProf Software



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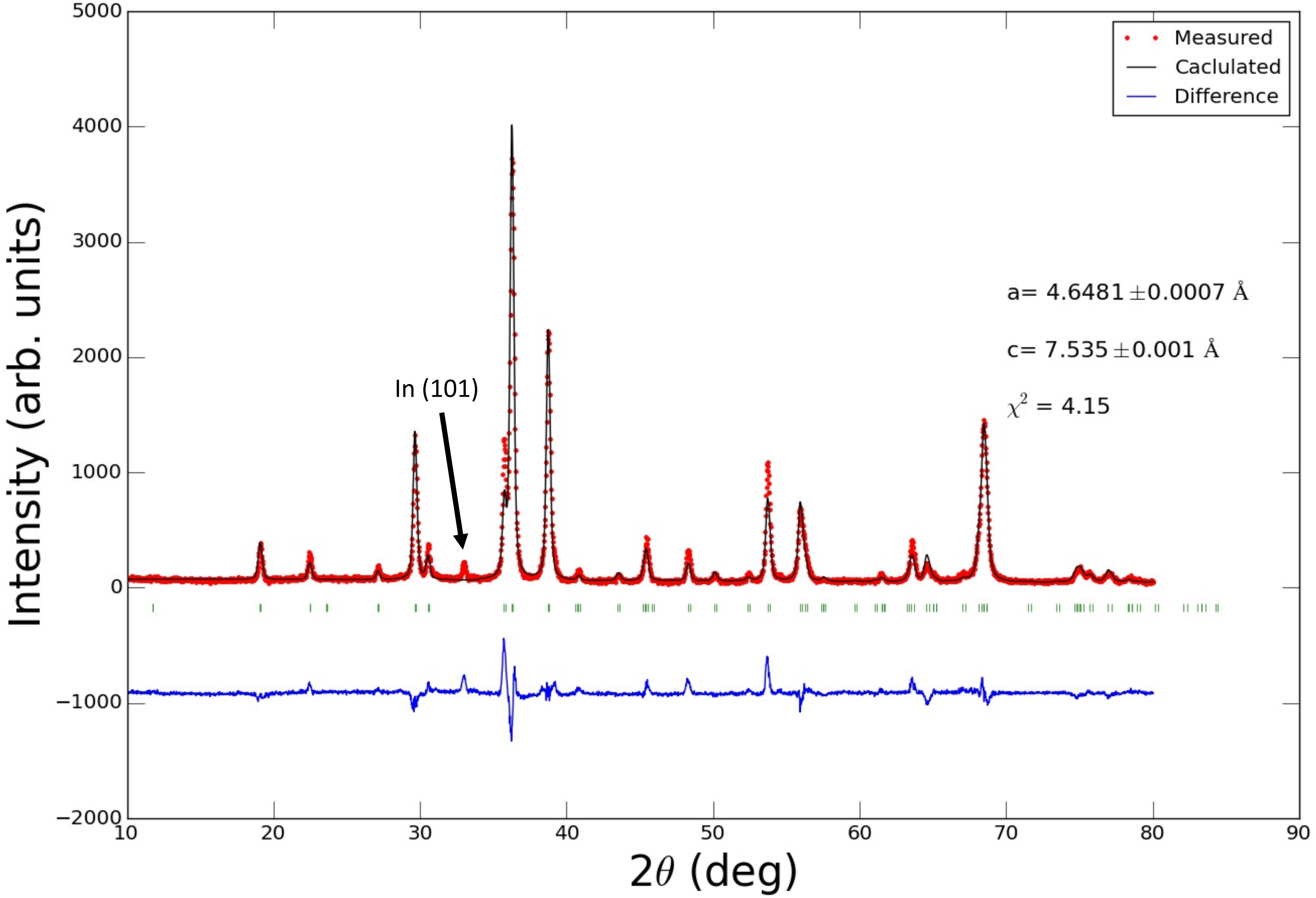
X-ray powder diffraction $Ce_{.91}Yb_{.09}RhIn_5$ (x=.09)

Rietveld refinement done with FullProf Software



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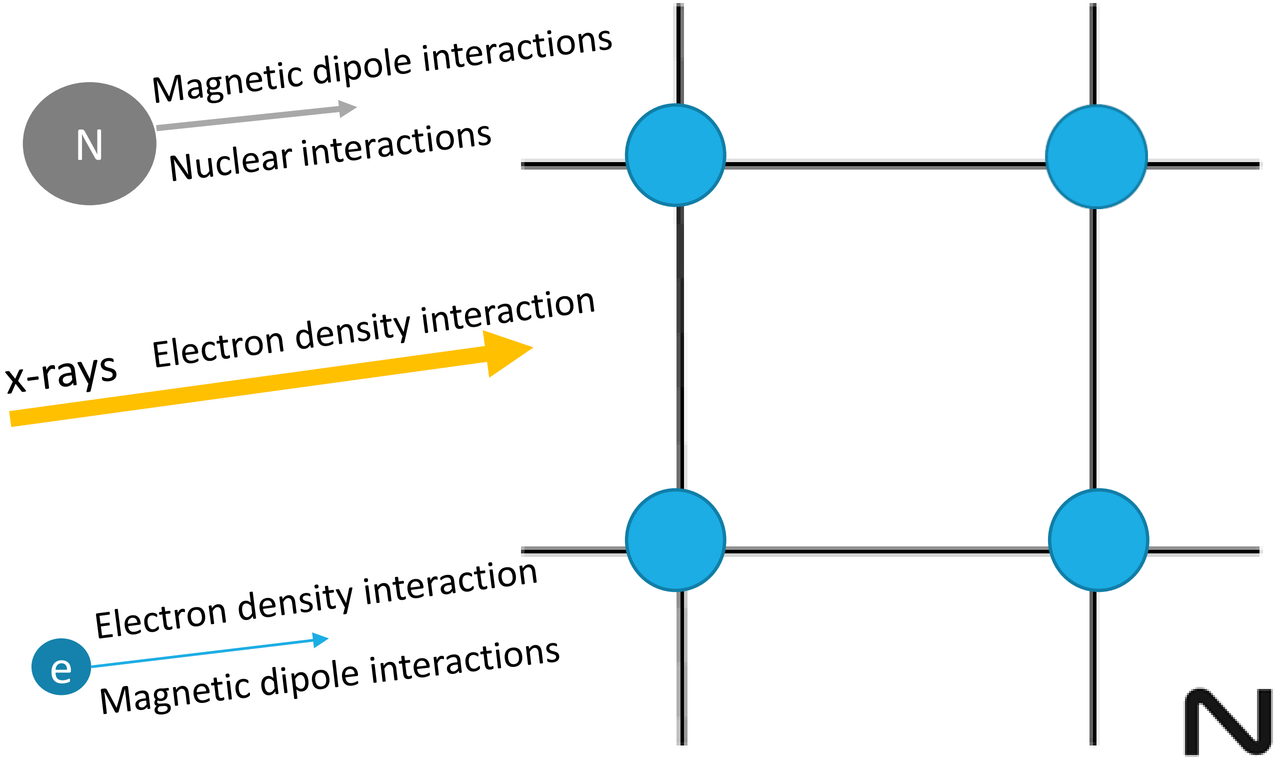
Why Neutrons?
The power of neutron scattering

- Neutrons have spin and zero charge (nuclear and magnetic scattering).
- Large penetration depth (bulk probe).
- Cross-sections good for low Z elements (Nuclear interactions).
- (More easily) Controllable energies.
- Energy scale great for dynamic interactions (inelastic scattering).



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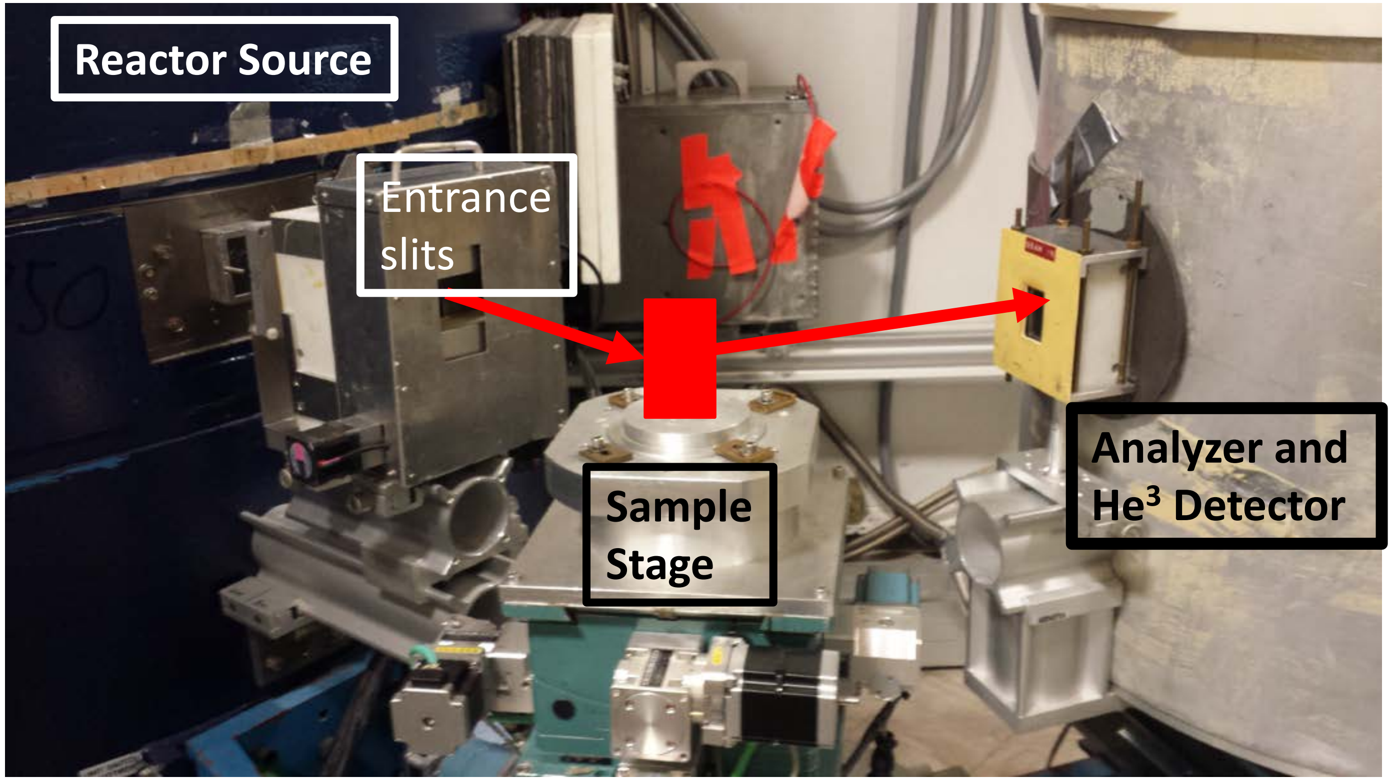
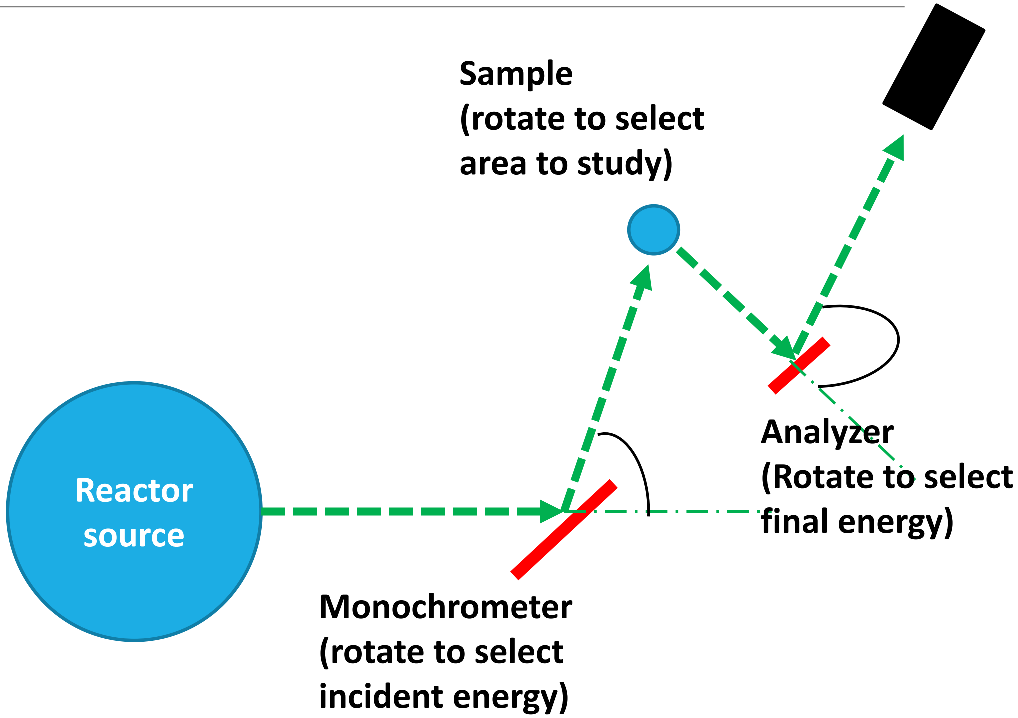
BT4 Triple Axis Spectrometer





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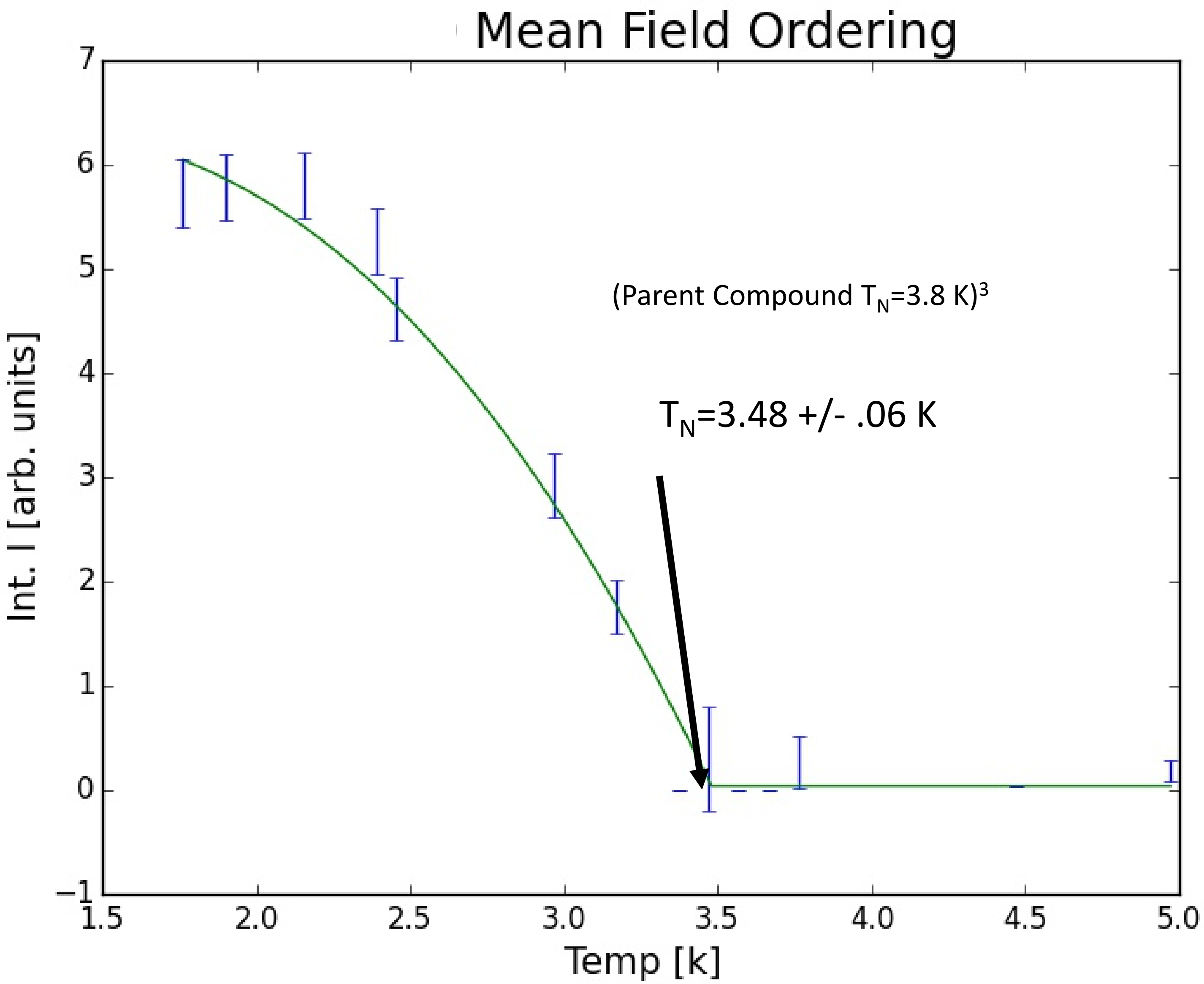
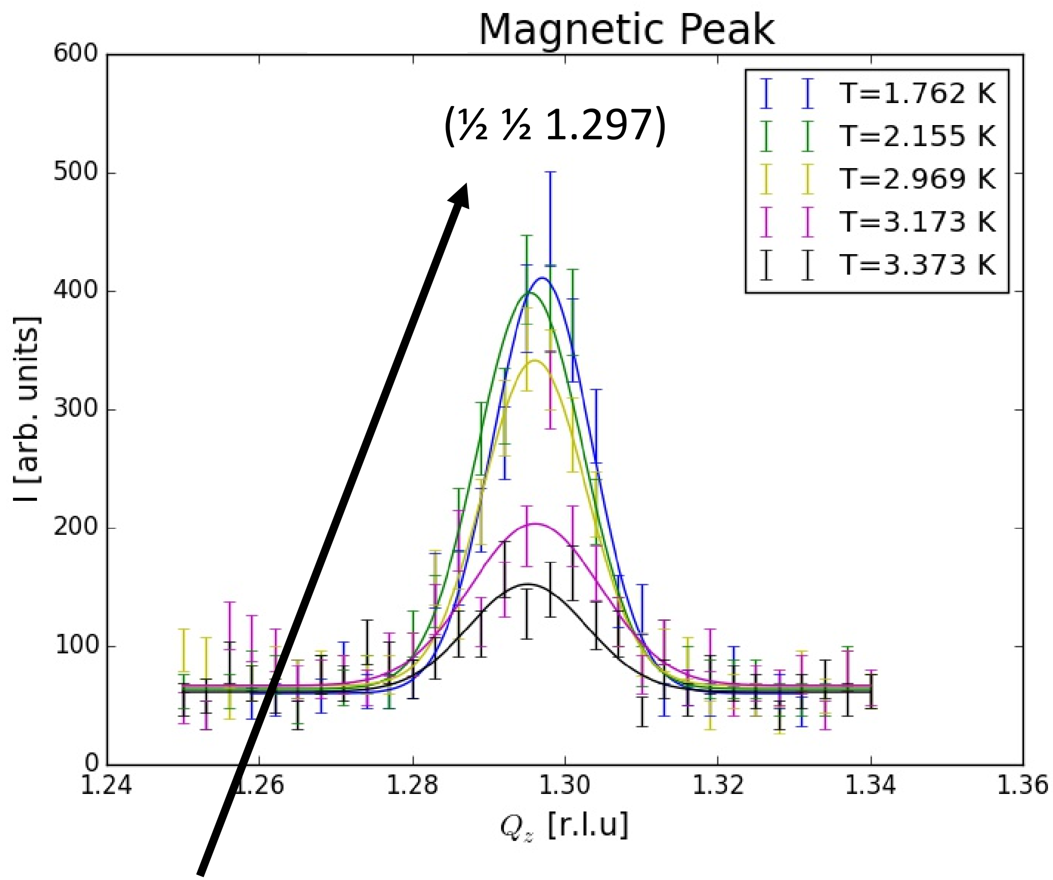
Measuring the Onset of Magnetic Ordering: x<1%



(Parent Compound T_N=3.8 K)[3]

T_N=3.48 +/- .06 K



(½ ½ 1.297)

Same structure as parent compound. [(001)+k peak]

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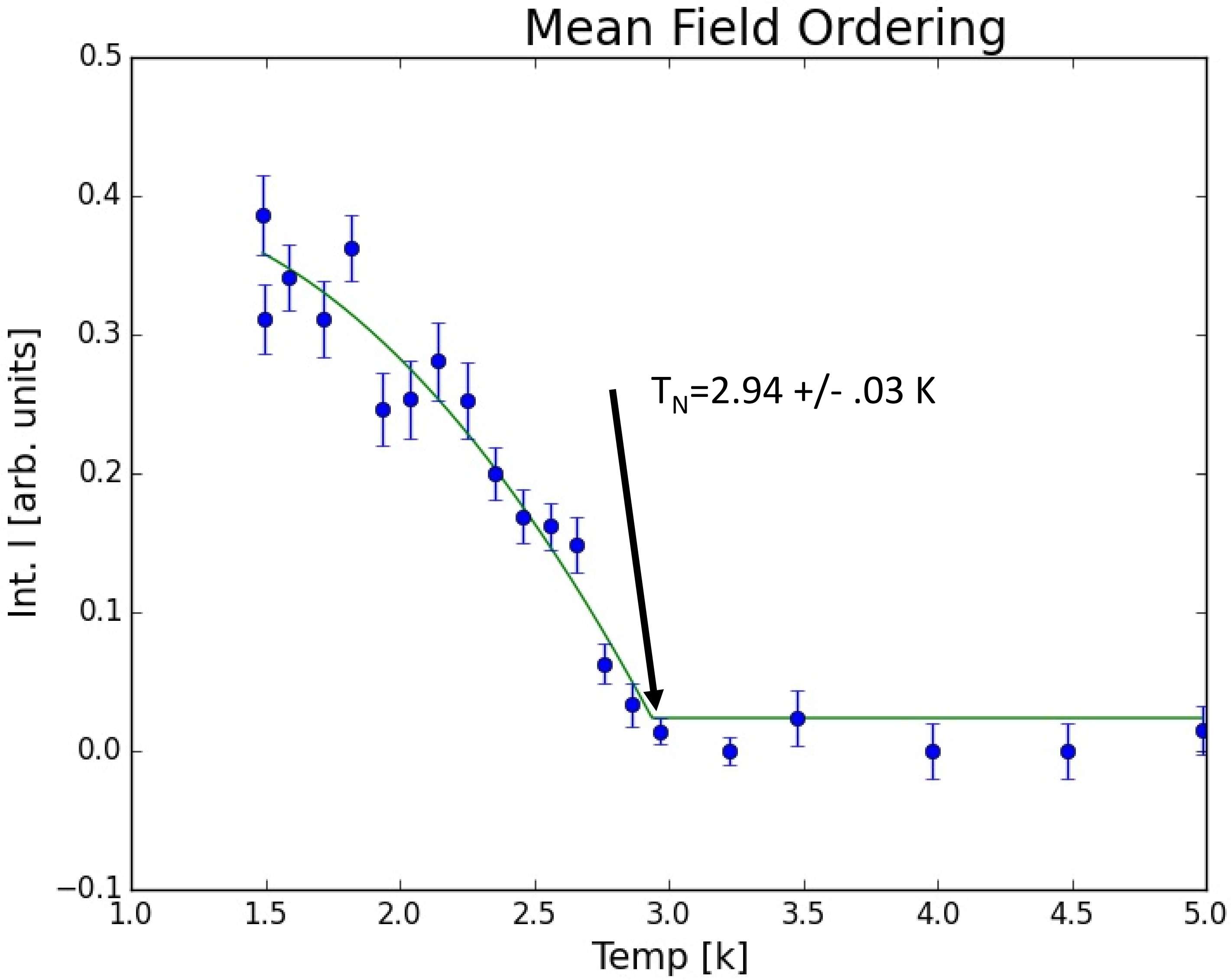
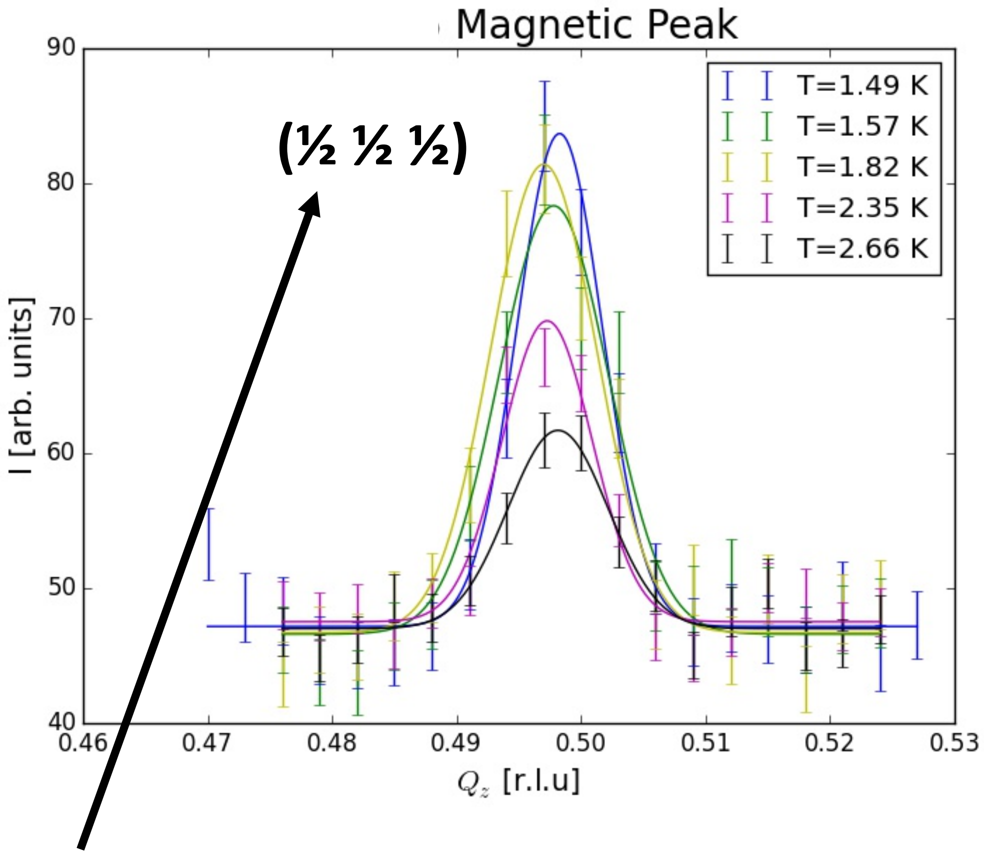
Measuring the Onset of Magnetic Ordering: x~50%



T_N=2.94 +/- .03 K



(½ ½ ½)

Changes from parent compound. New structure was formed!

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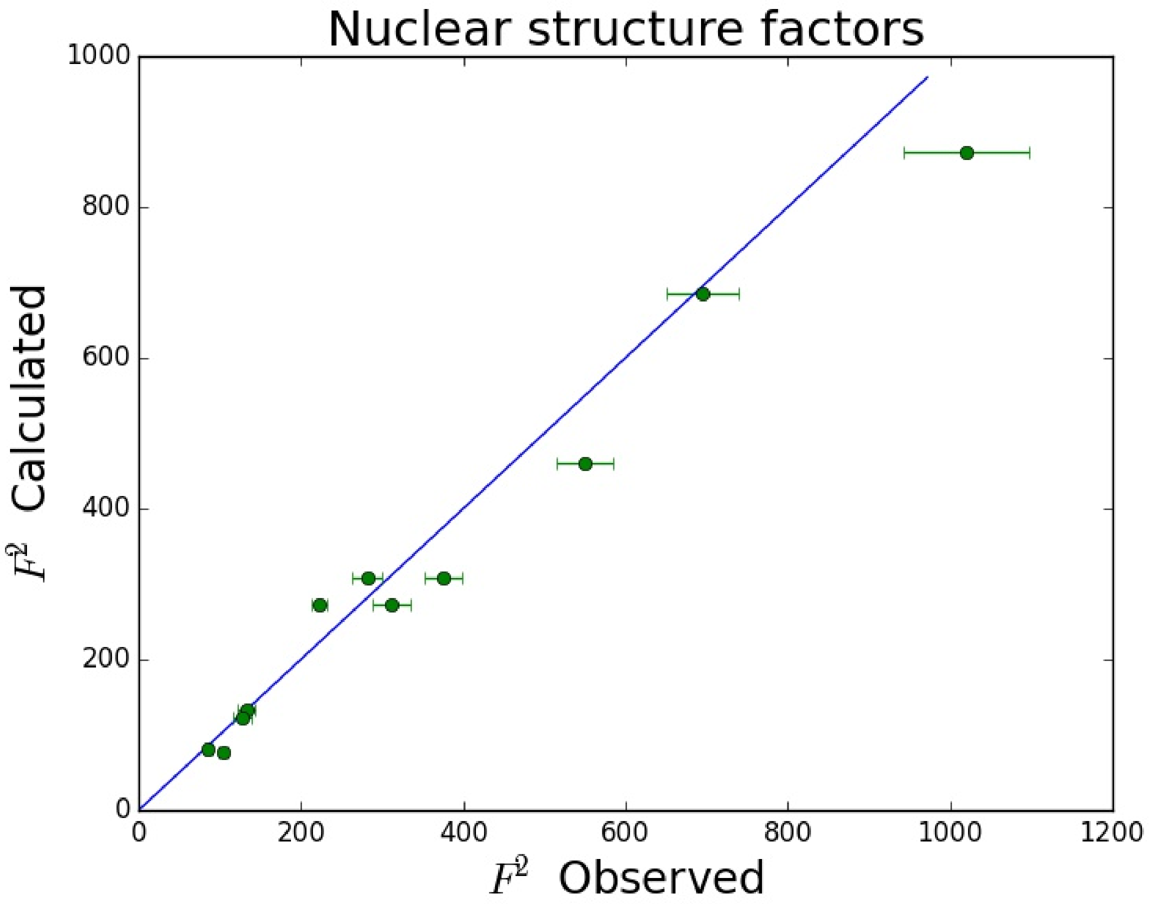
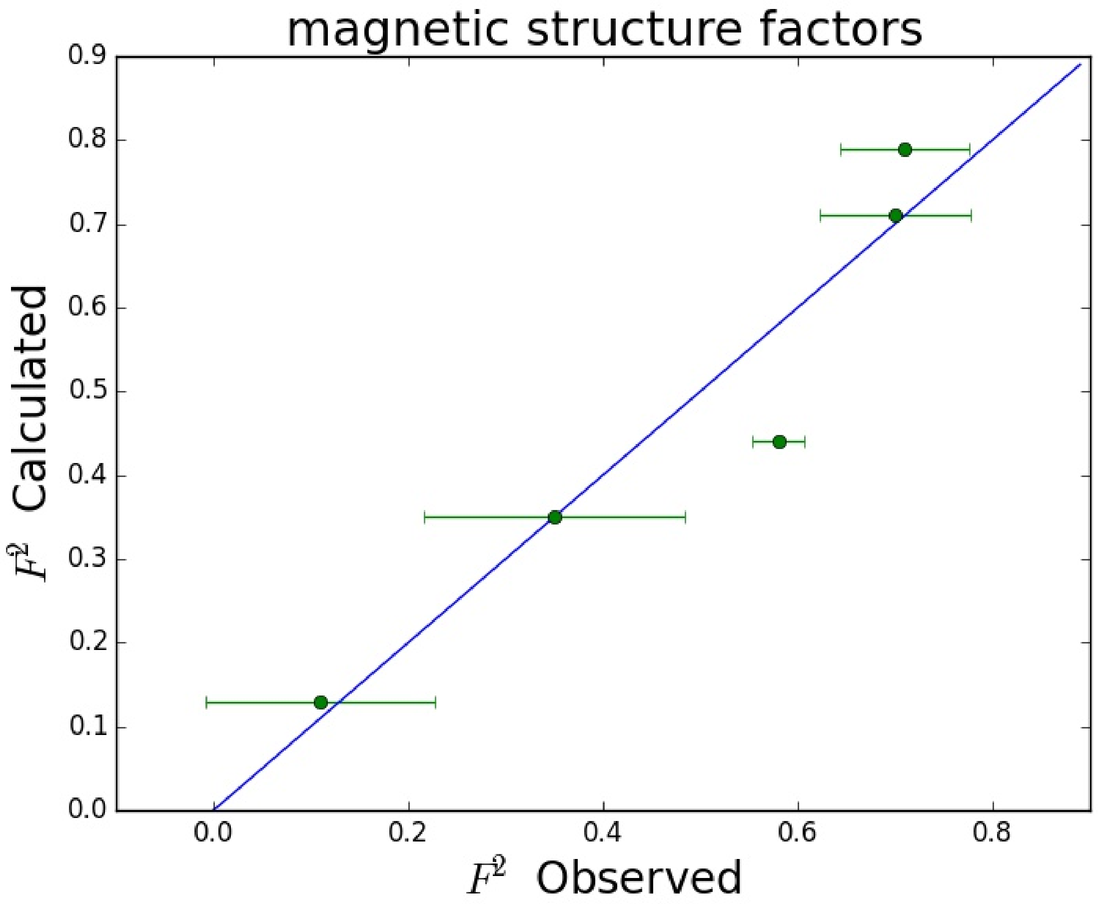
Measuring the Magnetic Structure: x~50%





Each point represents the structure factor of a single diffraction peak

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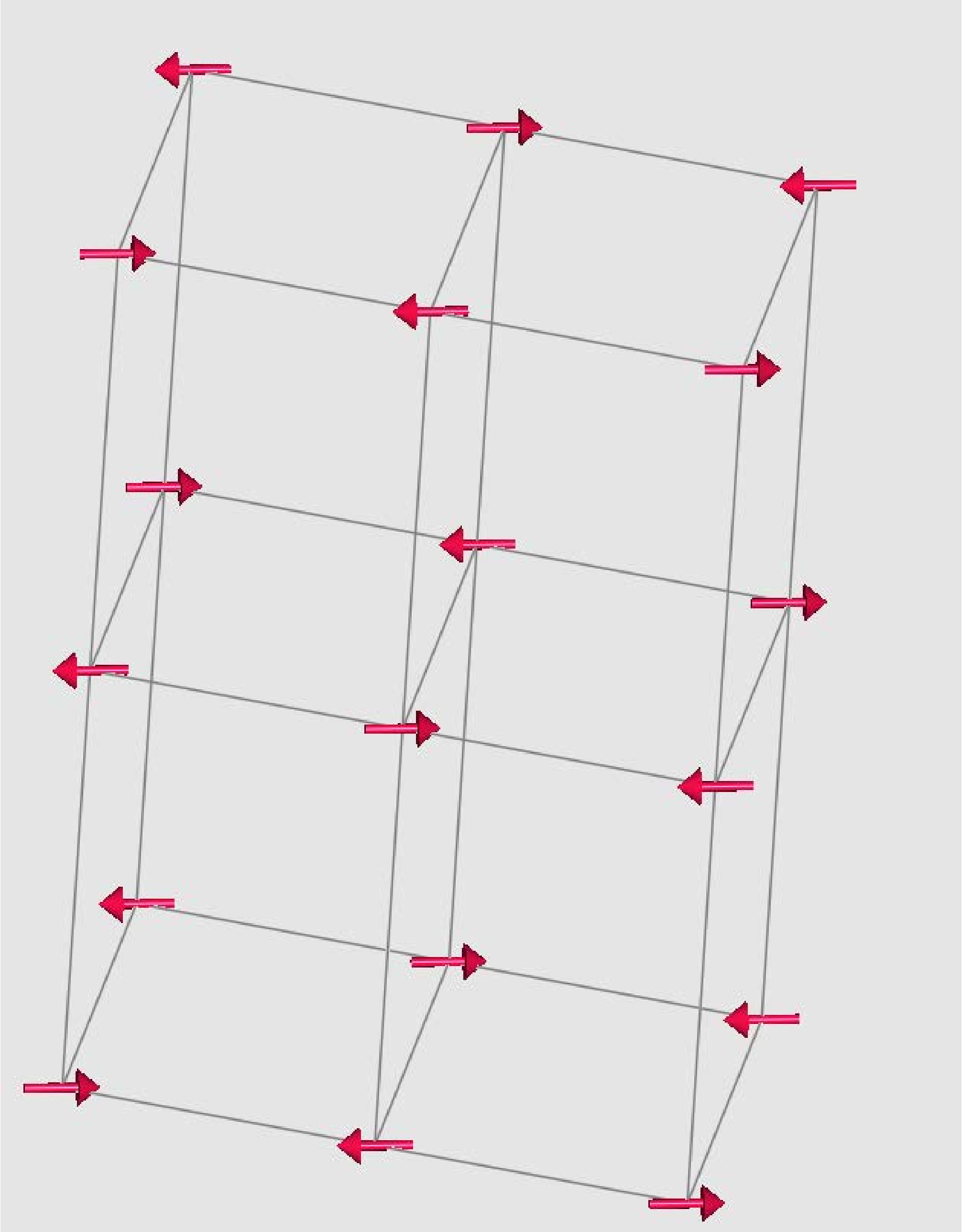

$Ce_{1-x}Yb_xRhIn_5$
k=(½ ½ ½) structure

$$\boldsymbol{\mu_{eff}} = \begin{pmatrix} .345 \pm .017 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ .119 \pm .030 \\ 0 \end{pmatrix}$$

$$\mu_{eff} = .365 \pm .034\ \mu_B$$

$\theta \cong 19$ degrees

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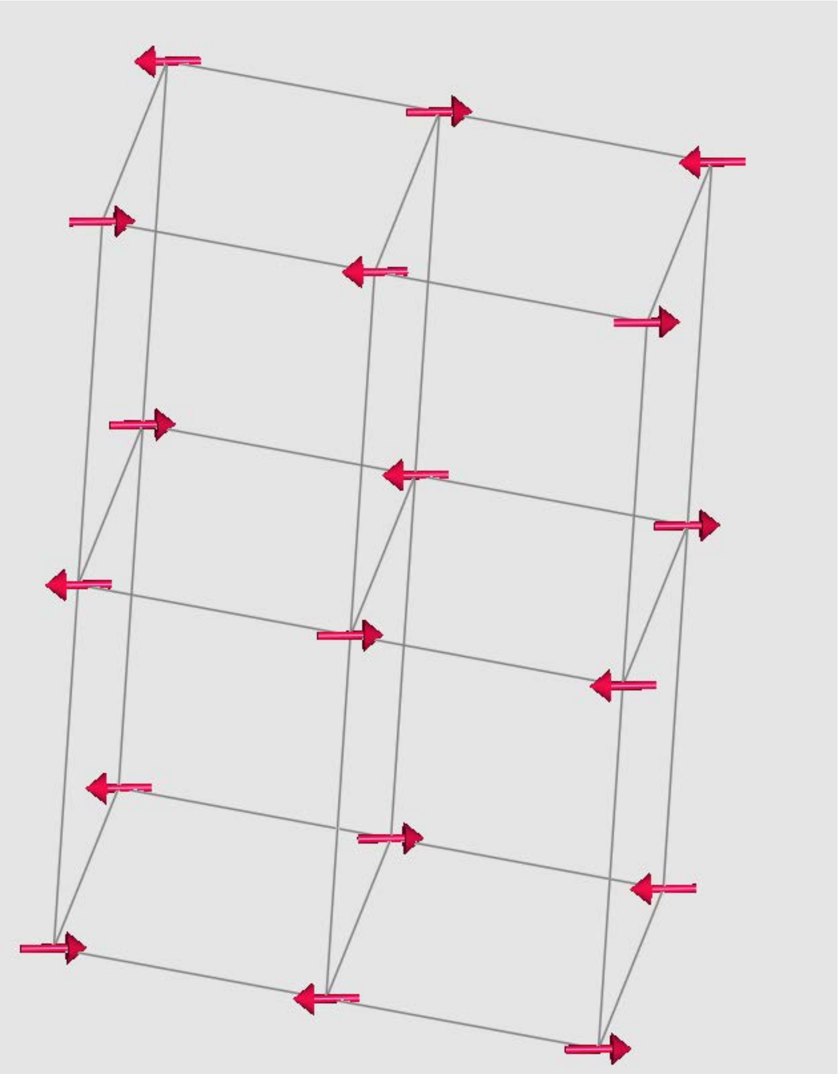
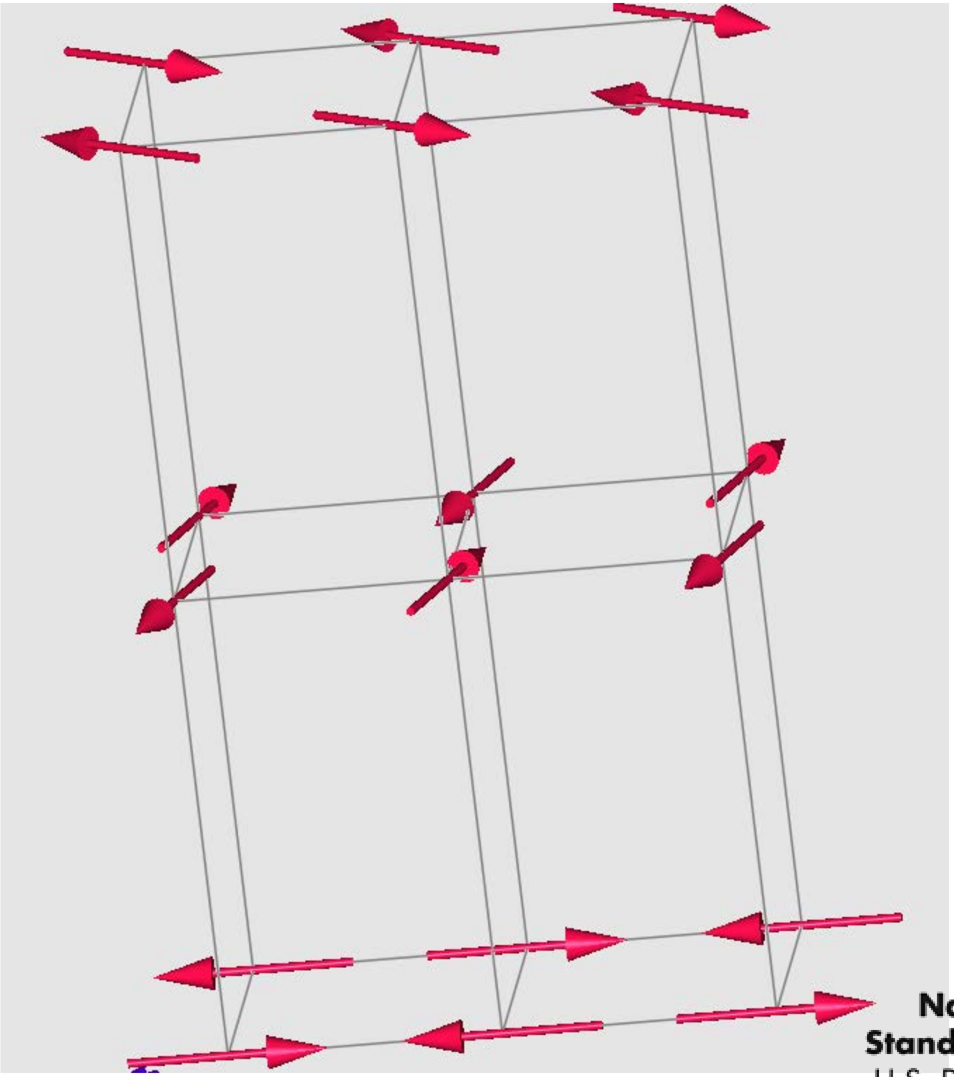
k=(½ ½ ½) structure [commensurate]
Intermediate Yb concentration



k=(½ ½ .297) structure [spiral]
Low Yb concentration



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Conclusion of $Ce_{1-x}Yb_xRhIn_5$

- We measured properties of $Ce_{1-x}Yb_xRhIn_5$ using a combination SQUID, XRD, and Neutron Scattering
- We found a limited solubility of Yb into CeRhIn5, which needs to be better understood to continue this study.
- Results:
    1. At low Yb concentrations, these compounds have a lower ordering temperature.
    2. At intermediate Yb concentrations, the magnetic structure changes from incommensurate to commensurate.
    3. A new magnetic structure was solved for these intermediate concentration.
- Future work :
    1. Apply pressure and magnetic field at low temperatures to induce new interesting phase transitions.
    2. Better measurements of the concentrations in these samples.
    3. Study why the magnetic structure changes with Yb concentration.
    4. Start to form a complete phase diagram from experiments to make better theories on how unconventional superconductivity works

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References and Citations

- Wei Bao, P. G. Pagliuso, J. L. Sarrao, J. D. Thompson, Z. Fisk,J.W. Lynn, and R.W Erwin. *Incommensurate magnetic structure of CeRhIn5*. **Phys. B 62-22**
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- P. Coleman. *Heavy Fermions: electrons at the edge of magnetism.* Rugters.
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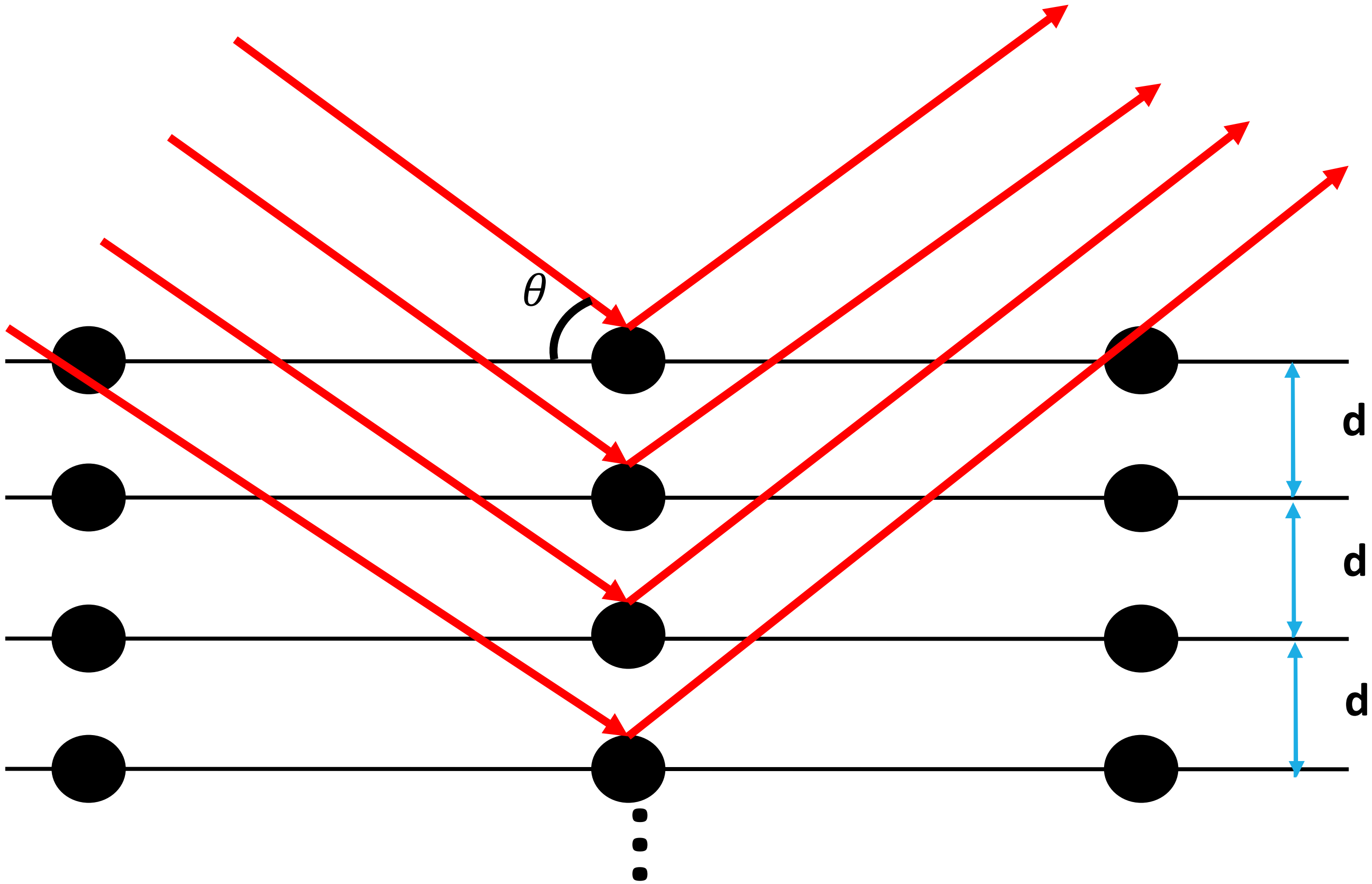
- Neil W. Ashcroft, N. David Mermin. *Solid State Physics*. Brooks/Cole.

Bragg’s Law for Crystal Diffraction

$$n\lambda = 2d\sin\theta$$



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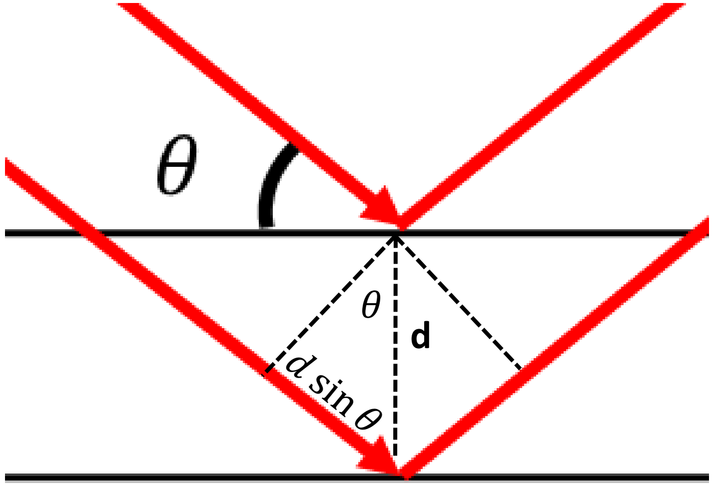
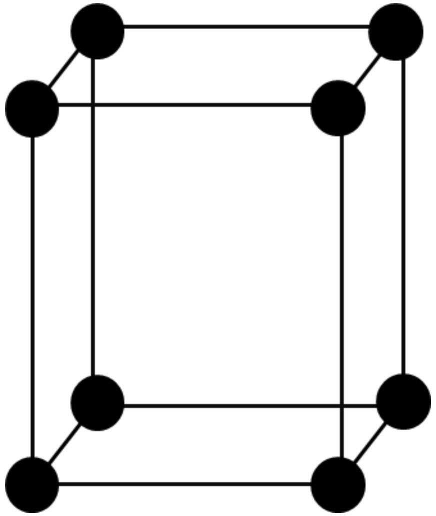
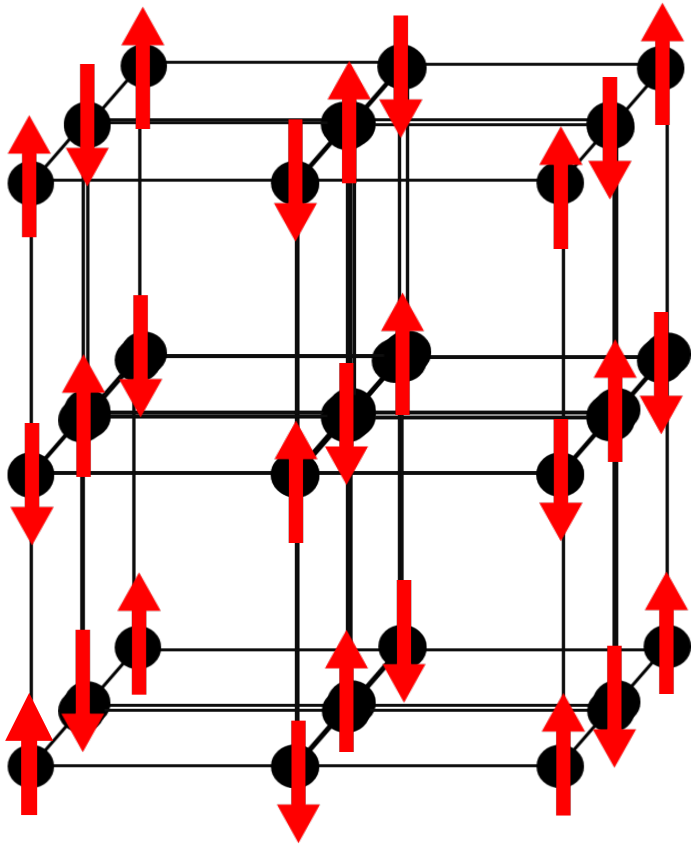


Nuclear vs. Magnetic Unit Cell in Neutron Scattering





k=(½, ½, ½)

(repeats every 2a,2b, and 2c)

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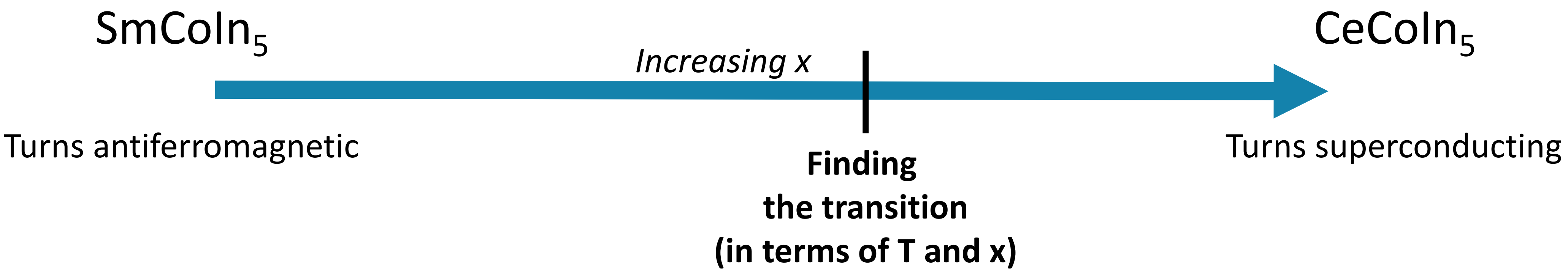
Original Goal: $Sm_{1-x}Ce_xCoIn_5$



$SmCoIn_5$

Increasing x

$CeCoIn_5$

Turns antiferromagnetic

Finding
the transition
(in terms of T and x)

Turns superconducting

$Sm_{(1-x)}Ce_xCoIn_5$ (Heavy Fermion Material)

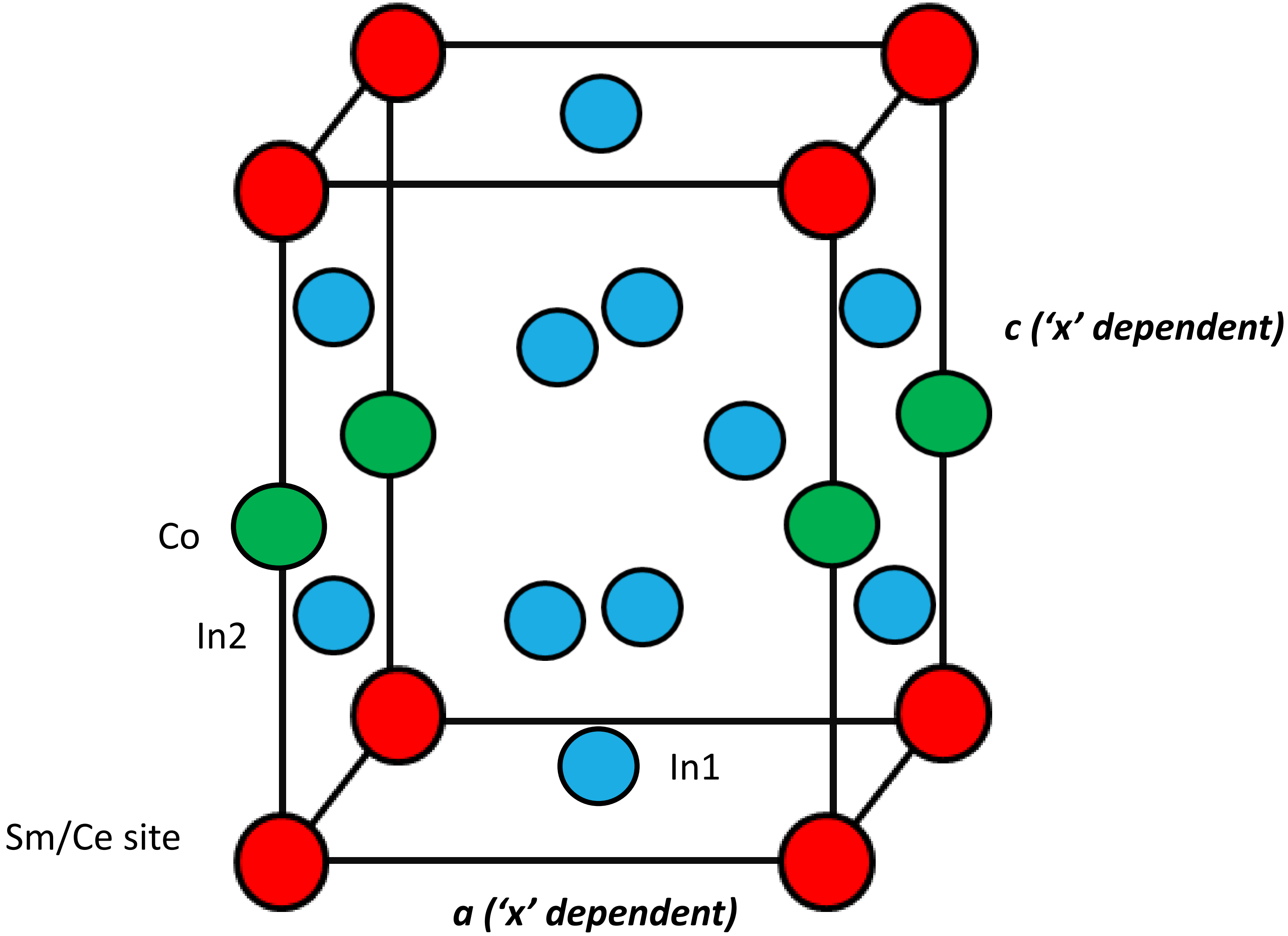
Tetragonal:

a=b≠c

α=β=γ=90°

Space group:

P 4/m m m

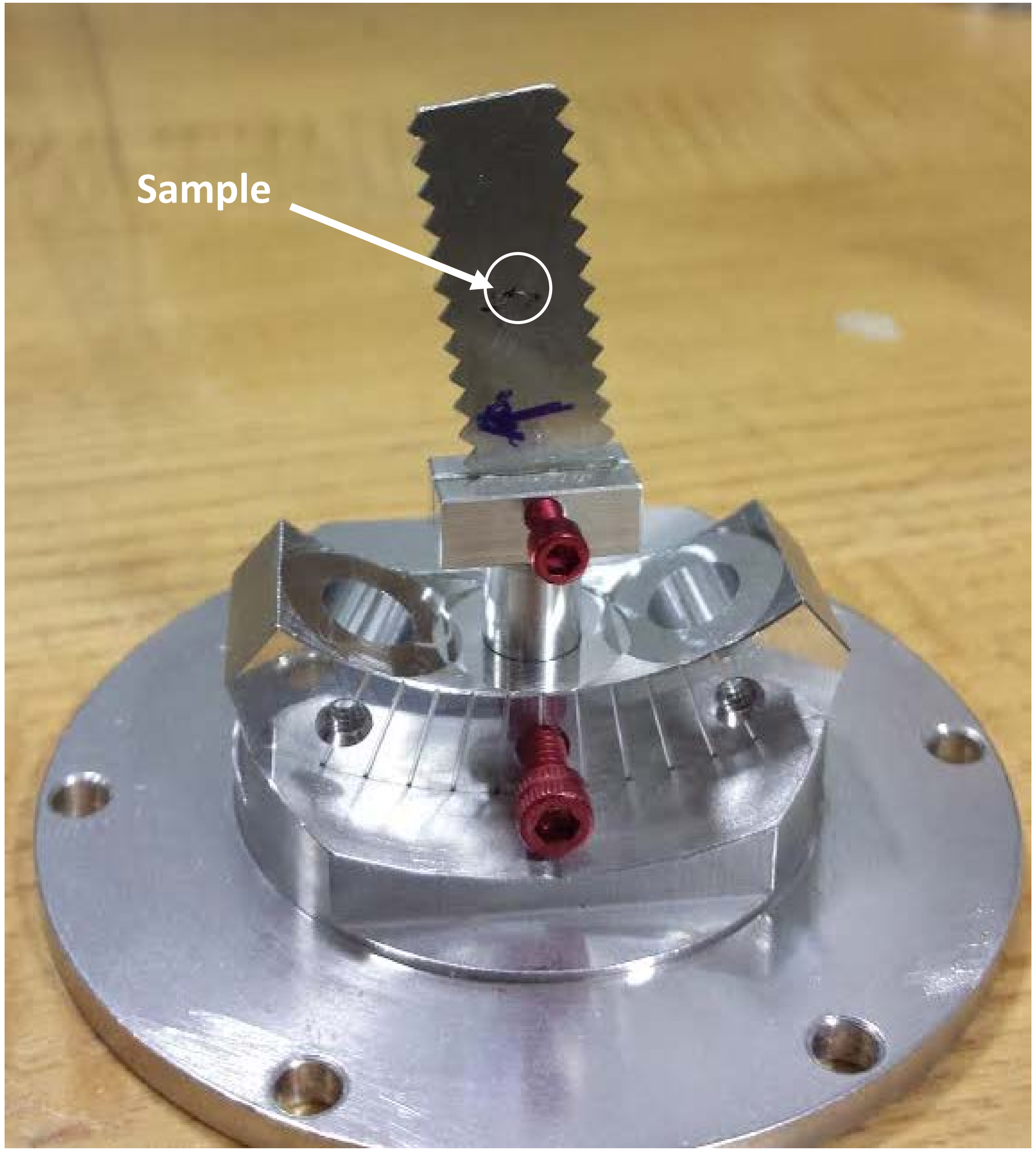


Measured Parameters (x-ray)

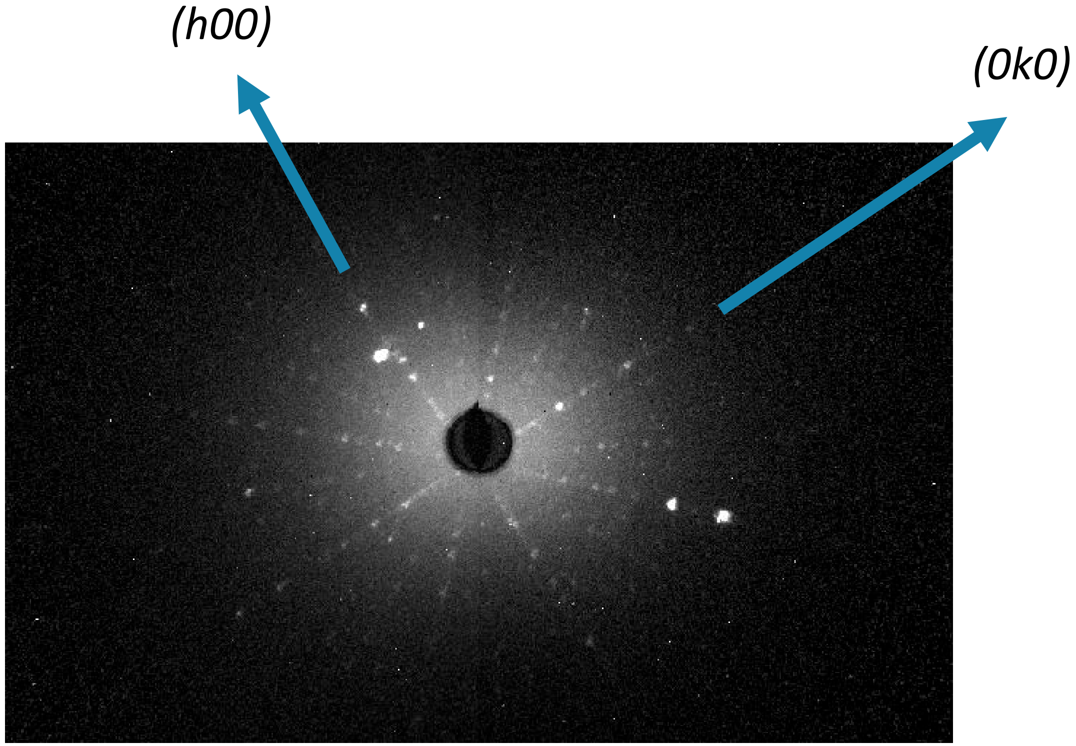
(x=0 powder)

a = 4.5798 ± .0001 Å

c = 7.4708 ± .0002 Å



Laue x-ray diffraction



(00l) face

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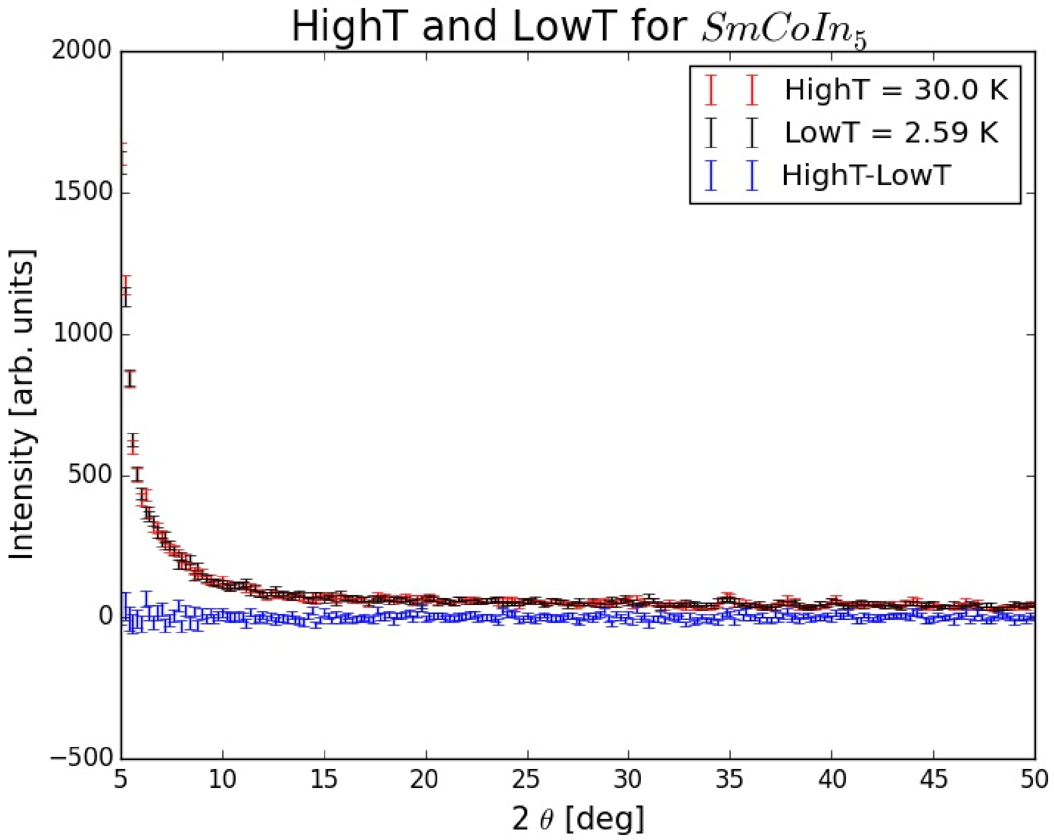
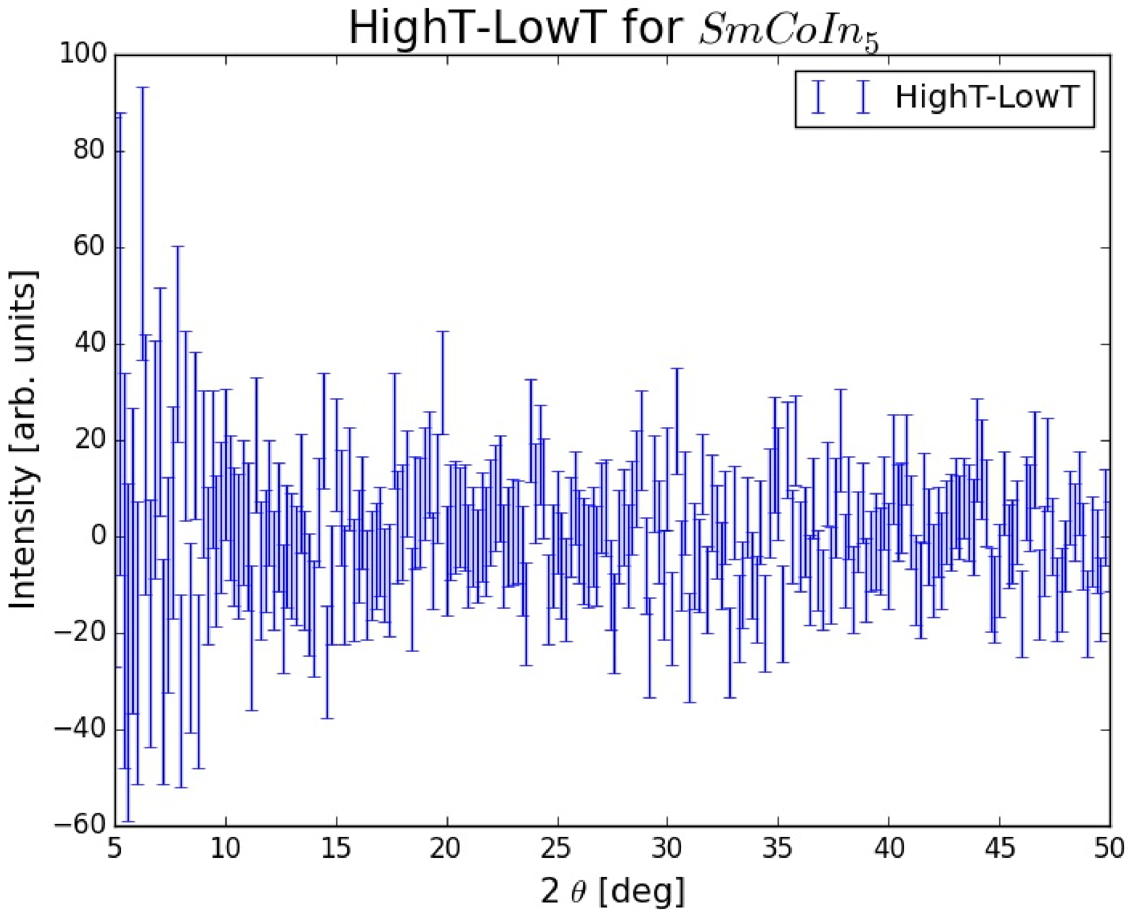
No Magnetic Peaks found for $SmCoIn_5$





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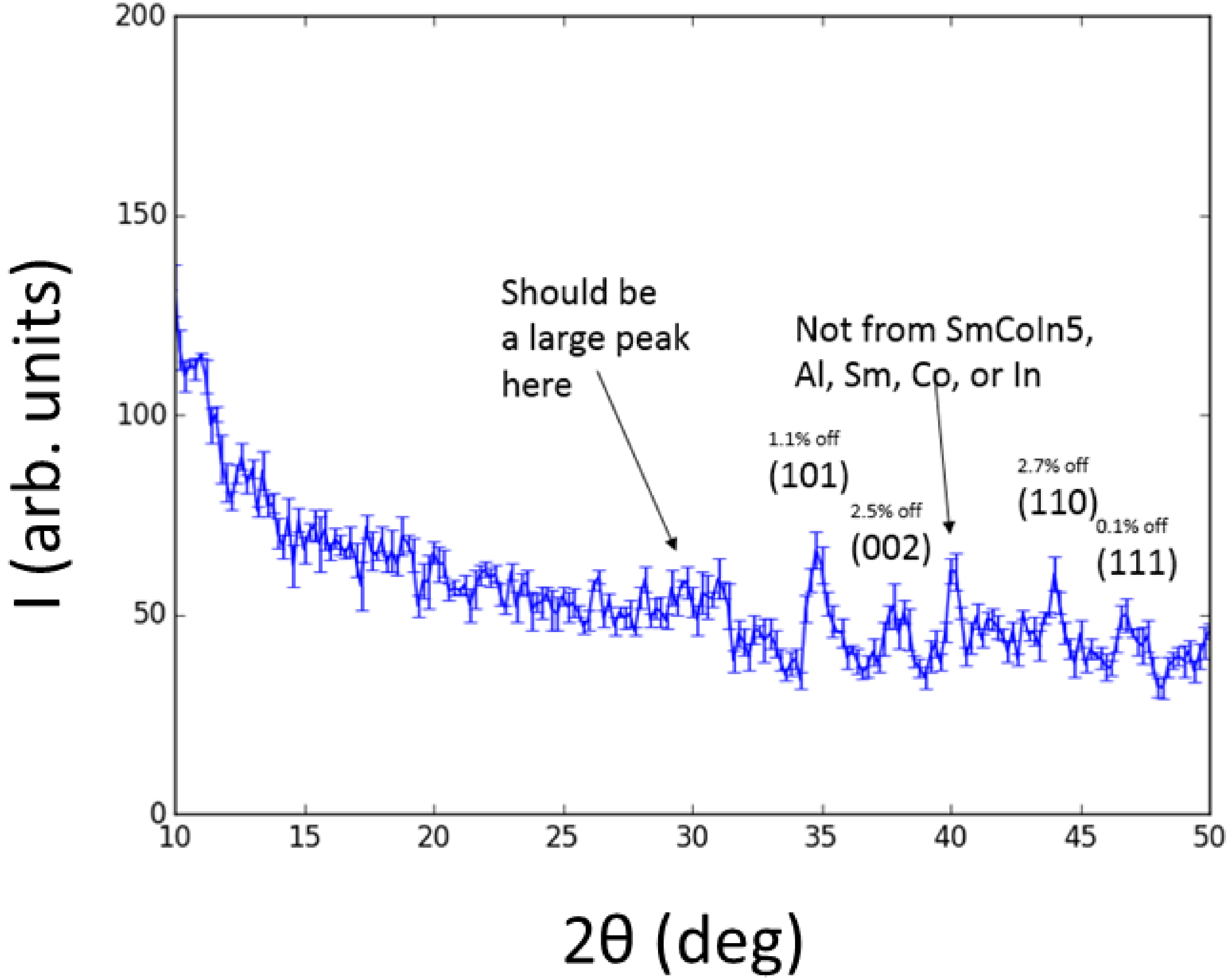
4 scans averaged together (powder) E=14.7meV



Should be a large peak here

Not from SmCoIn5, Al, Sm, Co, or In

Why?

E=35 meV

			Cross Sections (1×10^{-24} cm^2)		
Element	**Formula Unit**	**Atomic Wight (g/m)**	**Coherent**	**Incoherent**	**Absorption**
Sm	1	105.360	0.422	39.000	5072.236
Co	1	58.933	0.779	4.800	31.845
In	5	114.820	2.080	0.540	165.991

Data from NCNR Scattering and Activation Database

Determining μ_{eff} and x using the SQUID

Curie-Weiss Law for Paramagnetism

$$\chi(T) = \frac{\mu_{bulk}\,(T)}{H*moles} = \frac{C}{T-\theta_m} - \chi_0$$

T - Temperature [K]
C – Curie Number [(emu K)/or]
θ_m - Curie Temp. [K] (+ Ferro, - Anti)

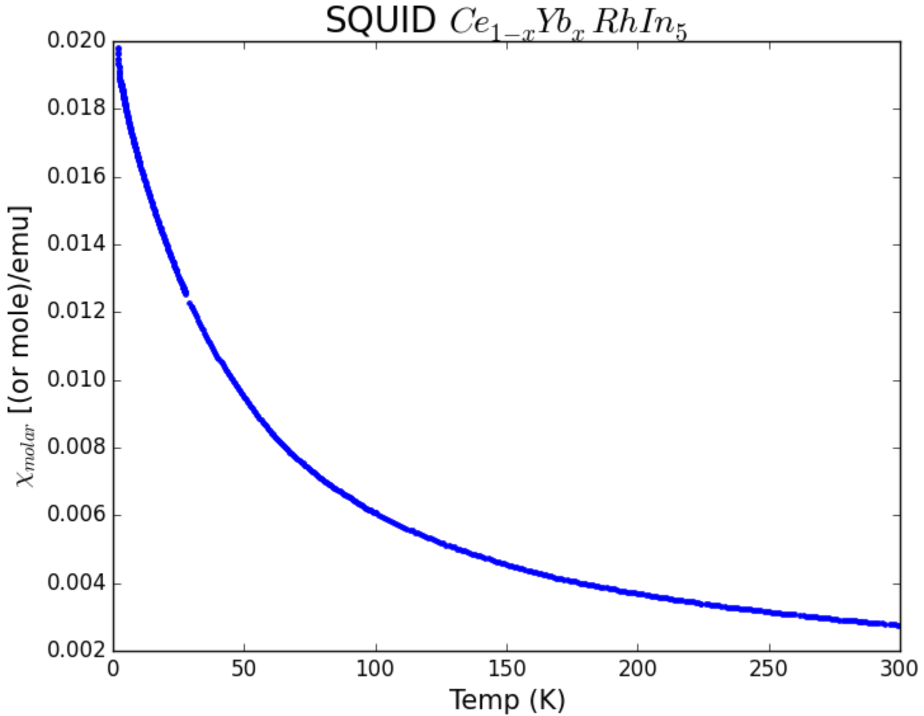
Fit using:

$$\frac{\mu_{bulk}(T)}{H} = \frac{a}{T-\theta_m} - b$$

$$C_{molar} = \frac{N_a \mu_{eff}^2(x)}{3k_B}$$

$$a = moles(x) * C(x)$$
$$b = moles(x) * \chi_0$$

$$\mu_{eff}^2(x) = xP_{Yb^{+3}}^2 + (1-x)P_{Ce^{+2}}^2$$



$$P_{Ce^{+3}} = 2.54\ \mu_B$$
$$P_{Yb^{+3}} = 4.54\ \mu_B$$

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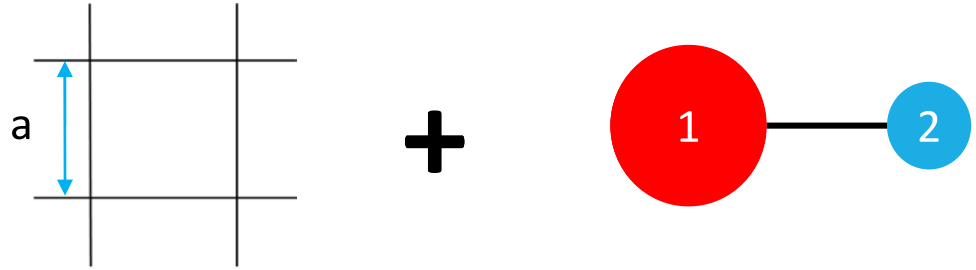
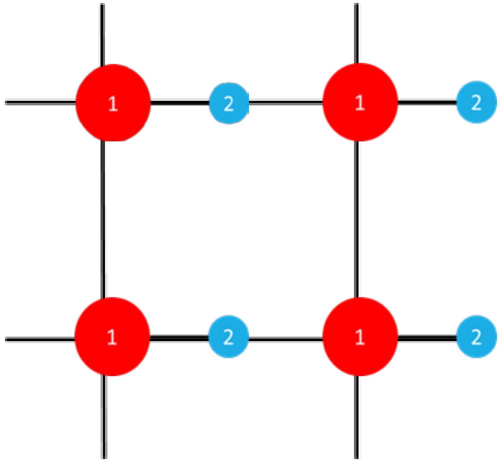
*numbers and equations from *Ashcroft Solid State Physics*

Crash course in crystallography

- Lattice + Atomic Basis = Crystal





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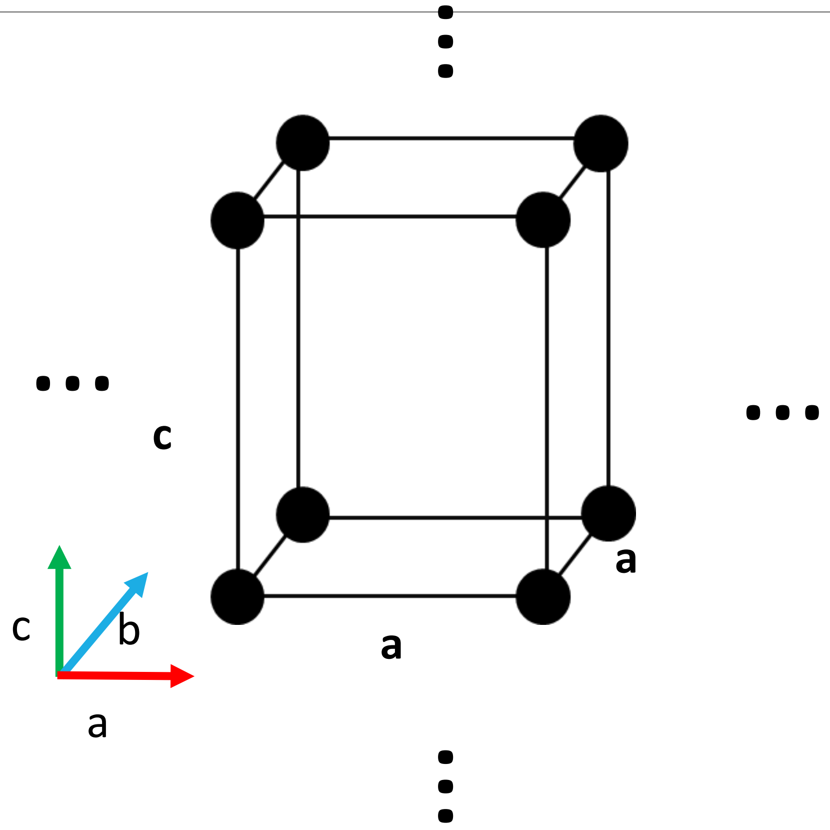
Crash course in crystallography

- Lattice + Atomic Basis = Crystal
- Unit cell



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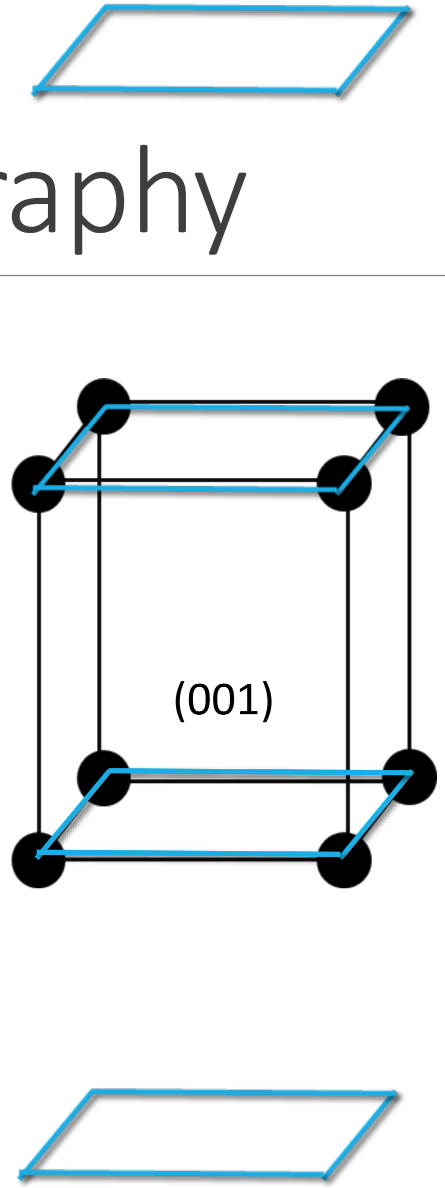
Crash course in crystallography

- Lattice + Atomic Basis = Crystal
- Unit cell
- Reciprocal space and the Miller indices

A measure of frequency.



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Crash course in crystallography

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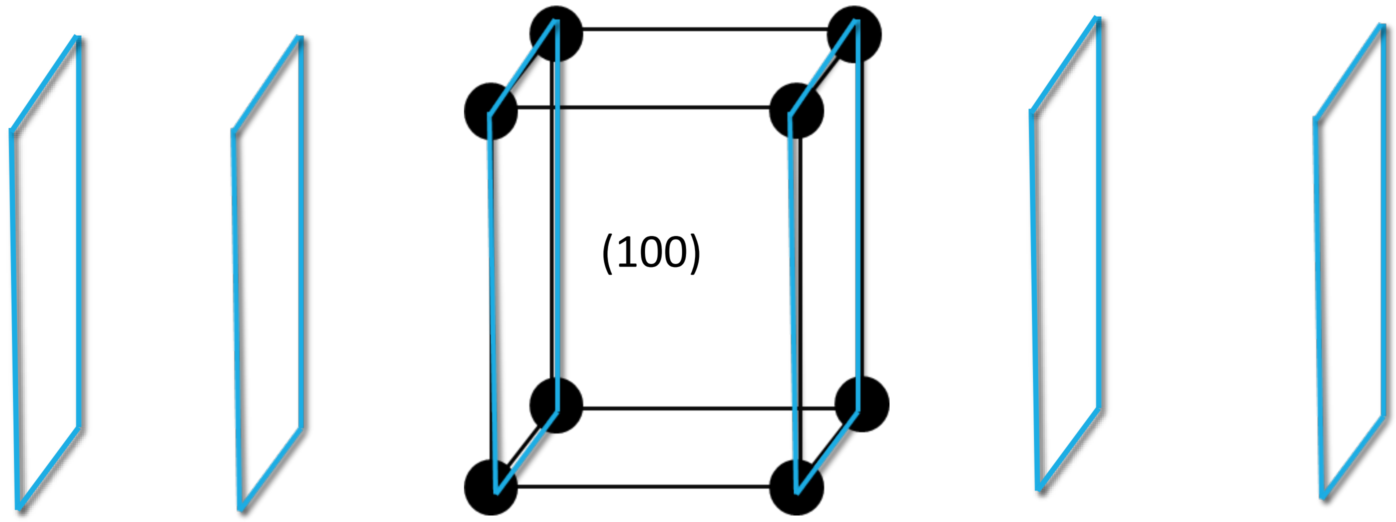

Crash course in crystallography

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