Introduction to neutron science

John B. Parise

Stony Brook
Outline

- Why neutrons?
  - Properties of neutron (esp. compared to X-rays)
  - Consequences and applications
  - Scientific opportunities
Neutron properties - often very different cf. X-rays
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- Electrically neutral - more penetrating than X-rays.
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- Neutrons act like both particles and waves
  - They have velocities, times of flight and diffract
  - Wavelength \( \lambda = \frac{h}{mv} \)
  - Thermal neutrons: \( \lambda \sim 1 \text{ Å} \) to 2 Å
  - Cold neutrons: \( \lambda \sim 3 \text{ Å} \) to 10 Å
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- Slow: $v \approx 4000\,\text{m/s} / (\lambda / \text{Å})$ and E distribution easily shifted
  - Same source - large E-range = many apps
  - Low energy, $E = \frac{mv^2}{2} \approx 82\,\text{meV} / (\lambda^2/\text{Å}^2)$
  - Neutron's mass $\sim ^1\text{H} -$ couple strongly with phonons
  - Relative E-changes large (spectroscopy) - X-rays?
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  - Relative E-changes large (spectroscopy) - X-rays?
- Neutrons have moments - interaction with unpaired electrons
  - Spin $1/2 --$ same as unpaired electron - magnetism
How do neutrons interact with atoms?

- **Neutron – nucleus interactions**
  - Most probable interaction
  - Short range - essentially point scattering
- **Neutron – electron interactions**
  - Spin-spin interaction (requires unpaired electrons)
  - Magnetic scattering
When a Neutron Collides with an Atom Nucleus...

- **Neutron is absorbed - radiography**
  - yielding a new isotope (stable or radioactive)
  - to yield an excited nuclear state

- **Neutron is scattered (momentum change)**
  - Energy can be lost/gained (inelastic)
  - No energy transfer (elastic)

*Also*
- Phase can be lost (incoherent)
- Phase can be retained (coherent)
Properties - charge

- Neutral - no interaction with Coulomb charge
- Highly penetrating
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  - Highly penetrating (except B, Cd, Gd, Hf ...)

Applications

- light-weight machinable shielding (BN); opaque self collimating anvils (c-BN); Imaging real rocks and parts

Radiographic images of highly Absorbing Hf sphere falling in silicate melt

Neutrons penetrate deep into matter
(Winkler et al, EJ Mineral., V14)
When a Neutron Collides with an Atom Nucleus...

- **Neutron is absorbed**
  - yielding a new isotope (stable or radioactive)
  - to yield an excited nuclear state - *Neutron Activation Analysis*

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http://www.ncnr.nist.gov/instruments/nactanal.html
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- “Neutron fluorescence” - either delayed or prompt
- Instrumental NAA - measure concentrations of many elements in single sample non-destructively
- Especially art, archaeological, botanical, geological
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Expose sample + standards to neutrons.
- most elements become radioactive.
- Wait or measure while sample in beam (prompt $\gamma$ - “neutron fluorescence”)
- $E$ of $\gamma$ allows ID of element
- $I \propto$ [element]
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Radiochemical NAA
- Activation + separation of species of interest
- low background, remove interference
### Elements Determined Using Nuclear Analytical Methods

<table>
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*NDP is used for surface analysis of B, Li, N, O.*

**Courtesy of Brian Toby, Argonne**
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Courtesy of Brian Toby, Argonne
Background: In 1998, percent levels of Cd were found in a chemical fertilizer that was applied to farmland in California. Many states proposed regulations limiting levels of 10 elements shown above. Fertilizer manufacturers and state regulators needed standards to develop methods and validate analytical results.

Project: Material was donated by the industry. Sieved fractions were analyzed by INAA and the decision was made to jet mill the material. XRF and PGAA were used to assess homogeneity of the final material.

Certification analyses underway in FY05. Certified or reference values planned for 23 elements, 19 to be determined by nuclear methods.
**Prompt-γ Activation Analysis**

- non-destructive analytical chemistry
- Detects ~1/3 of periodic table
- ppm sensitivity for hydrogen

**Example:** Attempted deuteration of HY (Fajasite)

\[ \text{H}_{0.28}\text{Al}_{0.28}\text{Si}_{0.72}\text{O}_2 \text{ vs } \text{D}_{0.28}\text{Al}_{0.28}\text{Si}_{0.72}\text{O}_2 \]

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  - Energy can be lost/gained (inelastic)
  - No energy transfer (elastic)

*Also*
  - Phase can be lost (incoherent) - no interference (diffraction) effects
  - Phase can be retained (coherent) - interference between scattering centers - diffraction effects
The Scattering (or X-ray or neutron) cross-section
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\[ \sigma \] (scattering cross section)

- Measure of the probability that an interaction of a given kind will take place between a nucleus and an incident neutron
- (elastic, inelastic for eg)
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- $\sigma$ (scattering cross section)
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- Difference between X-ray and neutron cross-sections ($\sigma_{\text{total}}$)
  - While the cross-section (probability of scattering) is positive, the atomic scattering length, $b$ ($\sigma = 4\pi b^2$) can be negative
    - +ve $b$, scattered neutron $\pi/2$ phase shifted (like X-rays)
    - $b$ is different for different isotopes, different nuclear spin states
The Scattering (or X-ray or neutron) cross-section

- Other differences
  - **The nucleus is a point** compared to electron cloud
  - No dependence on scattering angle
  - the neutron interaction stay the same - and weak!
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![Diagram showing electron cloud and nucleus with path difference angle θ]
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Electron cloud

Nucleus

Path (phase) difference

$sin \theta / \lambda$
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- Path (phase) difference

- As angle increases X-ray scattering factor decreases

\[ \sin \theta / \lambda \]
The Scattering (or X-ray or neutron) cross-section

Other differences

- The nucleus is a point compared to electron cloud
- No dependence on scattering angle
- Can’t be calculated; must be measured
- Probability of coherent (phase retained, interference effects) and incoherent (phase lost) varies with isotope (not just atom)

\[
\sigma_{coh} = 4 \pi (\bar{b})^2, \quad \sigma_{inc} = 4 \pi \left\{ \overline{b^2} - (\bar{b})^2 \right\}
\]

- Coherent scattering depends on correlation between positions of nuclei, interference effects, Bragg, phonon scattering (correlated motion)
- Incoherent scattering does not give rise to interference effects
  - Useful in studies of diffusion (uncorrelated motion), since it arises from correlations of the same nucleus at different times.
Probability for coherent vs. incoherent scattering changes with isotope
Van Hove’s scattering “law”: periodic structure or not

calculate this, exactly

\[
\left( \frac{d^2 \sigma}{d\omega dE'} \right)_{coh} = \frac{\sigma_{coh}}{4\pi} \frac{k'}{k} NS(Q, \omega)
\]

\[
S(Q, \omega) = \frac{1}{2\pi\hbar} \int G(r, t) \exp\{(iQ \cdot r - \omega t)\} \, dr \, dt
\]

\[
G(r, t) = \frac{\hbar}{(2\pi)^3} \int S(Q, \omega) \exp\{-i(Q \cdot r - \omega t)\} \, dQ \, d\omega
\]

\[G(r, t)\text{ is the time-dependent pair-correlation function (where the atoms are)}\]

\[S(Q, \omega)\text{ is the structure function, dynamical structure function, coherent scattering function, also referred to as the scattering function or scattering law. By inspection } S(Q, \omega) \text{ is the Fourier transform of } G(r, t) \text{ in space and time (dr dt).}\]
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\[S(Q, \omega)\] is the structure function, coherent cross section, \[\sigma_{coh}\], also very different X vs N neutron’s (unlike X-rays) “sensitivity” almost equal at all \(Q\) and a very wide range of \(\omega\); coherent cross section, \[\sigma_{coh}\], also very different X vs N.
Differences between X-ray and neutron cross-sections.
(1) Z-dependence - Application: finding light elements
Differences between X-ray and neutron cross-sections.

(1) Z-dependence - Application: finding light elements
Differences between X-ray and neutron cross-sections.

(1) Z-dependence - Application: finding light elements

BUT - every neutron is sacred - 6 - 10 orders less bright than X-ray sources.
**Why Neutrons?**

- Neutrons are electrically neutral & more penetrating than X-rays. tomography, radiography of real rocks and parts
- Neutrons act like particles
  - waveguides, gravitational effects
- **Neutrons act like waves**
  - Neutrons interact with nuclei & locate atoms more precisely.
    - Light atoms scatter neutrons as strongly as heavy atoms.
    - $b_{coh}$ independent of $Z$, $\sin \theta/\lambda$, can be -ve
    - Diffraction, D/H contrast, precise positions, PDF
- Neutrons have a moment, & can determine magnetic structures.
- Neutrons can study atom dynamics & the forces between atoms.
Neutrons are electrically neutral & more penetrating than X-rays.

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Neutrons have a moment, & can determine magnetic structures.

Neutrons can study atom dynamics & the forces between atoms.

Why Neutrons?

Application 1
- Bragg powder scattering - the experimental set-up looks familiar,
  - Data interpretation (peak position, unit cell, strain broadening, particle size effects, calculation of scattering factor) similar

Application 2
- Neutrons can be used for imaging & tomography, radiography of real rocks & parts
Properties of thermal/cold neutrons

- Wave-like nature and Bragg (elastic) scattering
- $\lambda = 2d\sin\theta$ - Same formalism as X-ray scattering
- Powder diffractometers, sample geometry similar - just bigger
powder diffractometers - just bigger
Modern neutron powder diffractometers use multiple detector; neutrons come from weak sources (cf. X-ray synchrotrons)
Neutron intensities are low, so large detectors are needed

Construction of a microstrip position-sensitive detector (printed circuit)

Anton Oed
Bruno Guerard
Pierre Convert
Thomas Hansen
Jacques Torregrossa
Construction of a microstrip position-sensitive detector (printed circuit)
Applications of large fast detectors/detector banks scattering

Complete diffraction pattern in 20 min. on small samples - at ambient or in environmental (high P) cells

21 mm$^3$ pellet recovered from HP synthesis


Incident neutrons

$\text{CaCu}_3\text{Ga}_2\text{M}_2\text{O}_{12}$

150° detector D20
Light element sensitivity: finding H(D) in minerals

- Sites for H (or D) precisely determined
- H(D) in topaz and topaz-OH
- Even in small samples H-positions easily determined

1. Parise, Cuff, Moore (1980) Min Mag, 43, 943
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New positions revealed by recent ambient (2) and high pressure work (3)

1. Parise, Cuff, Moore (1980) Min Mag, 43, 943
Light element sensitivity: joint X-N structural refinements
Note: less drop off in scattering at high angles for neutrons

LiMoN$_2$ X-7A data capillary, Si(111), $\lambda$=0.7122Å, Ge(111) analyser, 1x7 mm slits, Kevex detector

LiMoO$_2$ X-ray

LiMoO$_2$ Neutron

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LiMoO$_2$ X-ray

LiMoO$_2$ Neutron

LiMoN$_2$ X-7A data capillary, Si(111), $\lambda$=0.7122Å, Ge(111) analyser, 1x7 mm slits, Kevex detector

LiMoN$_2$ H4S Vanadium tube, Si(111), $\lambda$=1.3585, graphite analyser, 20'-40'-40'-20' sollar slits

Light element sensitivity: joint X-N structural refinements

Note: less drop off in scattering at high angles for neutrons

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LiMoN₂ data capillary, Si(111), \( \lambda = 0.7122 \) Å, Ge(111) analyser, 1x7 mm slits, Kevex detector

LiMoO₂ X-ray

LiMoO₂ Neutron

Li revealed in Neutron Structure

Differences in scattering power for isotopes
(2) Null scattering

\[ b_{\text{coh}} \text{(fm)} \]

\[ \text{Mean Atomic X-ray Scattering Factors (electrons)} \]

Atomic Number \((Z)\)

- H
- Li
- Ti
- Mn
- Fe
- Ni
- Zr
- \( ^{62}\text{Ni} \)
- V
Differences in scattering power for isotopes

(2) Null scattering

![Graph showing differences in scattering power for isotopes. The graph plots the mean atomic scattering factors against the atomic number (Z). Key elements include Li, Ti, Mn, Fe, Ni, Zr, H, and Ni(62).]
Differences in scattering power for isotopes

(2) Null scattering
Differences in scattering power for isotopes

(2) Null scattering

Applications - no equivalent for X-rays
- transparent metal in beam-path
- “invisible” containers and shields in cryostats
- Decrease interference from cell assembly

```
"TiZr"
```
Differences in scattering power (3) Contrast variation

![Graph showing differences in scattering power and contrast variation](image-url)
Differences in scattering power (3) Contrast variation

![Graph showing differences in scattering power and atomic number.]
Differences in scattering power (3) Contrast variation

![Graph showing differences in scattering power and atomic number variation.](image)
Differences in scattering power (3) Contrast variation

![Graph showing atomic number (Z) vs. b_{coh} (fm) and mean atomic X-ray scattering factors (electrons)]

- **Li**
- **H**
- **D**
- **Fe**
- **Ni**
- **Zr**
- **Ti**
- **Mn**
- **Ni**

- **6Li**
- **7Li**

[for] Atomic Number (Z)

[range] b_{coh} (fm)

[range] Mean Atomic X-ray Scattering Factors (electrons)
Why Neutrons?

- Neutrons are electrically neutral & more penetrating than X-rays.
- tomography, radiography of real rocks and parts
- Neutrons act like particles
  - waveguides, gravitational effects
- Neutrons act like waves
  - Neutrons interact with nuclei & locate atoms more precisely.
  - Light atoms scatter neutrons as strongly as heavy atoms.
  - $b_{coh}$ independent of $Z$, $\sin \theta / \lambda$, can be -ve
  - Diffraction, D/H contrast variation, precise positions, PDF
- Neutrons have a moment, & can determine magnetic structures.
- Neutrons can study atom dynamics & the forces between atoms.
Contrast variation: $b^H_	ext{coherent} \approx -4 \text{ fm}; b^D \approx 6 \text{ fm}; b^O \approx 5 \text{ fm}; b^{H\text{O}} \approx -3 \text{ fm}, b^{D\text{O}} \approx 17 \text{ fm}$

H$_2$O Liquid

D$_2$O

Hydrogenous particles
Contrast variation: $b^H_{\text{coherent}} \sim -4 \text{ fm}$; $b^D \sim 6 \text{ fm}$; $b^O \sim 5 \text{ fm}$; $b^{\text{H}_2\text{O}} \sim -3 \text{ fm}$, $b^{\text{D}_2\text{O}} \sim 17 \text{ fm}$

H$_2$O Liquid

Hydrogenous particles

D$_2$O

Less Hydrogenous particles
Contrast variation: $b^H_{\text{coherent}} \sim -4 \text{ fm}$; $b^D \sim 6 \text{ fm}$; $b^O \sim 5 \text{ fm}$; $b^{\text{H}_2\text{O}} \sim -3 \text{ fm}$, $b^{\text{D}_2\text{O}} \sim 17 \text{ fm}$

H$_2$O Liquid

D$_2$O

Hydrogenous particles

Less Hydrogenous particles

Mostly deuterated particles
Differences in scattering power (3) Contrast variation

Applications

Deriving partial G(r) by choosing appropriate isotopes

\[ \text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2 \] - site disorder of ALL metals over sites (Not HP)

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Breger, Dupre, Chupas, Lee, Proffen, Parise, Grey (2005), JACS, 127, 7529
Differences in scattering power (3) Contrast variation

Applications

Deriving partial $G(r)$ by choosing appropriate isotopes

$$G(r) = 4\pi r [\rho(r) - \rho_0] = \frac{2}{\pi} \int_0^{\infty} Q[S(Q) - 1] \sin(Qr) dQ$$

$$G_c(r) = \frac{1}{r} \sum_i \sum_j \left[ \frac{b_i b_j}{\langle b \rangle^2} \delta(r - r_{ij}) \right] - 4\pi r \rho_0$$

\textit{Determined experimentally (note this is }G(r)\textit{ not }g(r)\textit{ and its neutrons - it can be negative)}

\textit{Determined from model}

\textit{Breger, Dupre, Chupas, Lee, Proffen, Parise, Grey (2005), JACS, 127, 7529}
Differences in scattering power (3) Contrast variation

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Determined experimentally (note this is G(r) not g(r) and its neutrons - it can be negative)

Determined from model

Now, if \( b_i \) and/or \( b_j \) is zero, the partial (contributions from atom pair involving \( i \)), disappears. How do we play this game?

Breger, Dupre, Chupas, Lee, Proffen, Parise, Grey (2005), JACS, 127, 7529
Differences in scattering power (3) Contrast variation

**Applications**

- Deriving partial G(r) by choosing appropriate isotopes

\[
G(r) \quad \text{of} \quad ^7\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2 \quad \text{(blue)}
\]

\[
^7\text{Li}^\text{ZERO}\text{Ni}_{0.5}\text{Mn}_{0.5}\text{O}_2 \quad \text{(green)}
\]

\[
^6\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2 \quad \text{(red)}
\]

- \(b_{\text{Li-6}} = 2; \quad b_{\text{Li-7}} = -2\)
- \(b_{\text{Ni-58}} = 14; \quad b_{\text{Ni-62}} = -9\)
- \(b_{\text{Mn}} = -4\)

*Breger, Dupre, Chupas, Lee, Proffen, Parise, Grey (2005), JACS, 127, 7529*
Applications

partial $G(r)$ by choosing appropriate isotopes

$G(r)$ of $^7\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ (blue)

$^7\text{Li}\text{ZERONi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ (green)

$^6\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ (red)

$b_{\text{Li-6}} = 2; \quad b_{\text{Li-7}} = -2$

$b_{\text{Ni-58}} = 14; \quad b_{\text{Ni-62}} = -9$

$b_{\text{Mn}} = -4$

Breger, Dupre, Chupas, Lee, Proffen, Parise, Grey (2005), JACS, 127, 7529
SUMMARY

- **X-rays** scattered by electrons
- **Cross-section** increases with # of electrons
- **Cross-section** decreases with Q \([Q=4\pi \sin \theta / \lambda]\)
- **Energy:** 5,000 eV to 100,000 eV

- **Neutrons** scattered by nucleus
- **Cross-sections** “random” (function of isotope)
- **Cross-section** independent of Q
- **Energy:** 0.001 eV to 0.2 eV
**SUMMARY**

More penetrating; larger samples needed.

Good for light elements (usually).

Good high “angle” data -- provides more accuracy

Right range for diffusion & atom vibrations (BIGGER % change upon interaction)

- Neutrons scattered by nucleus
- Cross-sections “random” (function of isotope)
- Cross-section independent of Q
- Energy: 0.001 eV to 0.2 eV
### Types of neutron scattering phenomena

<table>
<thead>
<tr>
<th></th>
<th>Elastic Scattering</th>
<th>Inelastic Scattering</th>
</tr>
</thead>
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Much of the impact of neutron scattering related to inelastic - especially phonons and spectroscopic studies.
# Types of neutron scattering phenomena

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<td>(structural studies)</td>
<td>Phonons, magnons… (collective excitations) periodic and interference effects</td>
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<td>QENS (diffusion, low barrier motion)</td>
<td>Neutron Spectroscopies (atomic vibrations)</td>
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Much of the impact of neutron scattering related to inelastic - especially phonons and spectroscopic studies
Inelastic neutron scattering?

Addresses questions of the directions and time-dependence of atomic motions. Periodic, correlated or uncorrelated (diffusion for eg)? Etc.

Elastic line

Magnetic scattering

Intramolecular modes

Lattice modes

Neutron Compton scattering

Energy transfer (cm\(^{-1}\))

Timescale (s)

\(10^0\)

\(10^1\)

\(10^2\)

\(10^3\)

\(10^4\)

\(10^5\)

\(10^{-7}\)-\(10^{-11}\)

\(10^{-12}\)

\(10^{-13}\)

\(10^{-14}\)

\(10^{-15}\)

\(10^{-16}\)
Inelastic neutron scattering?

Addresses questions of the directions and time-dependence of atomic motions. Periodic, correlated or uncorrelated (diffusion for eg)? Etc.

Energy transfer (cm⁻¹)
- 10⁰

Timescale (s)
- 10⁻⁷-10⁻¹¹
- 10⁻¹²
- 10⁻¹³
- 10⁻¹⁴
- 10⁻¹⁵
- 10⁻¹⁶

Magnetic

Infrared and Raman

Intramolecular modes

Lattice modes

Neutron Compton scattering

Quasielastic scattering

Elastic line
Inelastic scattering in Real & Reciprocal space

The neutron changes both energy and momentum when inelastically scattered by moving nuclei

$$E_T = E_i - E_f$$

$$Q = k_i - k_f$$

These equations define the accessible energy and momentum transfers: limit of energy transfer = neutron energy and momentum is conserved; this is a huge range and covers wide variety of phenomena.
Expressions for $S(Q, \omega)$ can be worked out for e.g.

- Excitation or absorption of one quantum of lattice vibrational energy (phonon)
- Various models for atomic motions in liquids and glasses
- Various models of atomic & molecular translational & rotational diffusion
- Rotational tunneling of molecules
- Magnons and other magnetic excitations such as spinons
- Inelastic neutron scattering reveals details of the shapes of interaction potentials
Vibrational spectroscopy
Vibrational spectroscopy
Complementary to infrared and Raman.
Vibrational spectroscopy

Complementary to infrared and Raman.
No selection rules:- interaction is with nucleus *not* electrons.
Vibrational spectroscopy
Complementary to infrared and Raman.
No selection rules:- interaction is with nucleus not electrons.

Intensities straightforward to calculate:-
Since the neutron scattering law is DIRECTLY calculable, computational techniques are the natural partner to neutron spectroscopy

\[ S(Q,\omega) = \text{observed intensity of transition at energy } \omega, \sigma = \text{inelastic cross-section}, \]
\[ Q = \text{momentum transfer}, \]
\[ U_\omega = \text{amplitude of vibration for the mode at energy } \omega \]
\[ U_T = \text{total amplitude of motion}. \]
Intensities straightforward to calculate:-
Since the neutron scattering law is DIRECTLY calculable, computational techniques are the natural partner to neutron spectroscopy

$$S(Q,\omega) = \sigma Q^2 U_\omega^2 \exp(-Q^2 U_T^2)$$

$S(Q,\omega) =$ observed intensity of transition at energy $\omega$, $\sigma$ = inelastic cross-section,
$Q =$ momentum transfer,
$U_\omega =$ amplitude of vibration for the mode at energy $\omega$
$U_T =$ total amplitude of motion.

Vibrational spectroscopy
Complementary to infrared and Raman.
No selection rules:- interaction is with nucleus not electrons.
Planar Rotation of Molecular Hydrogen

Model for Dihydrogen Rotation

Energy level scheme differs appreciably from that for 3-D rotation

Deduce chemical binding of H₂?
Rotational Tunneling Spectroscopy

Rotational energy levels for unrestricted 3D rotation of $\text{H}_2$
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Restricted 2D rotation of $\text{H}_2$
Rotational Tunneling Spectroscopy

Rotational energy levels for unrestricted 3D rotation of $\text{H}_2$

Restricted 2D rotation of $\text{H}_2$

Energies typically range between 0.025- 30 meV

- How do we measure this?
Rotational Tunneling Spectroscopy

Rotational energy levels for unrestricted 3D rotation of H₂

Energies typically range between 0.025-30 meV

This is difficult to observe spectroscopically and selection rules in Raman do not allow these to be observed.

Restricted 2D rotation of H₂

- How do we measure this?
QENS

- 146 detectors
- Detector bank
- L-N$_2$ cooled Be filters
- Sample
- Small angles Diffraction bank
- Incident Neutron beam
- High angles Diffraction bank
- Crystal analyzer (PG)
It’s not just surface area: 
hydrogen uptake in porous systems.

Paul M. Forster
Juergen Eckert
Jong-San Chang
Anthony K. Cheetham
John B. Parise.

QENS Data

P. M. Forster, J. Eckert, A. K. Cheetham
Conclusions

• Neutrons have distinct advantages over all length scales of interest to earth and material scientists
  • Imaging and scattering
• Focusing and detector development (and new sources)
  • Increase neutrons on sample
  • Smaller single crystals/powder samples
  • New environmental equipment designs (P, T, s, e) measurements
• Prospect of
  • Work on “real” rocks and cores, slurries, in situ pilot plant studies
  • Under variety of conditions
Phenomena neutrons see:

Much of the Scientific Impact of Neutron Scattering Has Involved the Measurement of Inelastic Scattering in Glasses and Liquids.

Energy & Wavevector Transfers accessible to Neutron Scattering
Future

- Smaller samples
- Higher through-put