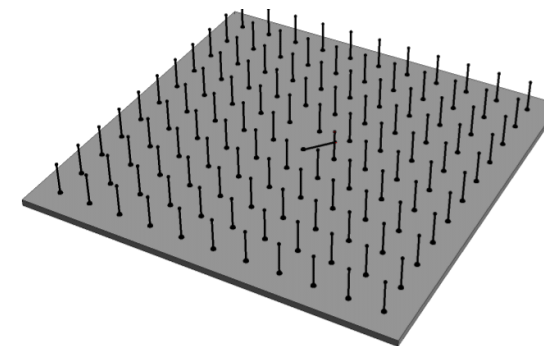
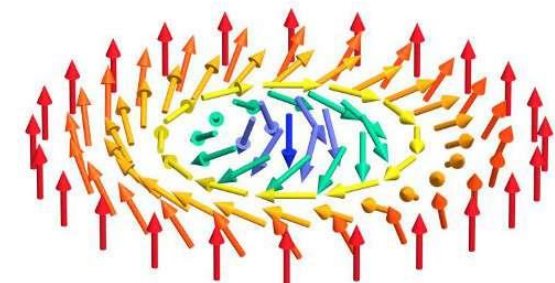
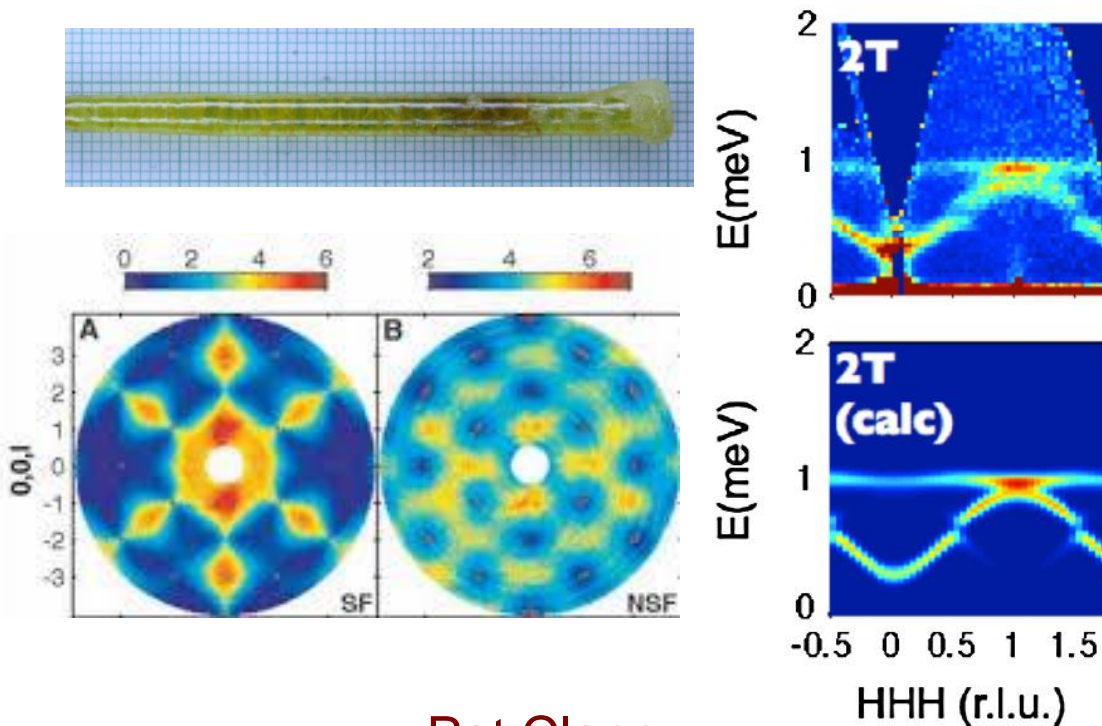
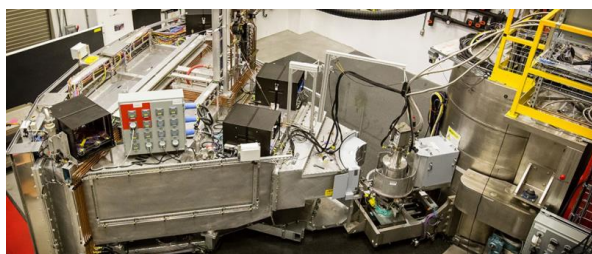




Magnetic Scattering



 Brockhouse Institute
for Materials Research

Pat Clancy
Dept. of Physics & Astronomy
McMaster University

McMaster
University 



Introduction to Magnetic Scattering

- Magnetic Scattering with **Neutrons**
 - Essential tool for the study of magnetic materials
 - Elastic Scattering (diffraction) – magnetic structure, phase transitions
 - Inelastic Scattering (spectroscopy) – magnetic dynamics, excitations, interactions
-
- Magnetic Scattering with **X-rays**
 - How does it work?
 - When is it a good idea?



Suggestions for Further Reading...

- Magnetic Scattering with **Neutrons**:

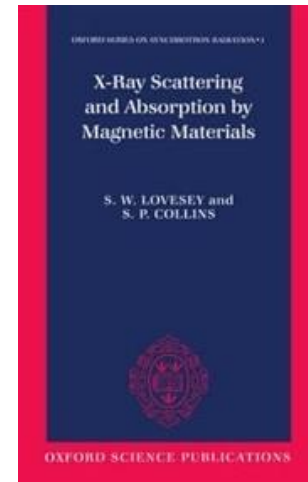
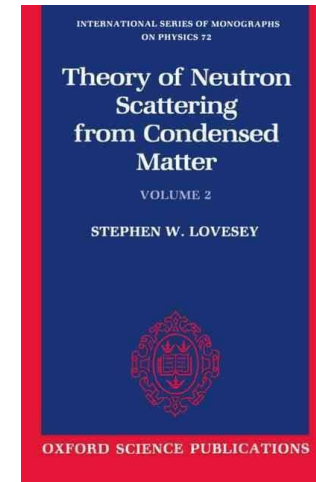
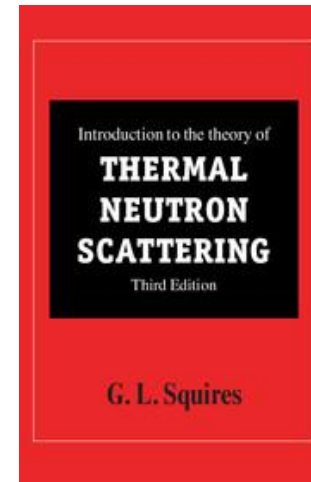
Introduction to the Theory of Thermal Neutron Scattering, G. L. Squires (2012)

Theory of Neutron Scattering from Condensed Matter (Vol. 2), S. W. Lovesey (1984)

- Magnetic Scattering with **X-rays**:

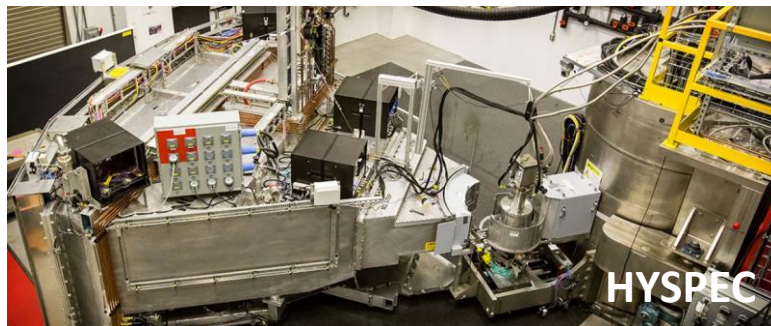
X-ray Scattering and Absorption by Magnetic Materials, S. W. Lovesey & S. P. Collins (1996)

“*Magnetic Scattering*” by J. W. Lynn and B. Keimer
in *Handbook of Magnetism* (arXiv:1910.01218)



Magnetic Scattering with Neutrons

- One of the “killer applications” of neutron scattering
- Essential tool for investigating magnetic materials



HYSPEC



PTAX (HB-1)



CTAX (CG-4C)



POWGEN



POWDER (HB-2A)



WAND² (HB-2C)



DEMAND (HB-3A)



MAGREF

Magnetic Scattering with Neutrons

- Neutrons are spin $\frac{1}{2}$ particles
- They carry no charge, but do carry a **magnetic dipole moment**:

$$\mu_n = -\gamma\mu_N\sigma$$

$\gamma = 1.913$
(Gyromagnetic ratio)

$\mu_N = \frac{e\hbar}{2m_n}$
(Nuclear magneton)

(Pauli spin operator)

- μ_n can interact with the electrons in a material via magnetic potentials
- **Scattering from these potentials can be comparable in strength to nuclear scattering**

Magnetic Materials

**Transition Metals:
Up to 10 d-levels to fill**

The periodic table shows the following elements highlighted:

- Transition Metals (Red Box):** Scandium (Sc) through Zinc (Zn) in the first row; Yttrium (Y) through Cadmium (Cd) in the second row; Lanthanum (La) through Mercury (Hg) in the third row; Actinium (Ac) through Copernicium (Cn) in the fourth row.
- Lanthanides/Actinides (Blue Box):** Cerium (Ce) through Lutetium (Lu) in the fifth row; Thorium (Th) through Lawrencium (Lr) in the sixth row.

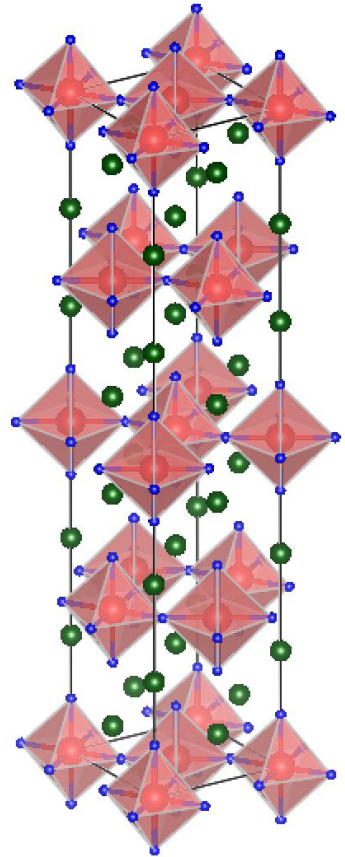
- **Magnetic moments** arise on atoms which have **unpaired electrons** in partially filled electronic orbitals

- Most common families of magnetic materials tend to be based on elements with partially filled d- or f-shells (e.g. **transition metals** or **rare earth/lanthanides**)

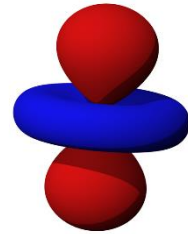
**Lanthanides/Rare Earths and Actinides:
Up to 14 f-levels to fill**

Magnetic Materials

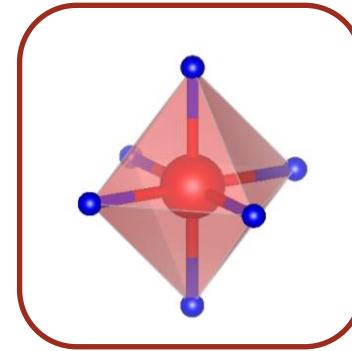
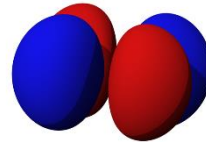
- Size of magnetic moments is determined by Hund's Rules:



$$3z^2 - r^2$$

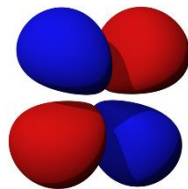


$$x^2 - y^2$$

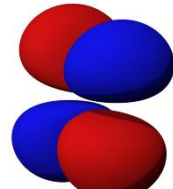


e_g orbitals

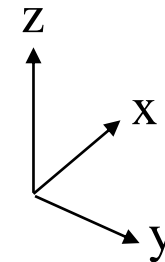
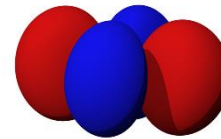
$$zx$$



$$yz$$



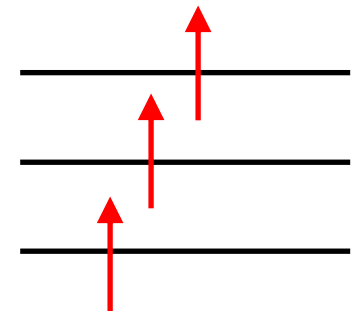
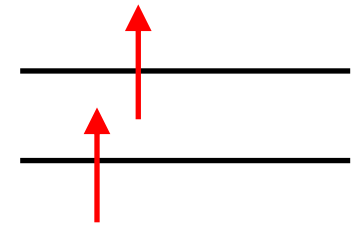
$$xy$$



t_{2g} orbitals

e.g. Mn^{2+} ($3d^5$)

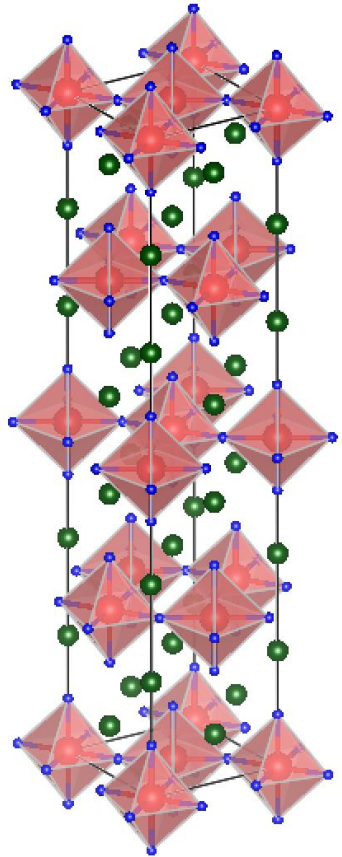
$$S = 5/2$$



Magnetic Materials

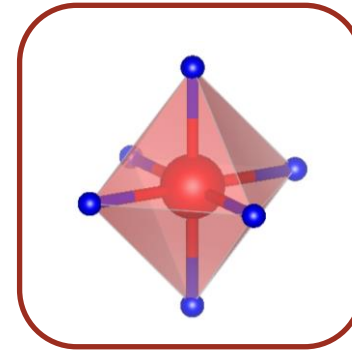
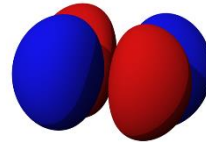
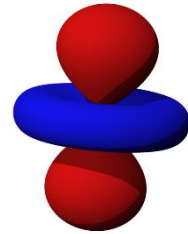
- Size of magnetic moments is determined by Hund's Rules:

e.g. Cu^{2+} ($3d^9$)



$3z^2 - r^2$

$x^2 - y^2$

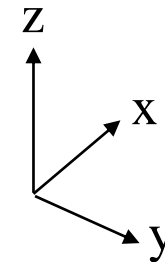
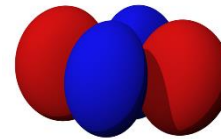
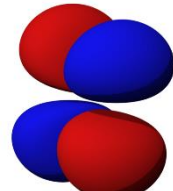
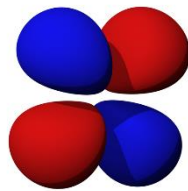


e_g orbitals

zx

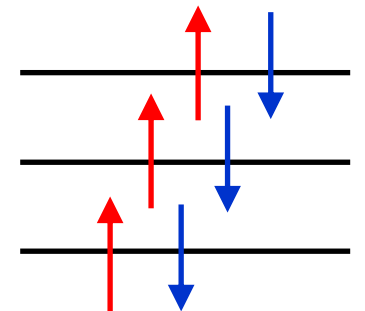
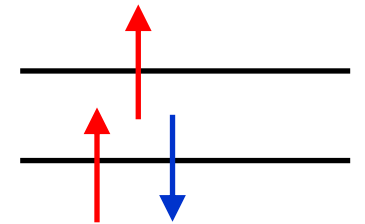
yz

xy



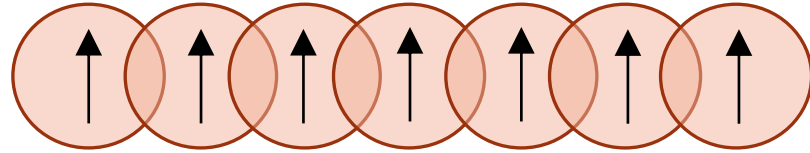
t_{2g} orbitals

$$S = 1/2$$

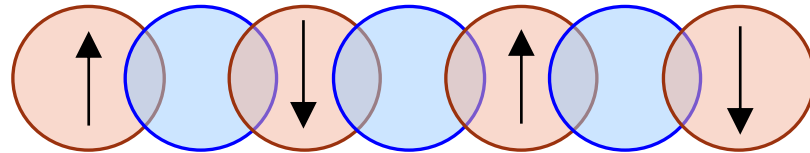


Magnetic Interactions

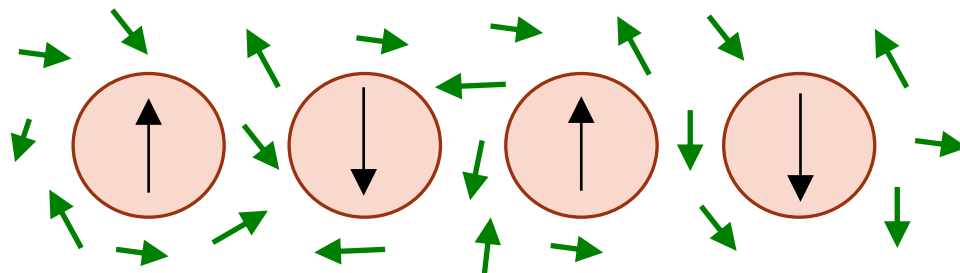
- Direct exchange:



- Superexchange:



- RKKY exchange:

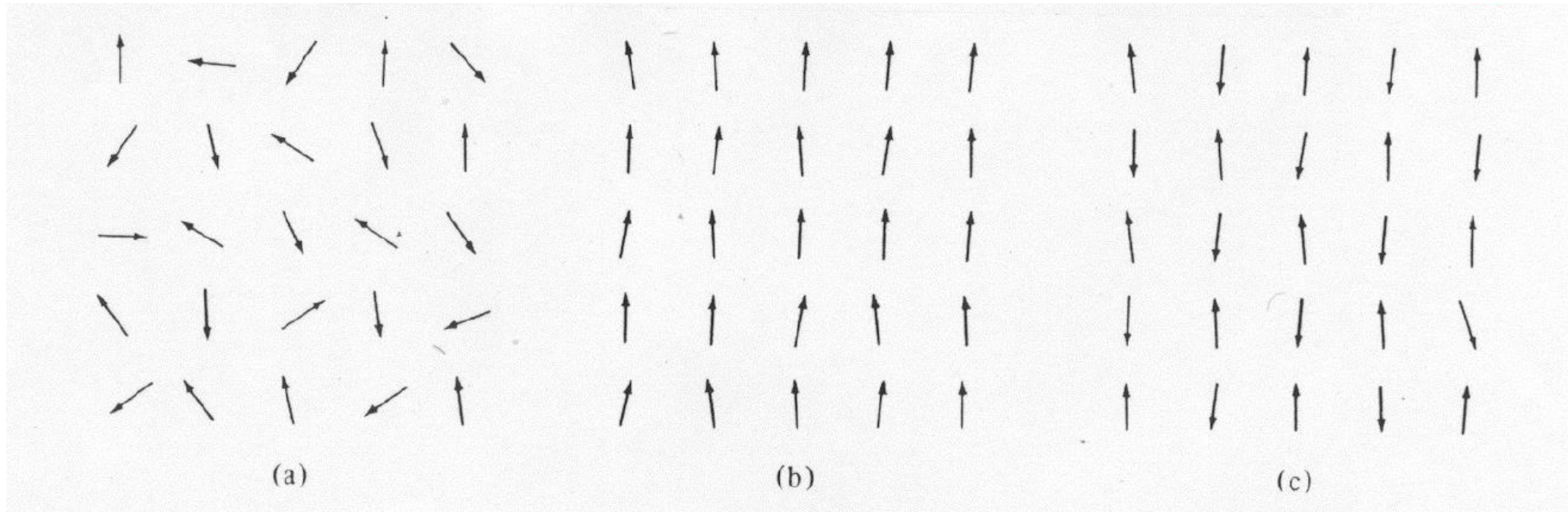


Describe interactions by a magnetic Hamiltonian:

$$\text{e.g. } H = J \sum_{i,j} S_i \cdot S_j$$

(exchange parameter)

Magnetic Order



Paramagnet

$(T > T_c)$

Ferromagnet

$(T < T_c)$

Antiferromagnet

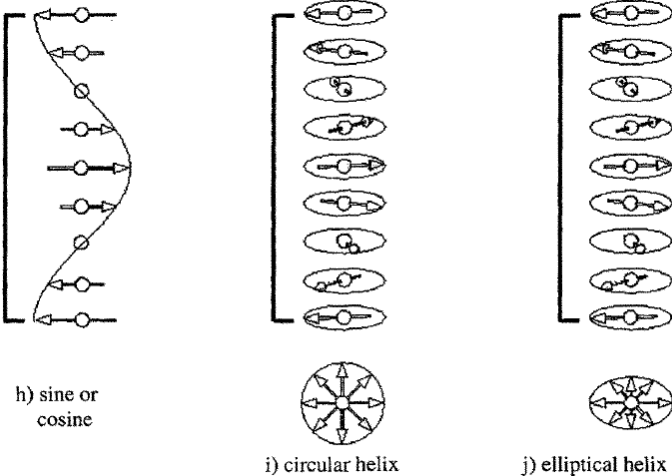
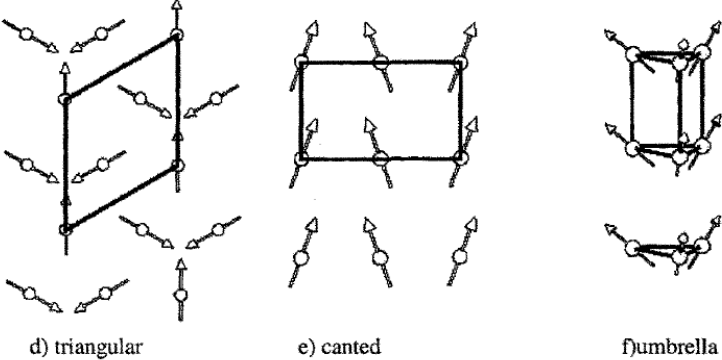
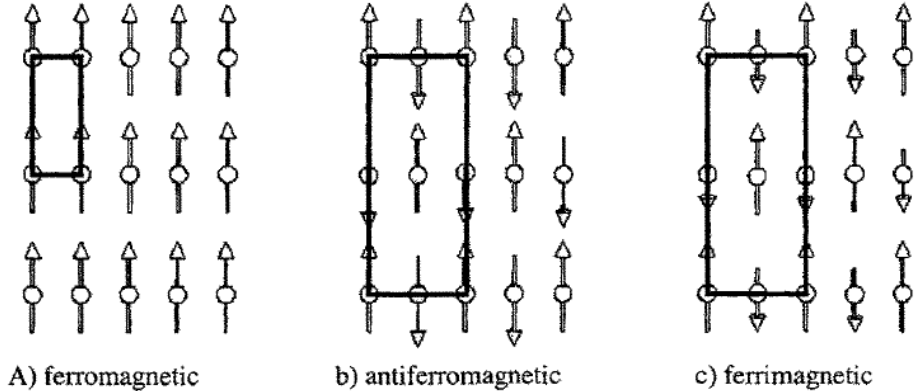
$(T < T_N)$

Magnetic Structures

- Magnetically ordered structure that develops in a material depends on nature of underlying magnetic interactions

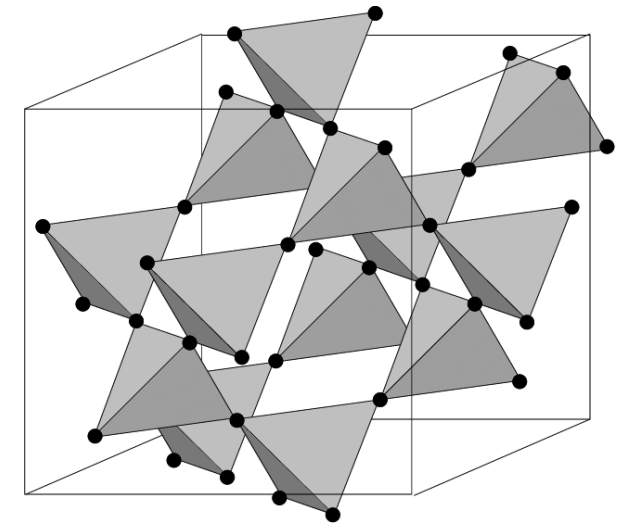
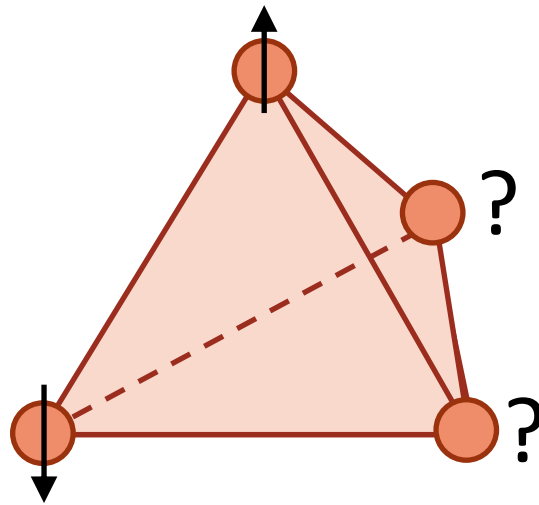
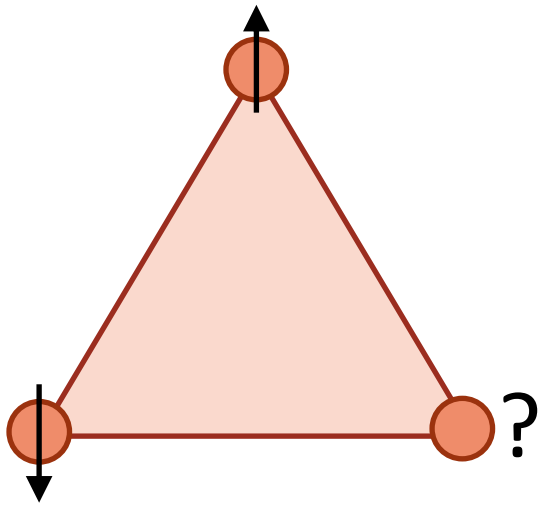
Structures can be relatively simple...

... or more complex



Geometric Frustration

- We can also try to design magnetic materials which don't order at all:



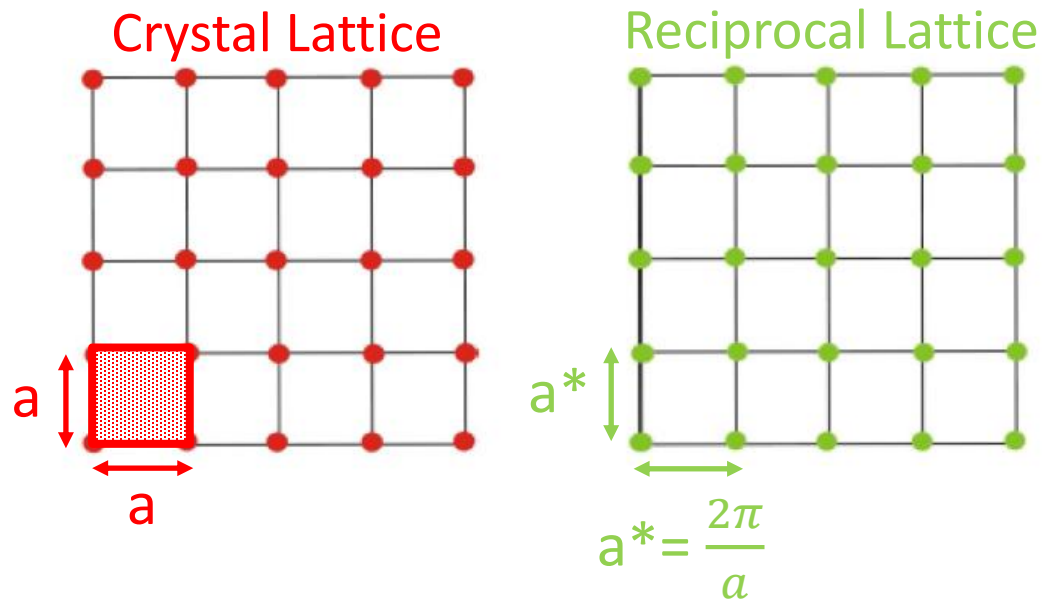
The Pyrochlore Lattice

- Geometrically frustrated magnets can display exotic quantum ground states at low temperatures, e.g. **quantum spin liquids**, **spin ices**, **spin glasses**...

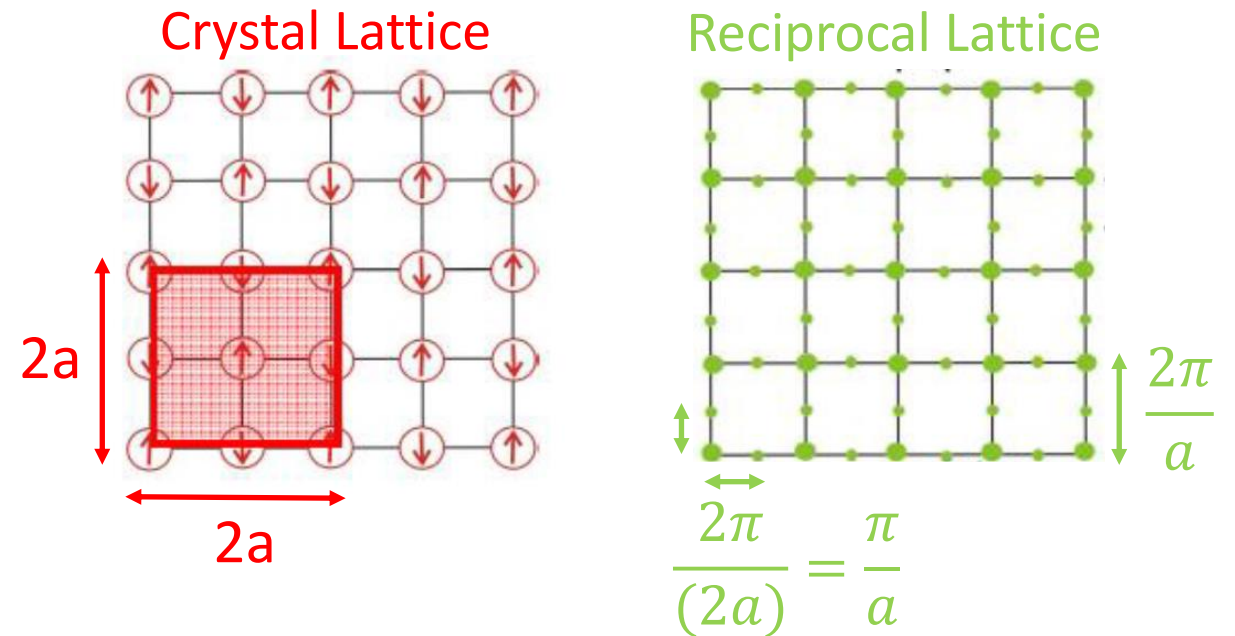
Scattering from a Magnetically Ordered Crystal

- How can we detect magnetic order in a neutron scattering experiment?

Paramagnetic State ($T > T_N$)



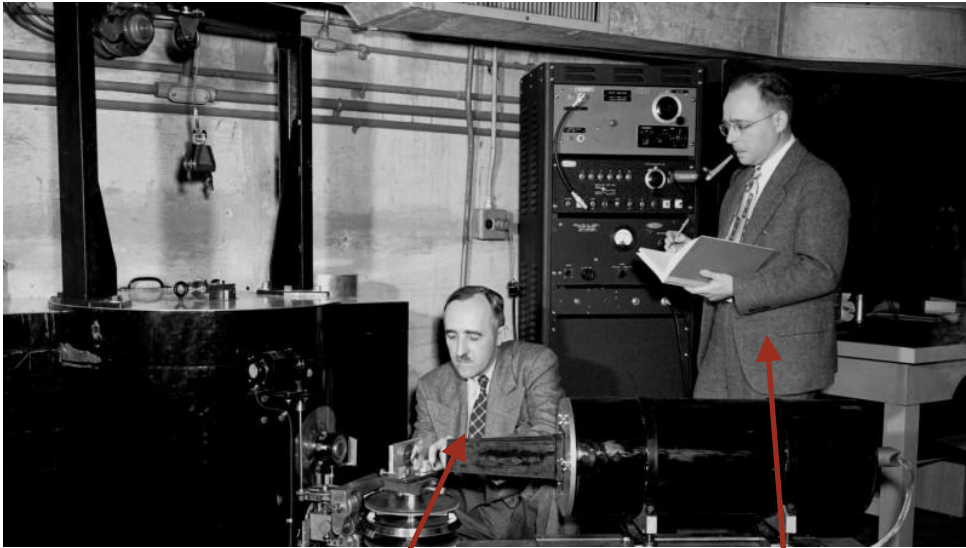
Antiferromagnetic State ($T < T_N$)



- Development of AF order increases size of unit cell → **new magnetic Bragg peaks appear**

First Observation: Magnetic Neutron Scattering from MnO

- Early neutron diffraction experiments at the ORNL X-10 Graphite Reactor:



Ernest Wollan

Clifford Shull

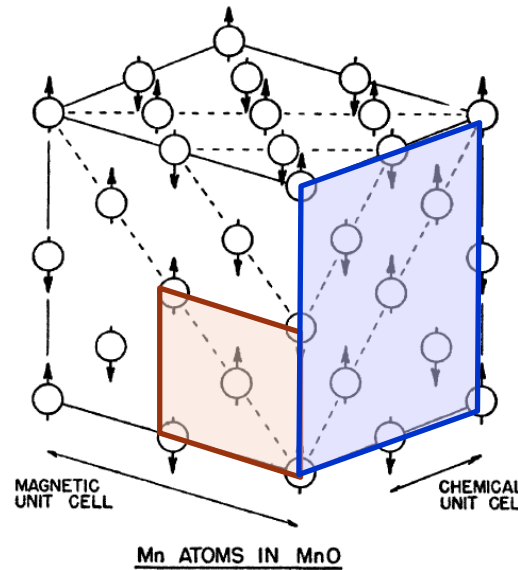


FIG. 5. Antiferromagnetic structure existing in MnO below its Curie temperature of 120°K. The magnetic unit cell has twice the linear dimensions of the chemical unit cell. Only Mn ions are shown in the diagram.

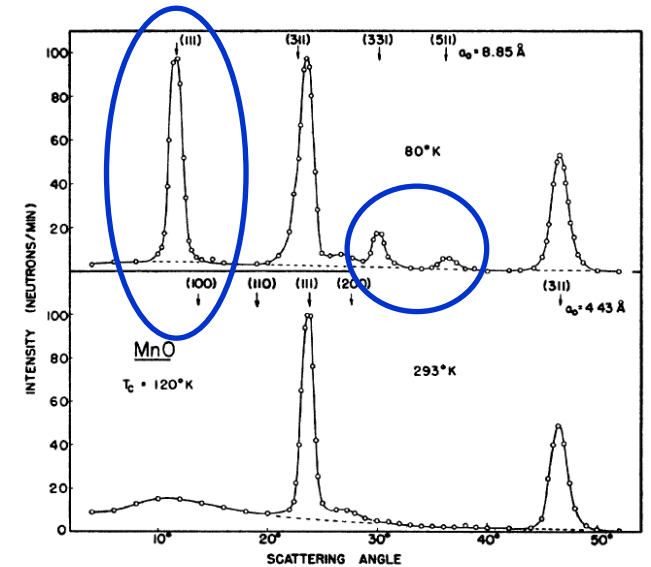


FIG. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

First direct evidence of antiferromagnetism

Shull, Strauser, and Wollan, Phys. Rev. 83, 333 (1951)

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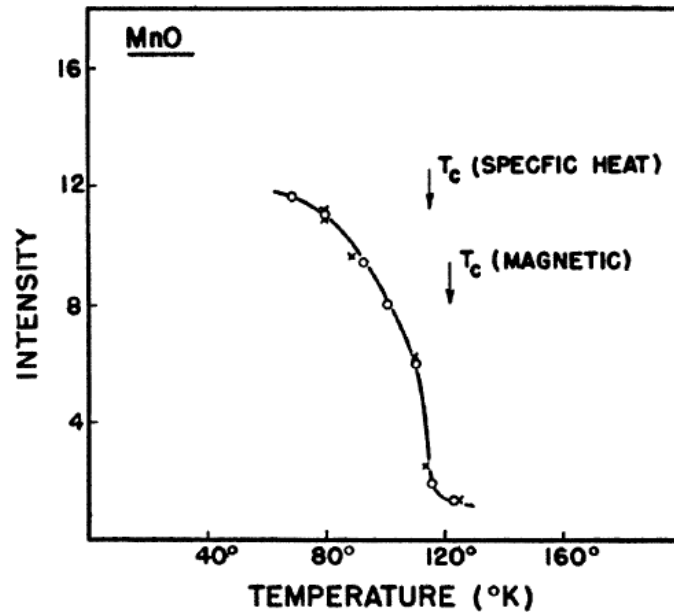


FIG. 7. Temperature dependence of magnetic intensity for MnO. The Curie temperatures suggested by specific heat and magnetic susceptibility data are shown.

Peak intensity \propto staggered magnetization

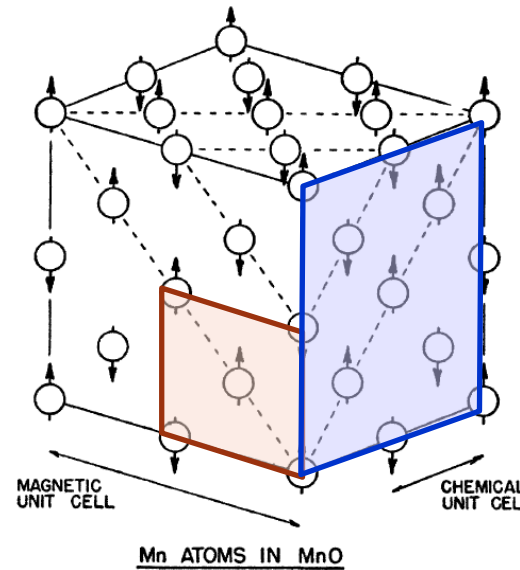


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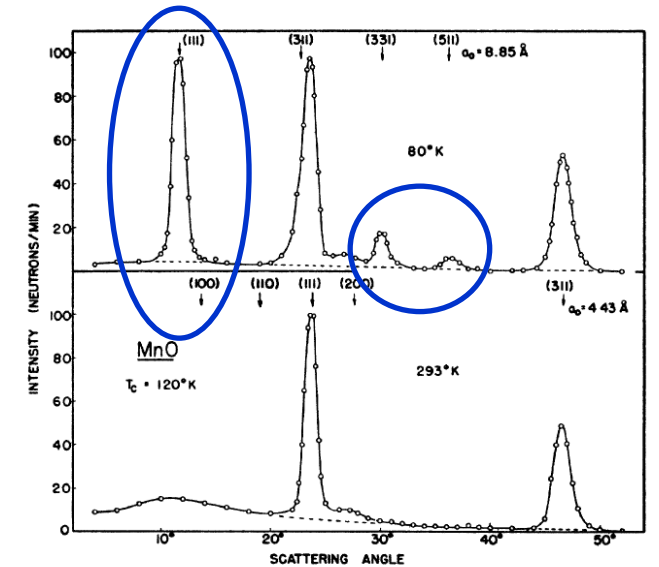


FIG. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

Magnetic Scattering Cross Section

- What fraction of neutrons will scatter off a sample with a particular change in energy and momentum?
- Change in momentum: $\vec{Q} = \vec{k} - \vec{k}'$
- Change in energy: $\Delta E = \hbar\omega = \frac{\hbar^2 k^2}{2m} - \frac{\hbar^2 k'^2}{2m}$
- Apply Fermi's Golden Rule (1st order perturbation theory):

$$\frac{d^2\sigma}{d\Omega dE'}_{k,\sigma,\lambda \rightarrow k',\sigma',\lambda'} = \underbrace{\left(\frac{m}{2\pi\hbar^2}\right)^2 \frac{k'}{k}}_{\text{(Kinematics)}} \underbrace{|\langle k' \sigma' \lambda' | V_m | k \sigma \lambda \rangle|^2}_{\text{(Interaction Term)}} \underbrace{\delta(E_\lambda - E_{\lambda'} + \hbar\omega)}_{\text{(Energy Conservation)}}$$

The Magnetic Potential

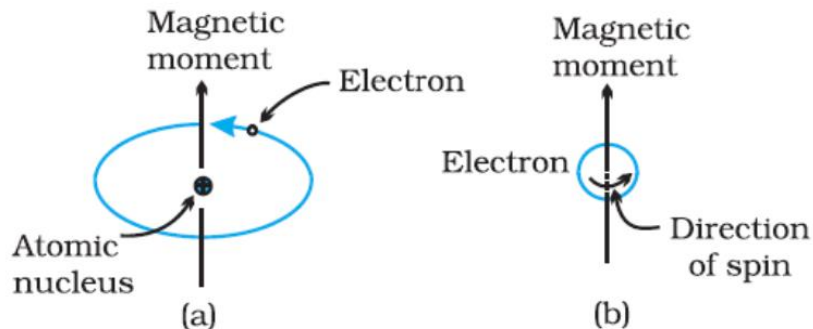
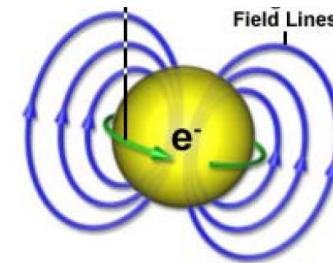
- In order to evaluate the matrix element in the interaction term, we need to determine the magnetic potential produced by all of the unpaired electrons in the material:

$$V_m = \vec{\mu}_n \cdot \vec{B}$$

(Magnetic Potential)

(Magnetic Dipole Moment of Neutron)

(Magnetic Field Produced by Unpaired Electrons)



Must consider:

B_l = Magnetic field from **orbital motion** of an electron

B_s = Magnetic field from **spin** of an electron

Magnetic Scattering Cross Section

- Evaluating the interaction term $|\langle k' \sigma' \lambda' | V_m | k \sigma \lambda \rangle|^2$ can be quite complicated.
- Jumping to the final result:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{(\gamma r_0)^2}{2\pi\hbar} \frac{k'}{k} N \left[\frac{1}{2} g F(\vec{Q}) \right]^2 \sum_{\alpha\beta} (\delta_{\alpha\beta} - \hat{Q}_\alpha \hat{Q}_\beta) \\ \times \sum_l e^{i\vec{Q}\cdot\vec{l}} \int \left\langle e^{-i\vec{Q}\cdot\vec{u}_0(0)} e^{i\vec{Q}\cdot\vec{u}_l(t)} \right\rangle \left\langle S_0^\alpha(0) S_l^\beta(t) \right\rangle e^{-i\omega t} dt$$

Key features:

1. From constants – magnetic scattering comparable in strength to nuclear scattering ($\sim r_0^2$)
2. Proportional to square of **magnetic form factor**, $F(\vec{Q})^2$

Magnetic Scattering Cross Section

- Evaluating the interaction term $|\langle k' \sigma' \lambda' | V_m | k \sigma \lambda \rangle|^2$ can be quite complicated.
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Key features:

3. **Polarization factor** – describes dependence on spin direction. Term vanishes if components of spin are parallel to scattering vector $\vec{Q} \rightarrow$ only sensitive to $S \perp \vec{Q}$

Magnetic Scattering Cross Section

- Evaluating the interaction term $|\langle k' \sigma' \lambda' | V_m | k \sigma \lambda \rangle|^2$ can be quite complicated.
- Jumping to the final result:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{(\gamma r_0)^2}{2\pi\hbar} \frac{k'}{k} N \left[\frac{1}{2} gF(\vec{Q}) \right]^2 \sum_{\alpha\beta} (\delta_{\alpha\beta} - \hat{Q}_\alpha \hat{Q}_\beta) \times \sum_l e^{i\vec{Q}\cdot\vec{l}} \int \left\langle e^{-i\vec{Q}\cdot\vec{u}_0(0)} e^{i\vec{Q}\cdot\vec{u}_l(t)} \right\rangle \left\langle S_0^\alpha(0) S_l^\beta(t) \right\rangle e^{-i\omega t} dt$$

Key features:

4. **Dynamic spin pair correlation function** – measures correlation between spin α at origin and $t = 0$ and spin β at position l and time t . The Fourier transform of this term is the **dynamic structure factor**, $S(\vec{Q}, \omega)$

Magnetic Form Factor

- $F(\vec{Q})$ = Fourier transform of the spin distribution in real space

$$F(\vec{Q}) = \int S(\vec{r}) e^{i\vec{Q}\cdot\vec{r}} d^3r$$

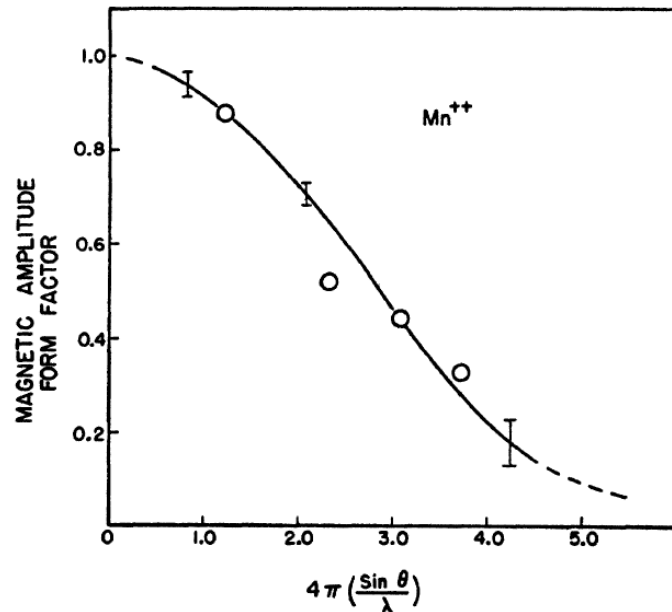
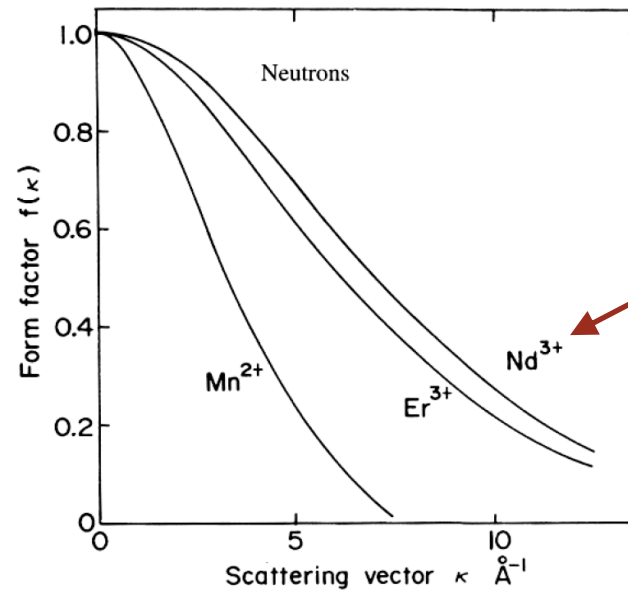


FIG. 2. Magnetic amplitude form factor for Mn²⁺ ions. The curve is that obtained from paramagnetic diffuse scattering with estimated error as shown. The points represent values of the form factor obtained from the low temperature antiferromagnetic reflections of MnO.



$F(\vec{Q})$ decreases faster as wavefunctions become more spatially extended

- Analogous to chemical form factor for x-ray scattering
- Typically drops off monotonically as \vec{Q} increases

Elastic Magnetic Scattering

- For elastic scattering (i.e. diffraction), we have: $\Delta E = \hbar\omega = \frac{\hbar^2 k^2}{2m} - \frac{\hbar^2 k'^2}{2m} = 0$
- What we measure is the **time-independent** structure factor, $S(\vec{Q})$

$$\frac{d\sigma}{d\Omega} = (\gamma r_0)^2 \frac{k'}{k} N \left[\frac{1}{2} gF(\vec{Q}) \right]^2 e^{-2W} \sum_{\alpha\beta} (\delta_{\alpha\beta} - \hat{Q}_\alpha \hat{Q}_\beta) \times \sum_l e^{i\vec{Q}\cdot\vec{l}} \int \langle S_0^\alpha \rangle \langle S_l^\beta \rangle$$

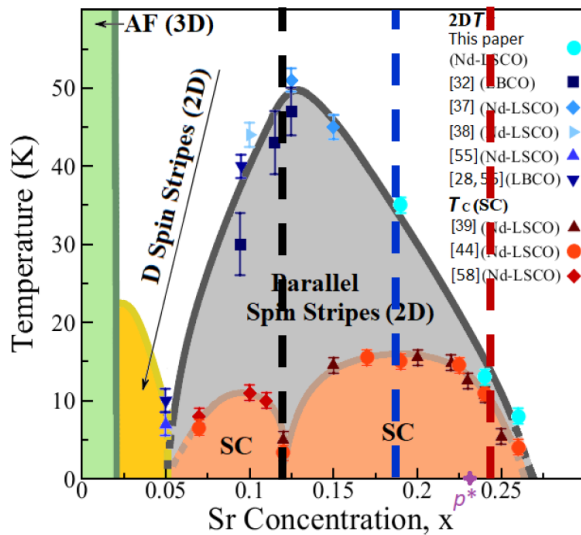
Debye-Waller Effect

Polarization Factor:
Only sensitive to $S \perp \vec{Q}$

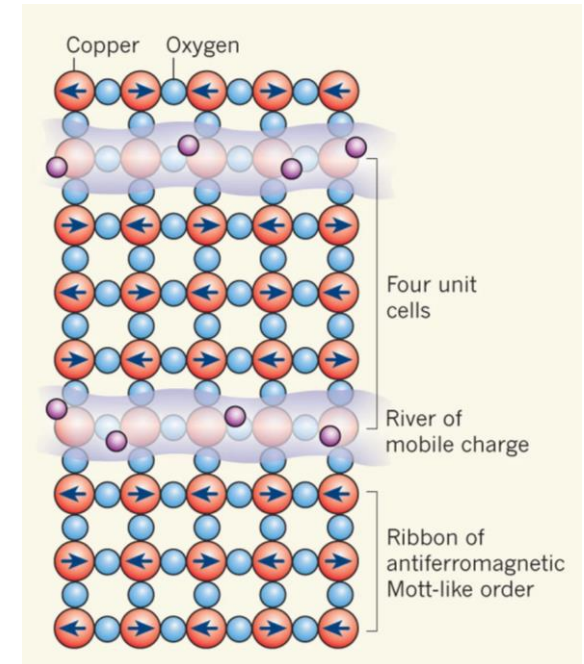
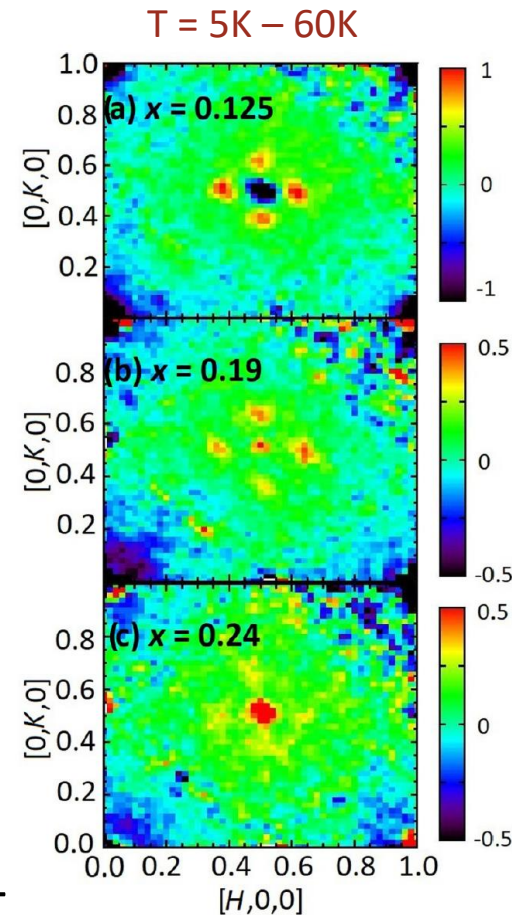
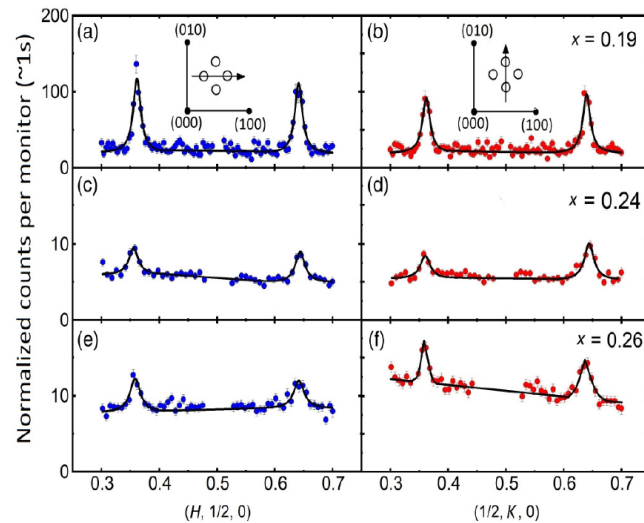
Add up spins with a
phase factor of $e^{i\vec{Q}\cdot\vec{l}}$

Elastic Magnetic Scattering: Examples

- High temperature superconductors
- e.g. $\text{Nd}_{0.4}\text{La}_{1.6-x}\text{Sr}_x\text{CuO}_4$ Single Crystal
- Measured on SEQUOIA at SNS, and HB3 at HFIR



Q. Ma et al, Phys. Rev. Res. 3, 023151 (2021)

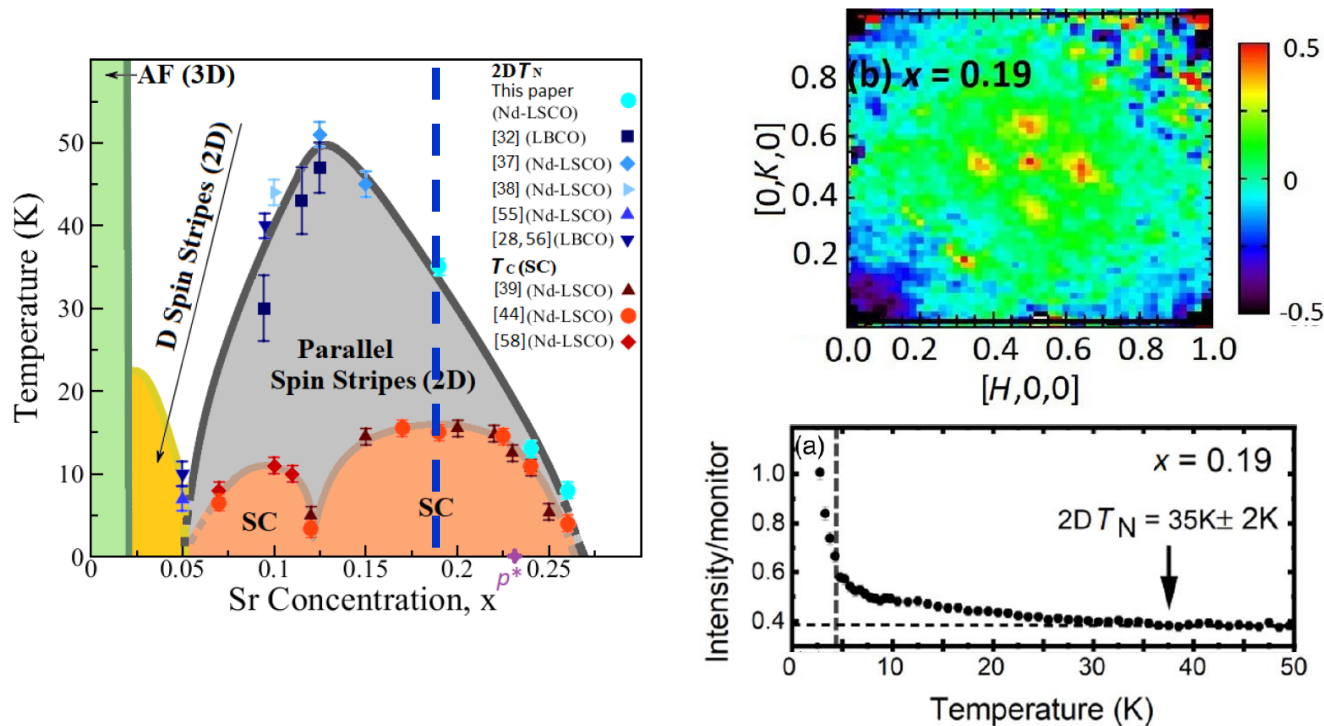


K. A. Moler, Nature 468, 643 (2010)

- Magnetic scattering is **incommensurate**, arising at $(0.5 \pm \delta, 0.5, L)$ and $(0.5, 0.5 \pm \delta, L)$ due to stripe order

Elastic Magnetic Scattering: Examples

- High temperature superconductors
- e.g. $\text{Nd}_{0.4}\text{La}_{1.6-x}\text{Sr}_x\text{CuO}_4$ Single Crystal
- Measured on SEQUOIA at SNS, and HB3 at HFIR



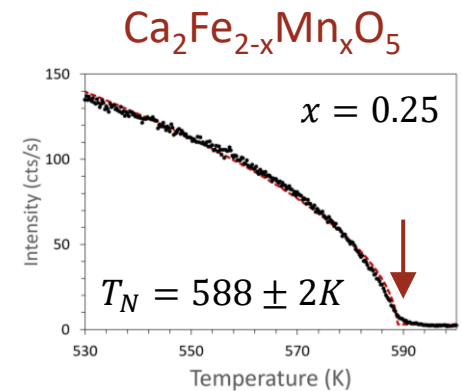
Q. Ma et al, Phys. Rev. Res. 3, 023151 (2021)

- Above $T = 5K$: **Rods** of diffuse scattering along the L-direction, indicates shorter-range **quasi-2D** magnetic correlations
- Below $T = 5K$: Well-defined **Bragg peaks**, indicates **3D long-range** magnetic order

$$\xi \propto \frac{1}{Q} = \text{correlation length}$$

- More conventionally:

$$I \propto M^2 = M_0^2 \left(1 - \frac{T}{T_C}\right)^{2\beta}$$



J. Greedan et al (2023)

Inelastic Magnetic Scattering

- For inelastic scattering (i.e. spectroscopy), we have: $\Delta E = \hbar\omega = \frac{\hbar^2 k^2}{2m} - \frac{\hbar^2 k'^2}{2m} \neq 0$
- This implies that $|\vec{k}| \neq |\vec{k}'| \rightarrow$ change in both \vec{Q} and ω
- What we measure is the **dynamical structure factor** $S(\vec{Q}, \omega)$

- Key points:

- Study *dynamic* magnetic moments (on time scales of 10^{-9} to 10^{-12} sec)

Bose (Temperature) Factor Imaginary part of dynamic susceptibility

- $S(\vec{Q}, \omega) = \frac{1}{1 - e^{-\beta\hbar\omega}} \frac{\chi''(\vec{Q}, \omega)}{\pi(g\mu_B)^2} = \boxed{n(\omega)} \boxed{\chi''(\vec{Q}, \omega)}$ (*Fluctuation-Dissipation Theorem*)

- Intensity integrated over all \vec{Q}, ω is constant: $\int d\omega \int_{BZ} d\vec{Q} S(\vec{Q}, \omega) \sim S(S + 1)$
(*Total Moment Sum Rule*)

Inelastic Magnetic Scattering: Spin Waves

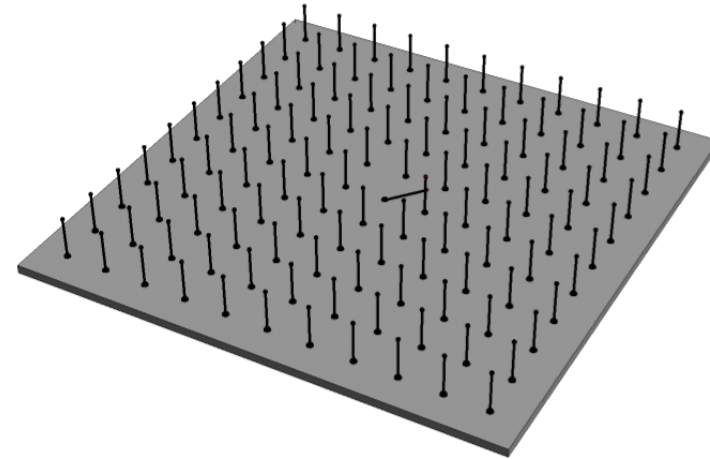
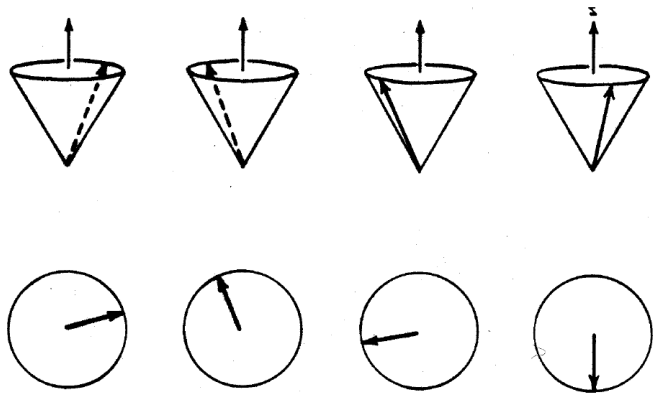
- When a neutron scatters off a sample it can create or destroy an excitation
- If sample is magnetically ordered (e.g. a FM spin chain), the incident neutron can create a spin “defect” which is distributed over all possible sites
- We call this collective excitation a **spin wave** or **magnon**



Spins are coupled through magnetic Hamiltonian:
$$H = J \sum_{i,j} S_i \cdot S_j$$

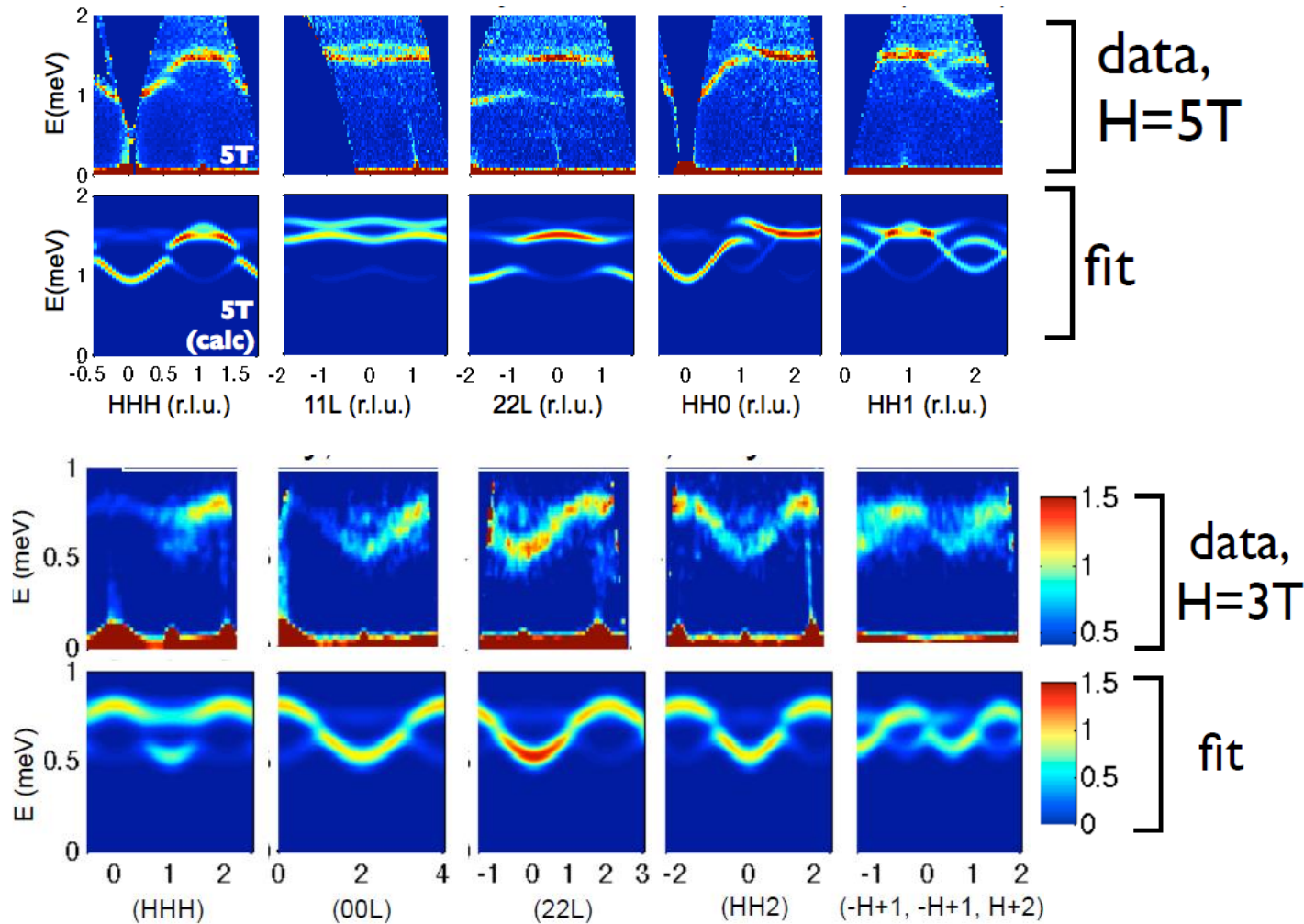
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Inelastic Magnetic Scattering: Examples



- Frustrated magnetism in pyrochlores
- $\text{Yb}_2\text{Ti}_2\text{O}_7$ (top) and $\text{Er}_2\text{Ti}_2\text{O}_7$ (bottom) Single Crystals
- Measured on DCS at NIST
- Fit spin wave dispersion to theoretical model and extract detailed exchange parameters (J_1, J_2, J_3, J_4)
- Magnetic interactions explain low temperature magnetic ground states

K. A. Ross et al, Phys. Rev. X **1**, 021002 (2011)

L. Savary et al, Phys. Rev. Lett. **109**, 167201 (2012)

How can we distinguish magnetic scattering?

(1) Temperature dependence:

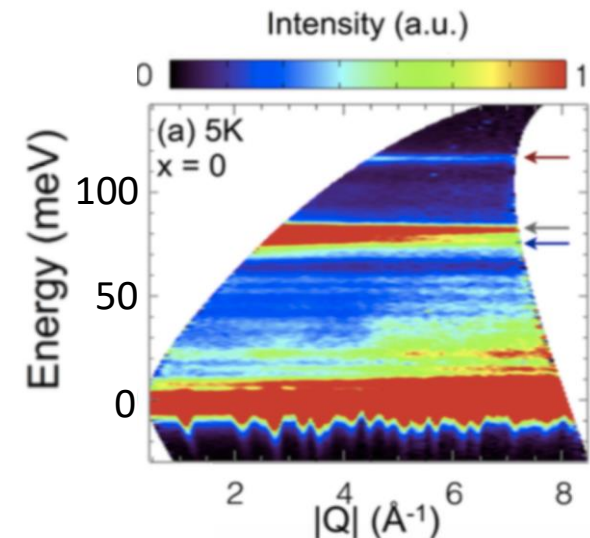
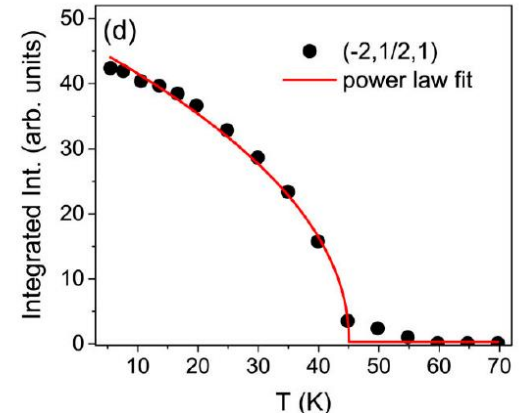
- Magnetic scattering **decreases** with increasing T (disappears at $T > T_C$)
- Phonon scattering **increases** with increasing T (\propto thermal population)

(2) Momentum dependence:

- Magnetic scattering **decreases** with increasing $|Q|$ ($\propto |F(Q)|^2$)
- Phonon scattering **increases** with increasing $|Q|$ ($\propto |e \cdot Q|^2$)

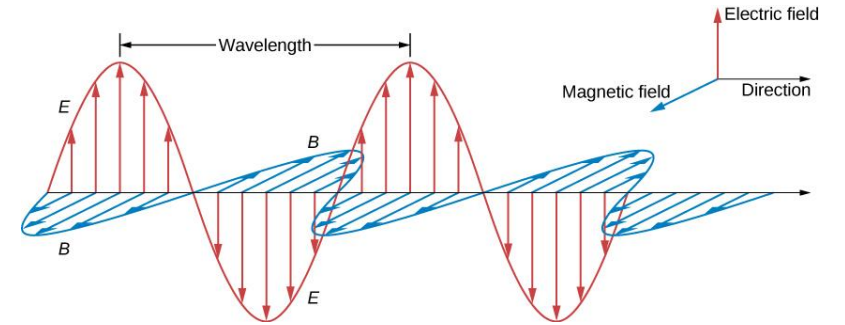
(3) Polarization dependence (with polarized beam):

- Magnetic scattering **mostly spin flip**
- Nuclear scattering **mostly non-spin flip**

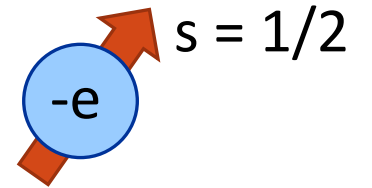


More on polarized neutrons from Barry Winn, Dean Myles & Josh Pierce on Wednesday

Magnetic Scattering with X-rays



- X-rays carry no magnetic moment
- Primary interaction with matter: **E-field** of x-ray + **charge** of electrons
- Also interacts through: **B-field** of x-ray + **spin** of electrons
- Unlike neutrons:



1. Magnetic scattering is MUCH weaker than charge scattering

$$\text{Amplitude ratio: } \frac{A(\text{magnetic})}{A(\text{charge})} = \frac{\hbar\omega}{mc^2} \quad (\text{for } \textit{single electron})$$

At $E_i \sim 5$ keV:
Amplitude ratio $\sim 10^{-2}$
Intensity ratio $\sim 10^{-4}$

2. X-ray photon energies (**~ 0.5 to 50 keV**) are orders of magnitude larger than typical energy scales for magnetic excitations (**~ 0.5 to 500 meV**)

First Observation: Magnetic X-ray Scattering from NiO

NiO: Antiferromagnet ($T_N \sim 250 \text{ }^\circ\text{C}$)

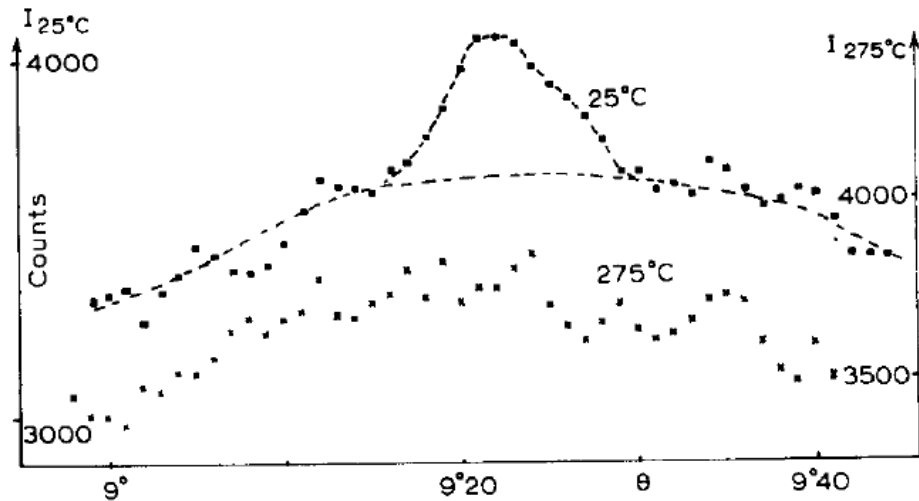


Fig. 1. Intensity $I_f(\theta)$ near the $(\frac{1}{2} \frac{1}{2} \frac{1}{2})$ position at $t = 25^\circ \text{C}$ and 275°C in counts/225 min. The hump which cover the interval could be due to some impurity.

De Bergevin and Brunel, Phys. Lett. 39A, 141 (1972)

- **NON-RESONANT magnetic x-ray scattering**

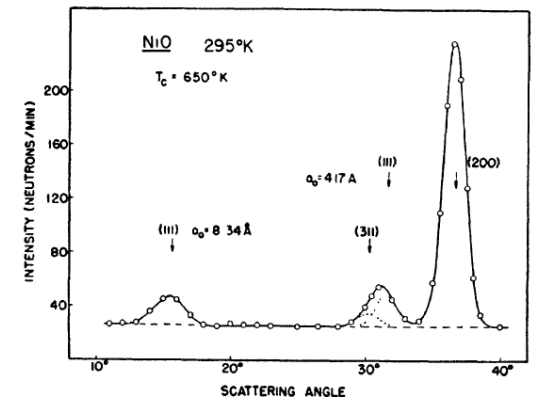
- Lab-based experiment carried out using x-ray tube source (Cu $K\alpha$, $\lambda = 1.54 \text{ \AA}$)

- Hard!

- Counting time: 3 days/scan
($\sim 2 \text{ cts/min}$ signal on $\sim 18 \text{ cts/min}$ bkgd)

- Compare to magnetic neutron scattering:

Shull et al, Phys. Rev. 83, 333 (1951)



To the Synchrotron: Magnetic X-ray Scattering from Ho

Ho: Incommensurate spiral antiferromagnet ($T_N \sim 131$ K)

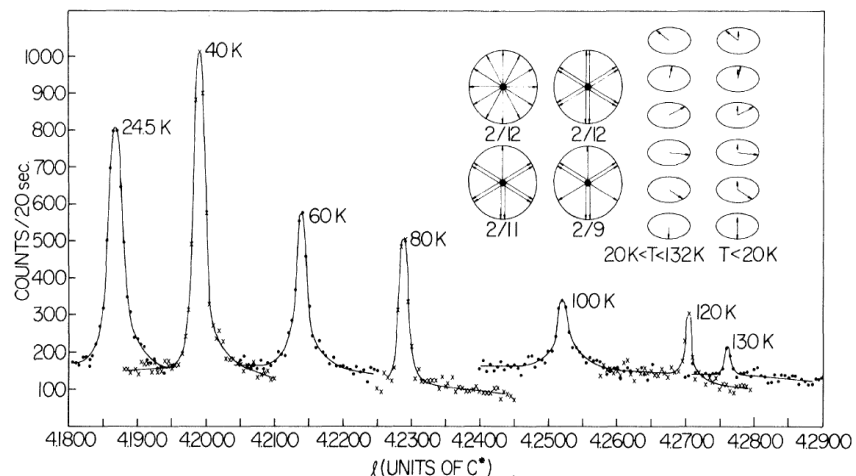
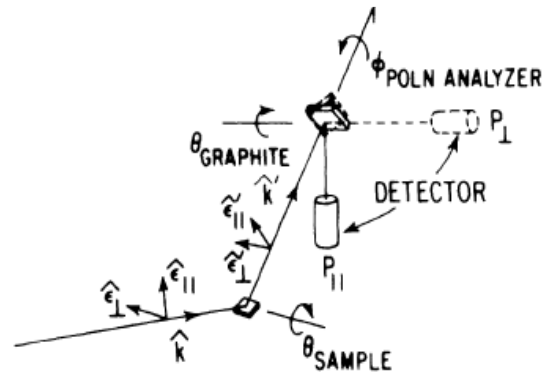
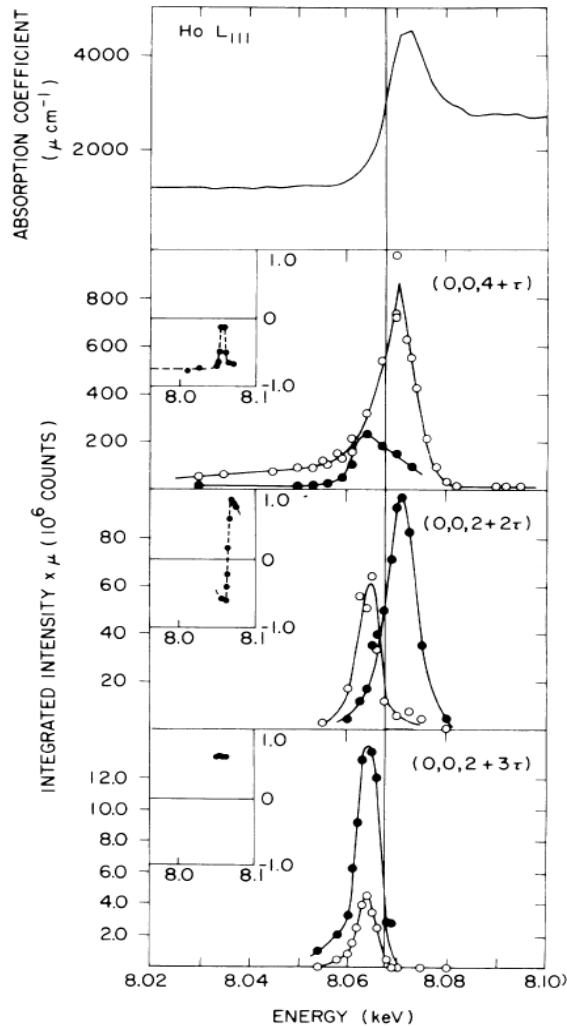


FIG. 1. Temperature dependence of the $\text{Ho}(004)^+$ magnetic satellite taken with synchrotron radiation (lines drawn to guide the eye). Inset: Right, schematic representation of the magnetic structure of Ho (after Koehler⁹). Left, projections of the magnetic unit cell for different spin-slip structures. For simplicity the doublet has been drawn as two parallel spins.

- **NON-RESONANT magnetic x-ray scattering**
- Synchrotron-based experiment (SSRL)
- Higher flux and higher momentum resolution
- Compare to magnetic neutron scattering:
 - X-ray: 25 cts/s on 10 cts/s, $\text{FWHM} = 0.001 \text{ \AA}^{-1}$
 - Neutron: 50 cts/s on 0.1 cts/s, $\text{FWHM} = 0.005 \text{ \AA}^{-1}$

D. Gibbs et al, Phys. Rev. Lett. 55, 234 (1985)

On Resonance: Magnetic X-ray Scattering from Ho



Gibbs et al, Phys. Rev. Lett. 61, 1241 (1988)

- **RESONANT MAGNETIC X-RAY SCATTERING**
- First predicted by M. Blume (1985)
- Synchrotron-based experiment (NSLS, CHESS)
- Tune incident energy to Ho L_3 -edge ($E_i = 8.067$ keV, $\lambda = 1.54$ Å)
- Take advantage of polarized beam and resonant enhancement at absorption edge
- Magnetic peak intensity enhanced by **$\sim 50x!$**

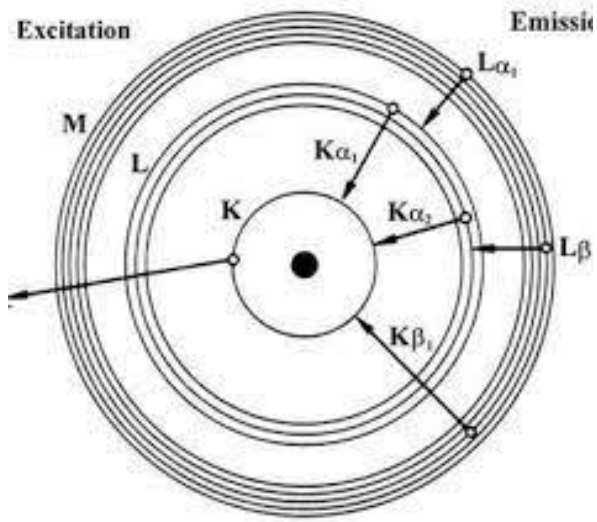
More on resonant scattering at
APS tutorials next week

Resonant Magnetic X-ray Scattering

Hard x-rays (> 5 keV)

Tender x-rays (1-5 keV)

Soft x-rays (< 1 keV)



1	H	Hydrogen
3	Li	Lithium
11	Na	Sodium
19	K	Potassium
37	Rb	Rubidium
55	Cs	Caesium
87	Fr	Francium
4	Be	Beryllium
12	Mg	Magnesium
20	Ca	Calcium
38	Sr	Strontium
56	Ba	Barium
88	Ra	Radium
21	Sc	Scandium
39	Y	Yttrium
57	La	Lanthanum
89	Ac	Actinium

2	Ti	Titanium
23	V	Vanadium
24	Cr	Chromium
25	Mn	Manganese
26	Fe	Iron
27	Co	Cobalt
28	Ni	Nickel
29	Cu	Copper
30	Zn	Zinc
41	Zr	Zirconium
42	Nb	Niobium
43	Mo	Molybdenum
44	Tc	Technetium
45	Ru	Ruthenium
46	Rh	Rhodium
47	Pd	Palladium
48	Ag	Silver
49	Cd	Cadmium
72	Hf	Hafnium
73	Ta	Tantalum
74	W	Tungsten
75	Re	Rhenium
76	Os	Osmium
77	Ir	Iridium
78	Pt	Platinum
79	Au	Gold
80	Hg	Mercury

5	B	Boron
6	C	Carbon
7	N	Nitrogen
8	O	Oxygen
9	F	Fluorine
10	Ne	Neon
13	Al	Aluminium
14	Si	Silicon
15	P	Phosphorus
16	S	Sulfur
17	Cl	Chlorine
18	Ar	Argon
31	Ga	Gallium
32	Ge	Germanium
33	As	Arsenic
34	Se	Selenium
35	Br	Bromine
36	Kr	Krypton
49	In	Indium
50	Sn	Tin
51	Sb	Antimony
52	Te	Tellurium
53	I	Iodine
54	Xe	Xenon
81	Tl	Thallium
82	Pb	Lead
83	Bi	Bismuth
84	Po	Polonium
85	At	Astatine
86	Rn	Radon
113	Nh	Nihonium
114	Fl	Flerovium
115	Mc	Moscovium
116	Lv	Livermorium
117	Ts	Tennesseum
118	Og	Oganesson

58	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
90	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

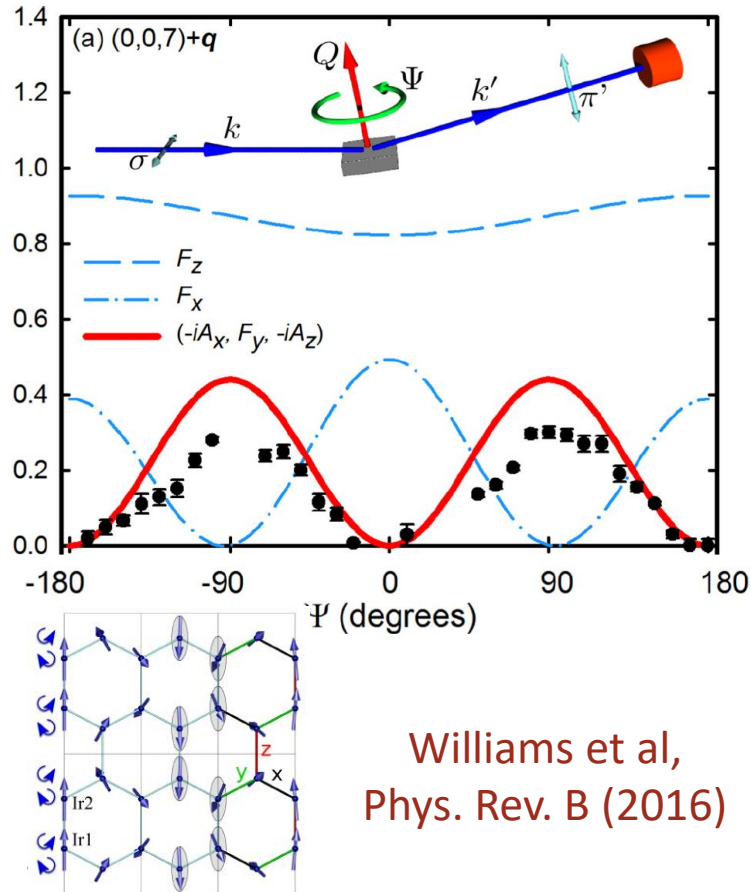
- Scattering tensor for magnetic x-ray scattering:

$$F_j(E) = \sigma^{(0)}(E) \varepsilon_i \cdot \varepsilon_0^* + \sigma^{(1)}(E) \varepsilon_i \times \varepsilon_0^* \cdot M_j + \sigma^{(2)}(E) \left[(\varepsilon_i \cdot M_j)(\varepsilon_0^* \cdot M_j) - \frac{1}{3} \varepsilon_i \cdot \varepsilon_0^* \right]$$

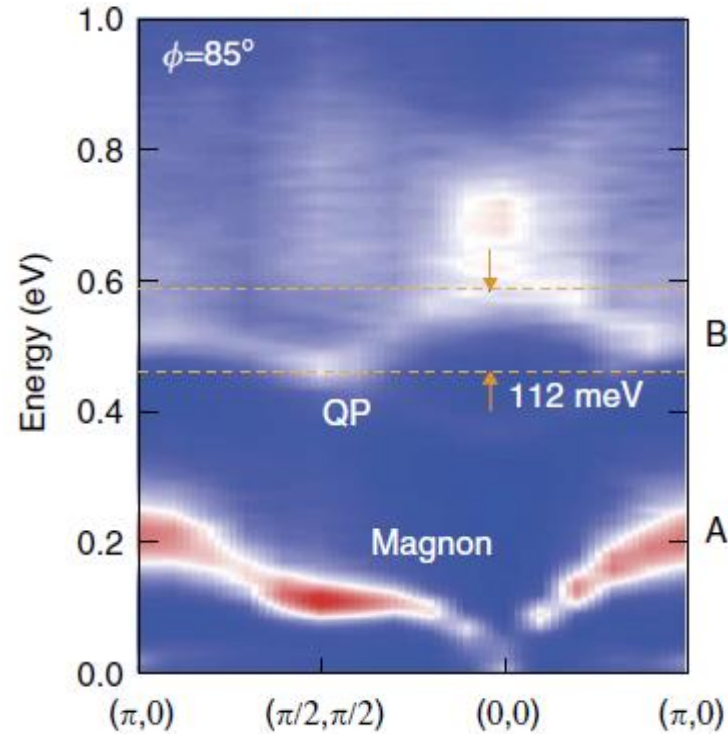
- Intensity of magnetic Bragg peaks:
$$I = \left| \sum_j e^{ig \cdot r_j} \sigma_j^{(1)}(E) \varepsilon_i \times \varepsilon_0^* \cdot M_j \right|^2$$

Resonant Magnetic X-ray Scattering: Examples

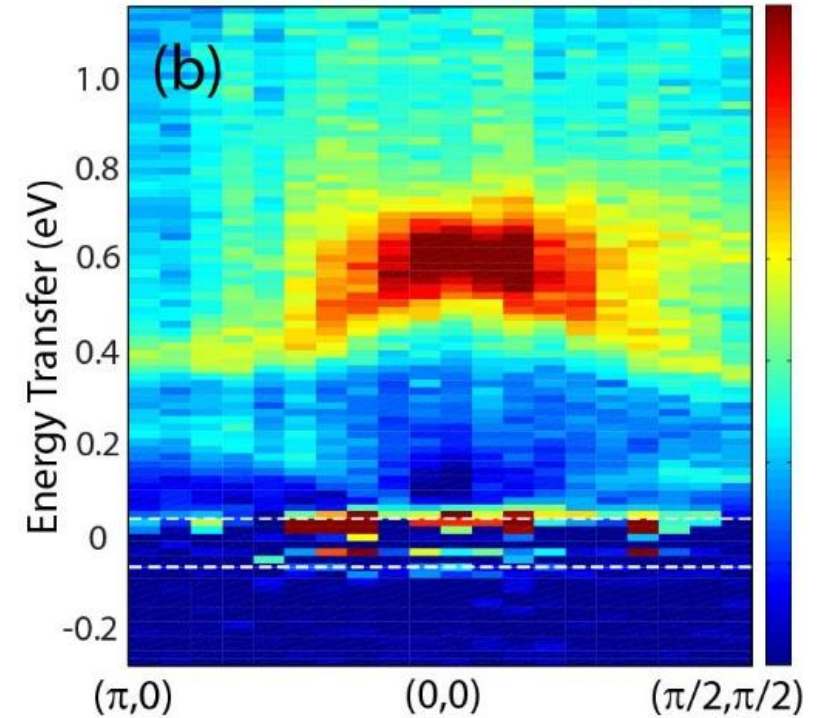
α - Li_2IrO_3 single crystal
(Kitaev model candidate)



Sr_2IrO_4 single crystal
(spin-orbital Mott insulator)



Ba_2IrO_4 thin film
(13 nm thickness = 10 ng)



Magnetic X-ray Scattering

Advantages:

- Element (and even orbital) specificity
- Smaller samples (ideal for thin films, high pressure diamond anvil cell experiments)
- Better resolution in momentum

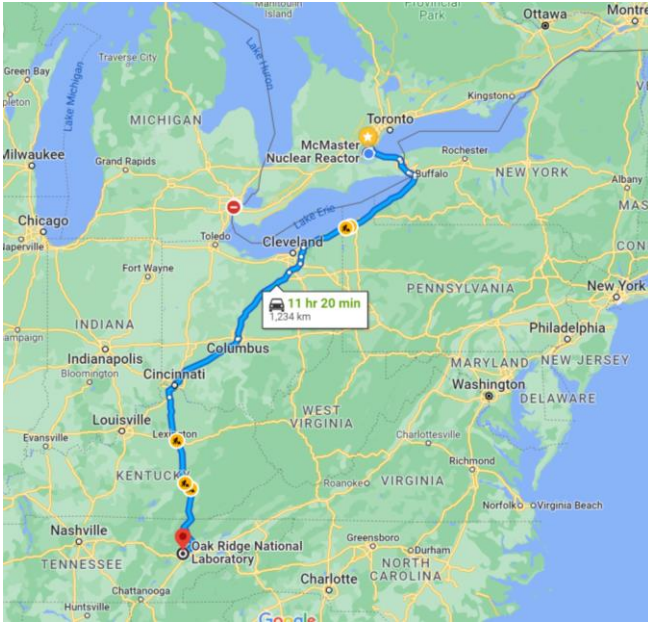
Disadvantages:

- More complicated theory/modeling
- Magnetic scattering much weaker than charge scattering
- Worse resolution in energy
- Restricted momentum transfer (soft x-ray)

X-ray and neutron scattering are highly complementary techniques for the study of magnetic materials

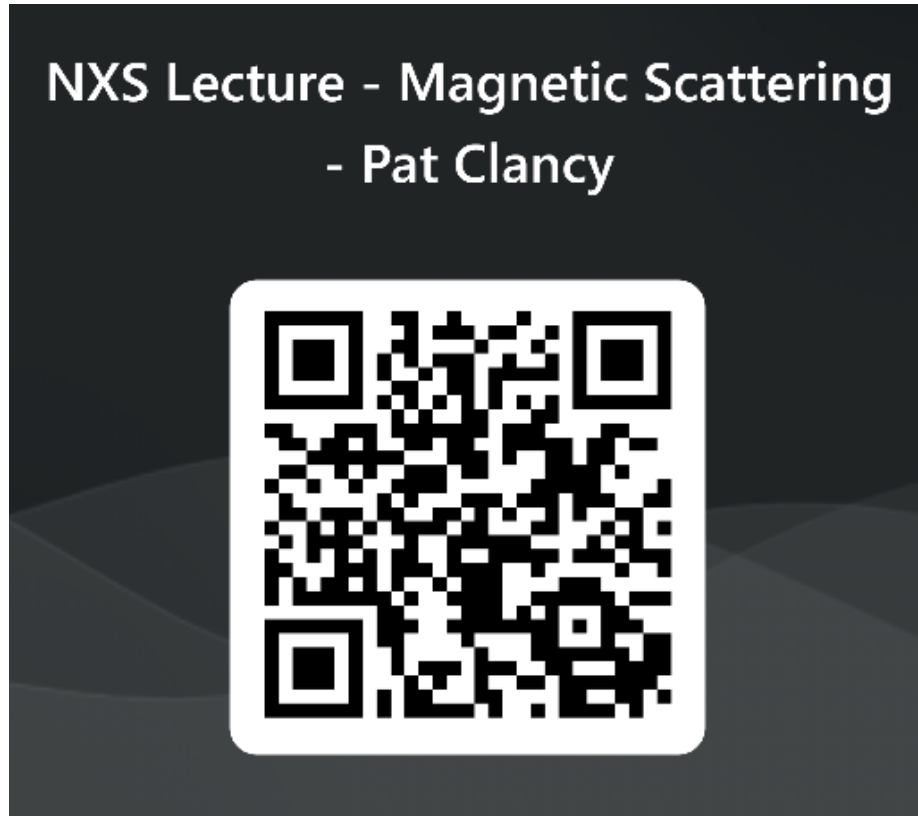
Neutron Scattering at McMaster

Home to **McMaster Nuclear Reactor** – Canada's most powerful neutron source



- 5 MW open-pool reactor used for **neutron scattering**, medical isotopes, neutron radiography, neutron activation/ irradiation studies, positron beams...
- Currently 2 neutron scattering beamlines: **MAD** (triple-axis) and **MacSANS** (more coming soon)

Lecture Feedback



<https://forms.office.com/g/CyZq6VzCqv>

Any Questions?



clancyp@mcmaster.ca