Neutron Scattering of Magnetic excitations

Magnetic excitations, magnons, and spin chains
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Outline

- Properties of the Neutron
- Spin, spin waves, and magnons
- Elastic/Inelastic Scattering and instrumentation
- Nuclear and Magnetic interactions
- Perovskite example
# Properties of the Neutron

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass</strong></td>
<td>$1.67495 \cdot 10^{-27} \text{ kg}$</td>
</tr>
<tr>
<td><strong>Charge</strong></td>
<td>0</td>
</tr>
<tr>
<td><strong>Magnetic monopole moment</strong></td>
<td>0</td>
</tr>
<tr>
<td><strong>Electric dipole moment</strong></td>
<td>0</td>
</tr>
<tr>
<td><strong>Spin</strong></td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td><strong>Magnetic dipolar moment</strong></td>
<td>$\mu_n = -\gamma \cdot \mu_N$</td>
</tr>
</tbody>
</table>
Spin Waves (magnons)

- All electrons carry a spin of 1/2
- Intuitively, spin is the rotation of electrons about their axis.
- Spins produce a dipolar magnetic field (bar magnet like)
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Spin Waves (magnons)

- Diamagnetism
- Paramagnetism (Li, Mo, Ta)
  - Ferromagnetism (Fe, Ni, Co, and their alloys)
  - Antiferromagnetism (Hematite, Cr, FeMn, NiO)
    - Spin glass
  - Ferrimagnetism (YIG, FeO ferrites, Mn)
Elastic Scattering

In an elastic scattering event, a momentum is transferred from the neutron to the sample, but the internal state of the sample remains unchanged.

\[ \hbar Q = \hbar (\vec{k}_f - \vec{k}_i) \]

\[ k_f = k_i \]
\[ \omega = 0 \]
Inelastic Scattering

Inelastic scattering of neutrons creates or annihilates an excitation inside the sample, so that both the energy of the neutron and the internal state of the sample are changed. Both flight direction and energy must be tracked.

\[
\begin{align*}
k_f &> k_i \\
\omega &> 0
\end{align*}
\]

\[
\begin{align*}
k_f &< k_i \\
\omega &< 0
\end{align*}
\]
Inelastic Scattering

- Triple Axis Spectrometer
- Time of Flight Spectrometer
- Spin Echo Spectrometer
Inelastic Scattering

- Triple Axis Spectrometer
- **Time of Flight Spectrometer**
- Spin Echo Spectrometer
Inelastic Scattering

- Triple Axis Spectrometer
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- Spin Echo Spectrometer

Max-Planck Institute for Solid State Research
Magnetic and Nuclear Scattering

- Nuclear
  - strong interaction of particle physics responsible for binding neutrons and protons in the nuclei.

- Magnetic
  - Interaction between dipolar moments of neutrons and magnetic field of unpaired electrons.
Cross section

Elastic case

\[ \frac{d\sigma}{d\Omega} = |\langle \vec{k}' \mid \hat{V} \mid \vec{k}\rangle|^2 \]

Energy conservation

\[ h\omega = E_\lambda - E_\lambda' \]

Inelastic case

\[ \left( \frac{d^2\sigma}{d\Omega dE'} \right)_\lambda^{\lambda'} = \frac{k'}{k} |\langle \vec{k}'\lambda' \mid \hat{V} \mid \vec{k}\lambda \rangle|^2 \delta(h\omega + E_\lambda - E_{\lambda'}) \]

First Born approximation

\[ \frac{d^2\sigma}{d\Omega dE'} = \frac{k'}{k} \sum_{\lambda\lambda'} p_\lambda |\langle \vec{k}'\lambda' \mid \hat{V} \mid \vec{k}\lambda \rangle|^2 \delta(h\omega + E_\lambda - E_{\lambda'}) \]

Interaction with magnetic field

\[ \frac{d^2\sigma}{d\Omega dE'} = r_0^2 \frac{k'}{k} \sum_{\alpha\beta} (\delta_{\alpha\beta} - \hat{q}_\alpha \hat{q}_\beta) \sum_{\lambda\lambda'} p_\lambda \langle \lambda \mid \hat{Q}_\alpha \mid \lambda' \rangle \langle \lambda' \mid \hat{Q}_\beta \mid \lambda \rangle \delta(h\omega + E_\lambda - E_{\lambda'}) \]

Spin only interaction

\[ \langle \lambda' \mid \hat{Q} \mid \lambda \rangle = \sum_l \exp(i\vec{q} \cdot \vec{R}_l) F(q) \langle \lambda' \mid \hat{S}_l \mid \lambda \rangle \]

Spin only magnetic scattering

\[ \frac{d^2\sigma}{d\Omega dE'} = \frac{k'}{k} | F(q) |^2 \sum_{\alpha\beta} (\delta_{\alpha\beta} - \hat{q}_\alpha \hat{q}_\beta) S_{\beta\lambda} \]

Structure Factor

\[ S_{\beta\lambda} = \sum_{\lambda',\lambda''} p_{\lambda'} \sum_{l,d} \exp(i\vec{q} \cdot (\vec{R}_d - \vec{R}_l)) \langle \lambda \mid S_{\alpha l} \mid \lambda' \rangle \langle \lambda' \mid S_{\beta d} \mid \lambda \rangle \delta(h\omega + E_\lambda - E_{\lambda'}) \]
Magnetic and Nuclear Scattering

- Neutron magnetic interference effect
  - Both magnetic and nuclear scattering contribute to a Bragg reflection.

- Neutron spin filter
  - The reaction proceeds through an intermediate state $S=0$. Thus, the absorption cross section for neutrons with spins antiparallel is therefore about three orders of magnitude larger than if neutron and $^3$He spins are parallel.

\[
\frac{d\sigma}{d\Omega} = \sum_K \left| b + \sigma \gamma f(Q) \langle m_f, \sigma \cdot \hat{n}_f | m_i \rangle \right|^2 \delta(Q - \bar{K})
\]

\[
= \sum_K \left( b^2 + \gamma f(\Omega) \right) \delta(Q - \bar{K})
\]

\[
= \sum_K \left| b \pm \gamma f(\Omega) \right|^2 \delta(Q - \bar{K})
\]
Polarized Neutrons

http://www.orau.org/council/02presentations/klose.pdf
Magnetic and Nuclear Scattering

- Magnetic interactions, described by $F(Q)$, decreases towards large $Q$, whereas there is no form factor for nuclear scattering. Strong reflections with large $Q$ must therefore be nuclear in origin.

- Magnetic Bragg peaks vanish at the magnetic ordering temperature (the Curie temperature $T_c$ for ferromagnets, or the Néel temperature $T_n$ for antiferromagnets). Nuclear Bragg peaks vanish at the melting temperature, which is typically larger than the ordering temperature.

- The neutron spin operator does not appear in the cross section for coherent nuclear scattering. The neutron spin state is therefore unaffected by nuclear scattering. By contrast, magnetic neutron scattering can be (but does not have to be) associated with a spin-flip of the neutron.

- Utilize the different temperature dependences of the two contributions, since the nuclear scattering normally changes relatively slowly with temperature.

- If this is not adequate, perform polarized neutron scattering, in which the spin states of the incoming and scattered neutrons are determined, making it possible to isolate the scattering of purely magnetic origin (Moon, Riste and Koehler 1969).
Perovskites


Fig. 1. High-temperature neutron diffraction data for ErFeO$_3$. 
Perovskites


Fig. 2. Temperature dependence of $(011, 101)$ magnetic reflection of rare-earth orthoferrites. The Néel temperatures are obtained by extrapolation.
Perovskites

Perovskites


Fig. 6. Proposed magnetic structures for HoFeO$_3$ and ErFeO$_3$ at 1.3°K. The structures shown are highly idealized. The displacements of the rare-earth ions from special parameterless positions and the nonequivalence of their anion surroundings (not shown) are significant to the nonideal antiferromagnetic configurations of these compounds.
Neutrons have a small dipole moment that causes them to scatter from magnetic fields produced by electrons.

Magnetic scattering cross section is similar in magnitude to the nuclear cross section.

Polarized neutrons and transition temperatures allow the distinction of nuclear and magnetic events.

Neutrons are the probe for investigating magnetic properties.
References

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Thank You!