NRC·CNRC

From **Discovery** to **Innovation...**

Basic theory II: inelastic neutron scattering

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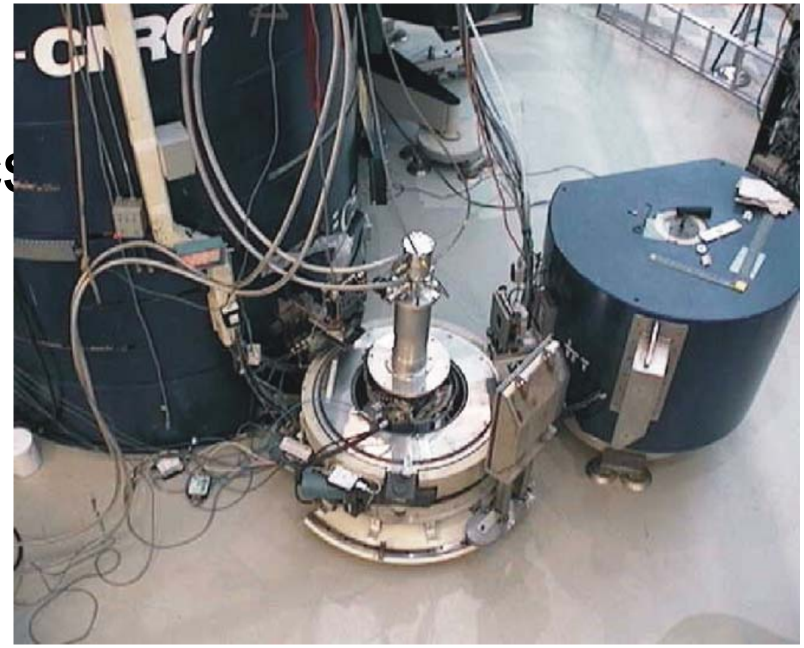
Summer School, June 15-18 2009

NRC - Canadian Neutron Beam Centre, Chalk River, Canada

National Research Council Canada / Conseil national de recherches Canada

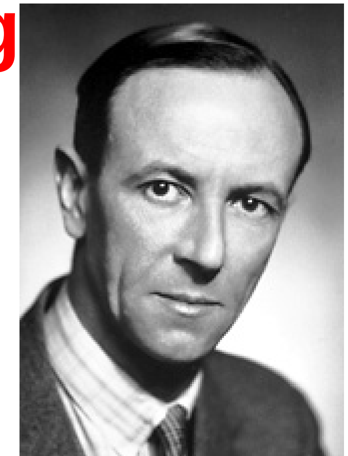
Canada

Overview



- Neutron scattering & dynamics
- Lattice vibrations
- Magnetic excitations
- Double differential cross section.
- Dynamic structure factor
- Fluctuation dissipation theorem
- Detailed balance
- Scattering triangle: elastic vs. inelastic
- Triple-axis spectroscopy
- Phonon scattering
- Magnon scattering

Neutron scattering

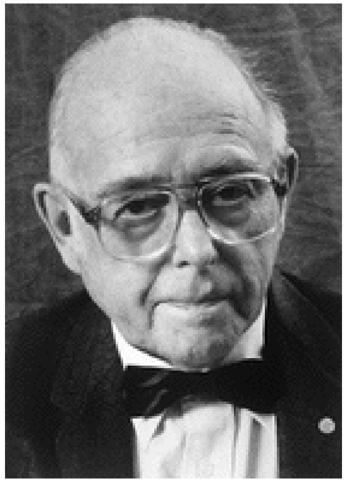


James Chadwick
1891-1974

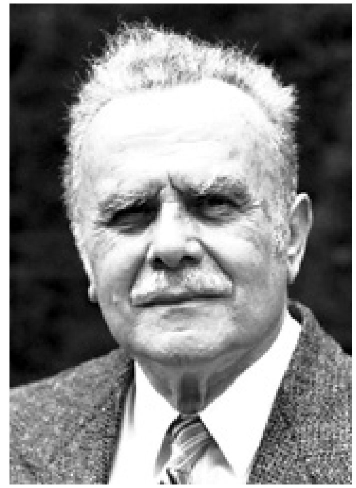
Nobel Prize 1935 for "the discovery of the neutron"

Nobel Prize 1994

"for the development of the neutron diffraction technique"



Clifford Schull
1915-2001

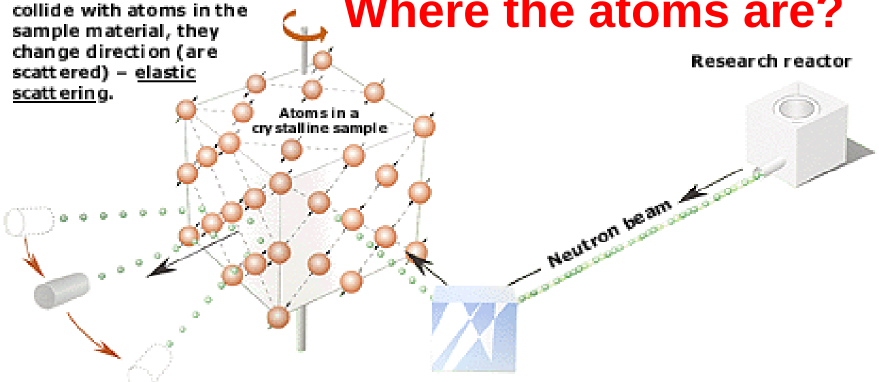


Bertram Brockhouse
1918-2003

"for the development of neutron spectroscopy"

Where the atoms are?

When the neutrons collide with atoms in the sample material, they change direction (are scattered) – elastic scattering.

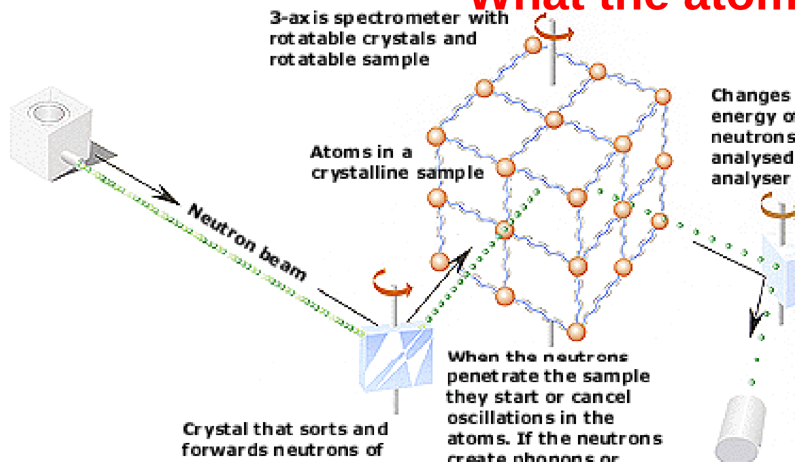


Detectors record the directions of the neutrons and a diffraction pattern is obtained.
The pattern shows the positions of the atoms relative to one another.

Crystal that sorts and forwards neutrons of a certain wavelength (energy) – mono-chromatized neutrons

What the atoms do?

3-axis spectrometer with rotatable crystals and rotatable sample



Changes in the energy of the neutrons are first analysed in an analyser crystal...

Crystal that sorts and forwards neutrons of a certain wavelength (energy) – mono-chromatized neutrons

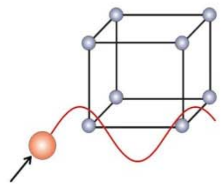
When the neutrons penetrate the sample they start or cancel oscillations in the atoms. If the neutrons create phonons or magnons they themselves lose the energy these absorb – inelastic scattering

...and the neutrons then counted in a detector.

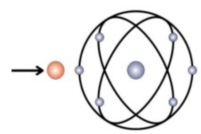
Why neutrons?

Remember what you learned about the **properties of neutron** from Ian's lecture:

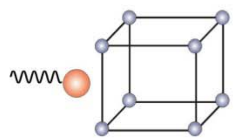
Neutrons are **neutral** particles. They
- are highly penetrating
- can be used as nondestructive probes, and
- can be used to study samples in severe environments



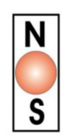
The **wavelengths** of neutrons are similar to atomic spacing. They can determine
- crystal structures and atomic spacing, and
- other structural information.



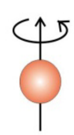
Neutrons "see" **nuclei**. They
- are sensitive to light atoms.
- can exploit isotopic substitution, and
- can use contrast variation to differentiate complex molecular structures.



The **energies** of thermal neutrons are similar to the energies of elementary excitations in solids. Hence they can be used to study
- lattice dynamics, and
- molecular dynamics.



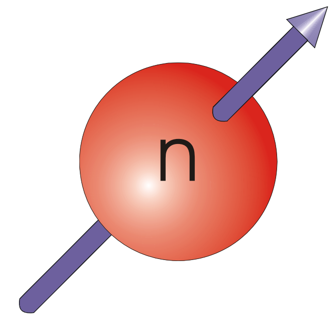
Neutrons have a **magnetic moment**. They can be used to study
- microscopic magnetic structure, and
- study magnetic fluctuations.



Neutrons have **spin**. They can be
- formed into polarized neutron beams, and
- used to study complex magnetic structures and dynamics.

http://neutrons.ornl.gov/aboutsns/importance.shtml#properties

Neutron scattering



Neutron is scattered by matter via:

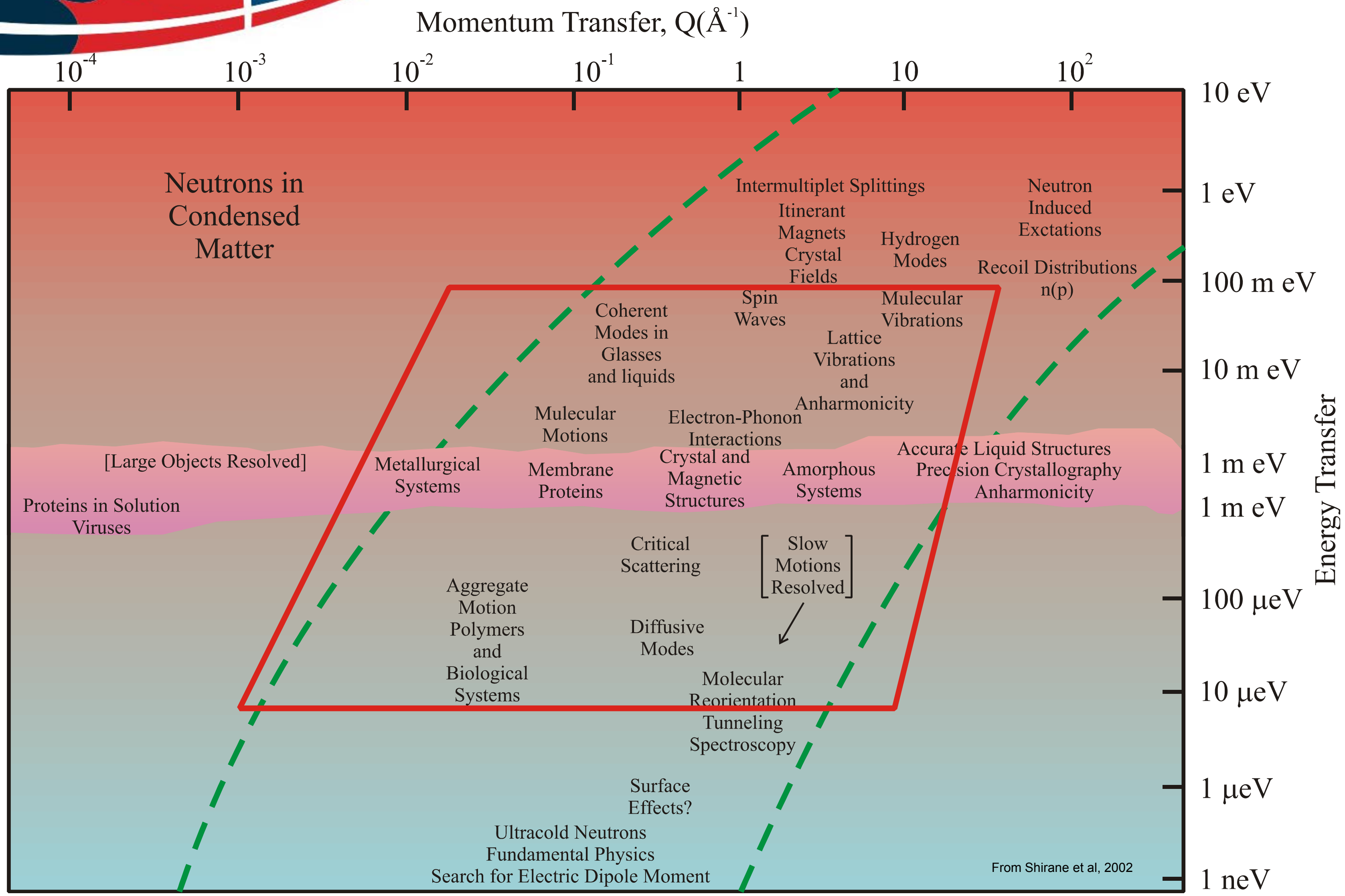
- interaction with nucleus structural studies, this lecture
- interaction with spin of unpaired electrons, magnetic scattering Dominic Ryan's Lecture

These interactions can be:

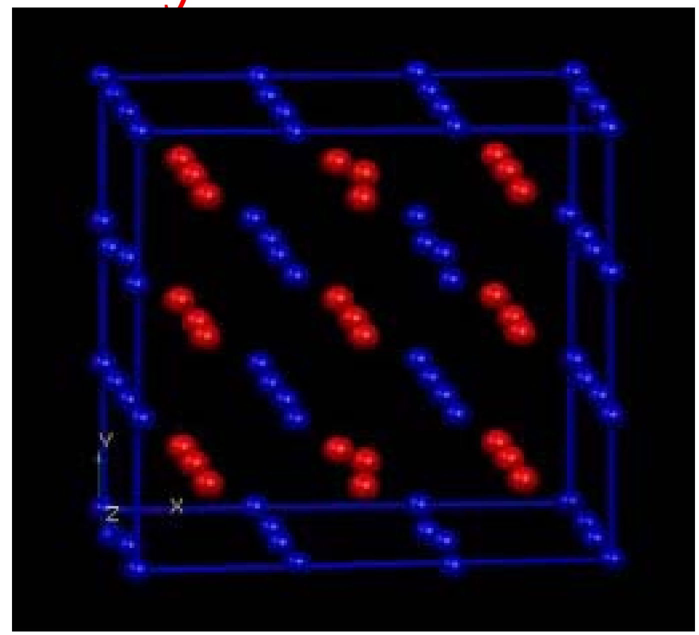
- elastic (diffraction) structural studies, yesterday lecture
- inelastic (spectroscopy) dynamical studies, today

  analysis of the energy of scattered neutrons provides information on excitations (**lattice vibrations** and **magnetic excitations**)

Neutron scattering and dynamics



Lattice vibrations & why study them?

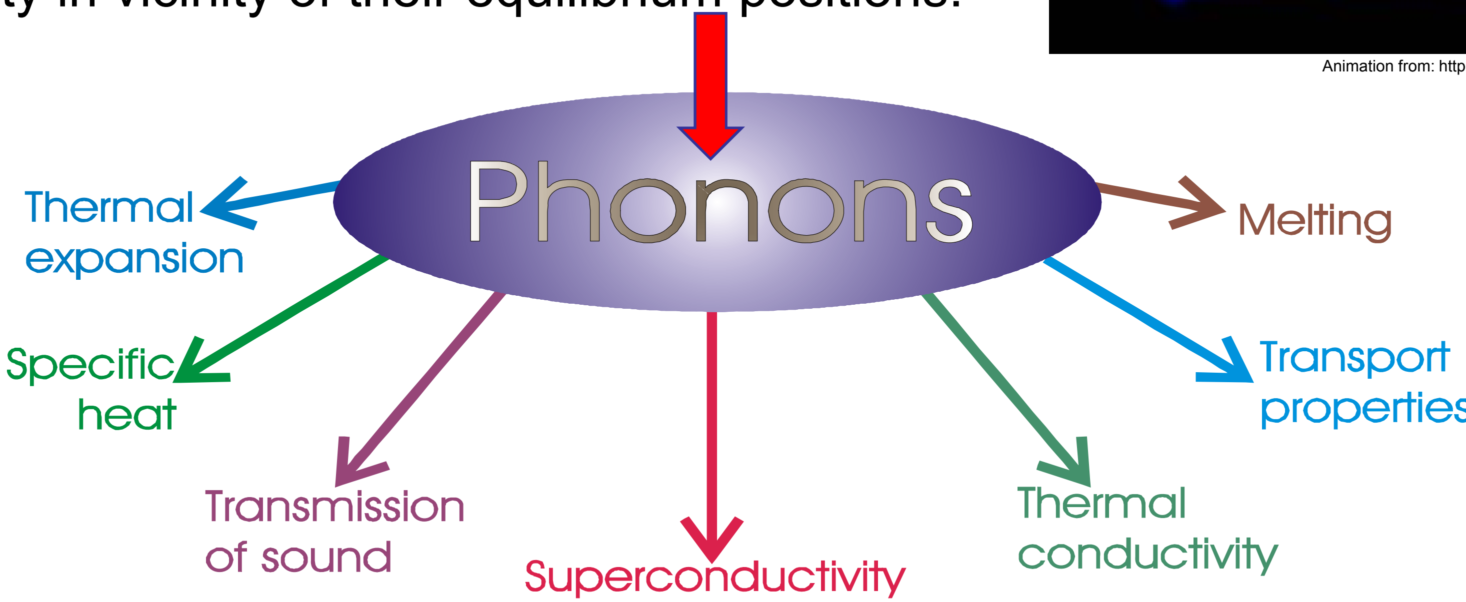

Animation from: http://wolf.ifj.edu.pl/phonon/animation/

Can a rigid fixed model of lattice describe properties of materials?

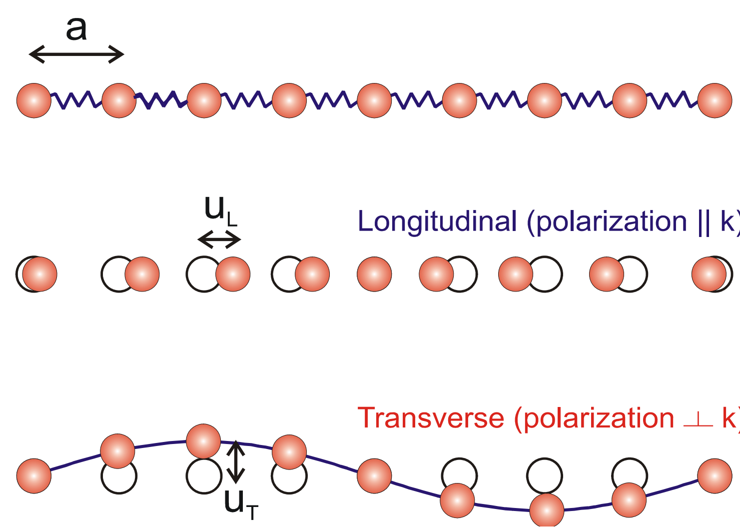
Atoms are not infinitely massive nor held in place by infinitely strong forces → in classical theory rigid model is valid only at T=0!

In quantum theory even at T=0, rigid model incorrect!

At T≠0, ions will have thermal energy: they have mobility in vicinity of their equilibrium positions:



Lattice waves (phonons)



Many important features of crystal dynamics is explained with atoms coupled via spring-like forces!

Coupled atomic vibrations generate a traveling wave with displacements along the chain (longitudinal) or perpendicular to it (transverse).

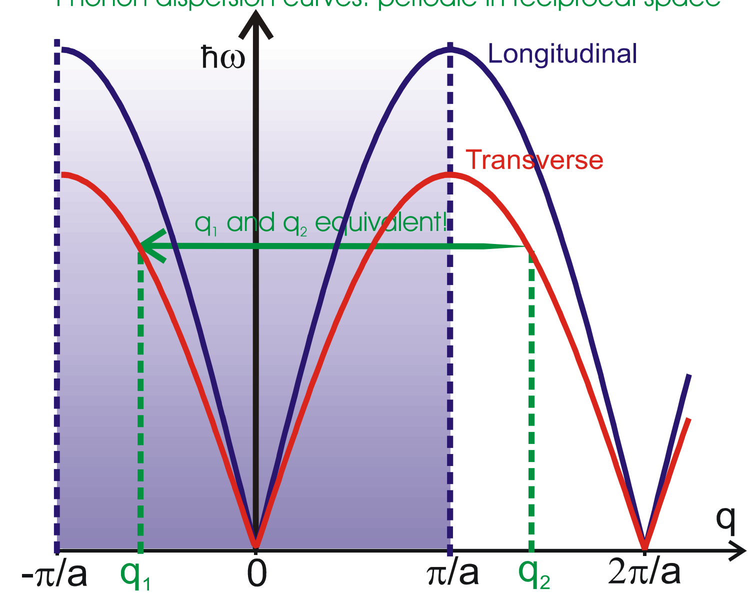
Normal modes: all atoms vibrate with same frequency.

$$M\frac{d^2u_i}{dt^2} = C(u_{i+1}-u_i)+C(u_{i-1}-u_i)$$

$$\omega(\mathrm{q}) = \sqrt{\frac{4C}{M}}\left|\sin(\frac{1}{2}\mathrm{qa})\right|$$

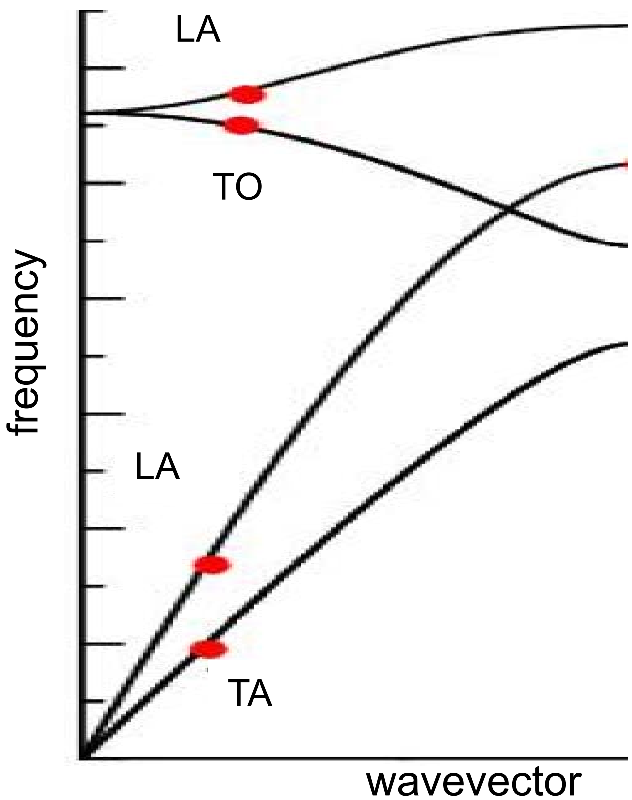
C=force constant between nearest neighbours & can be measured with neutrons.

Quantum energy of lattice vibrations=phonon

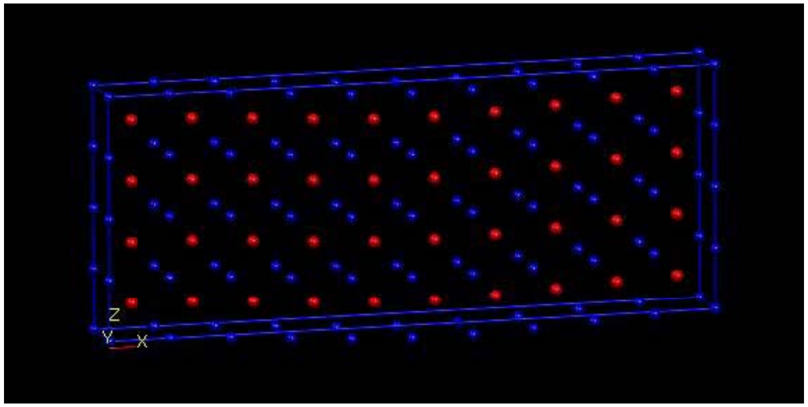


More on phonons: acoustic vs. optic

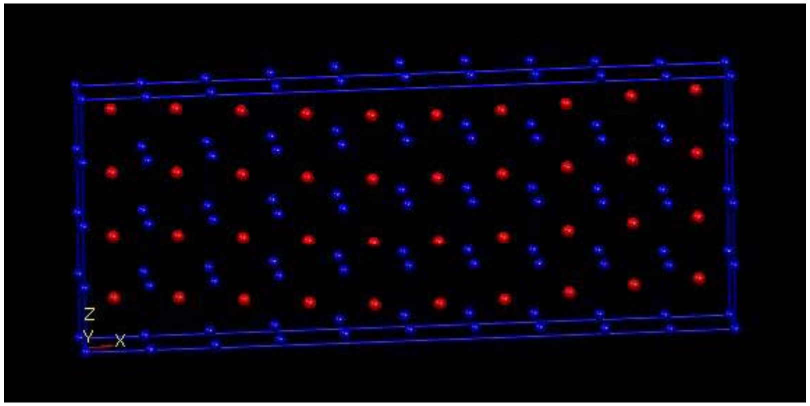
Normal-mode vibrations of primitive bcc AB crystal, with atoms A and B at positions (0,0,0) (blue) and (1/2,1/2,1/2) (red).



TA



TO



Animations from: http://wolf.ifj.edu.pl/phonon/animation/

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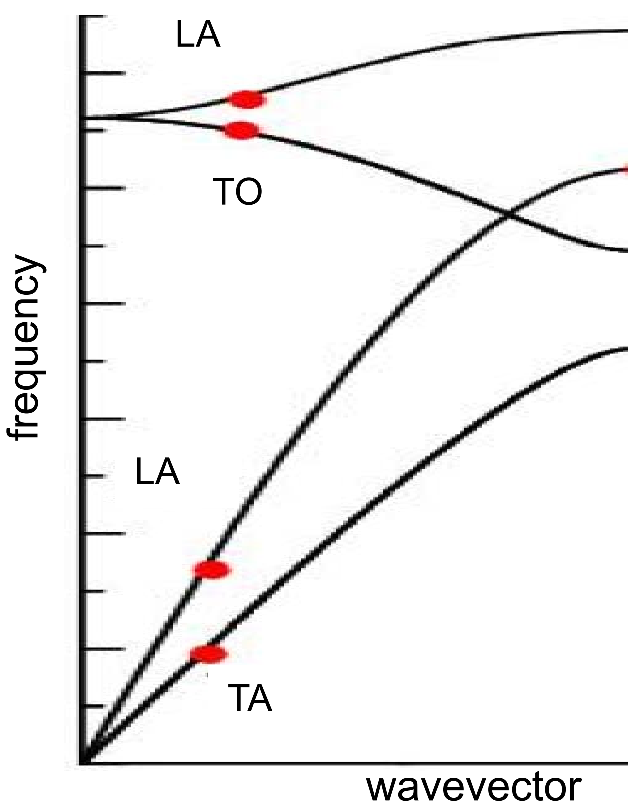
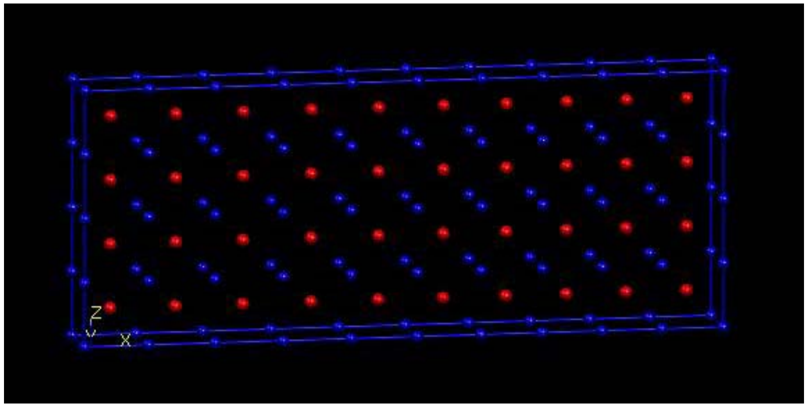


LA



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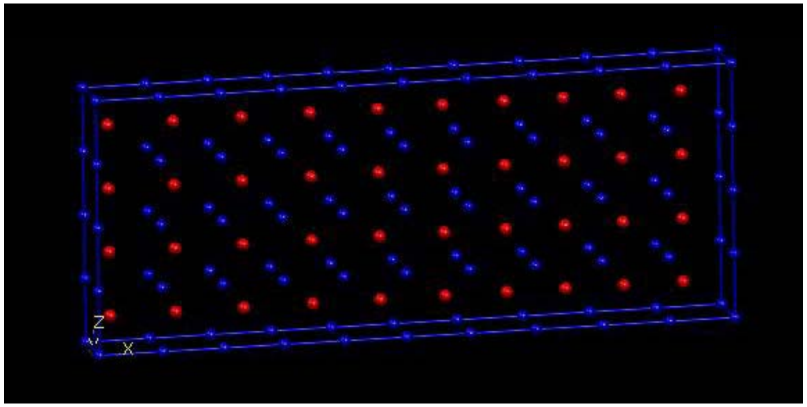
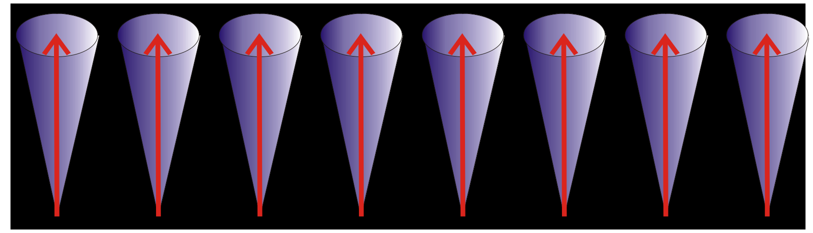


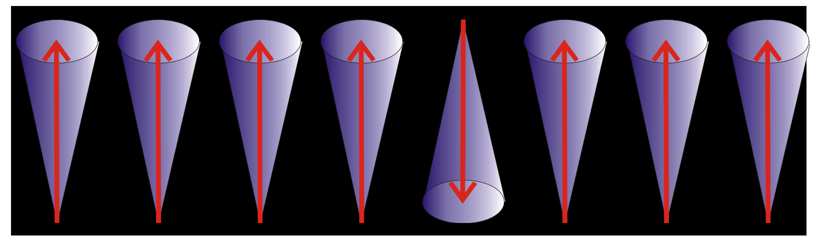
Animations from: http://wolf.ifj.edu.pl/phonon/animation/

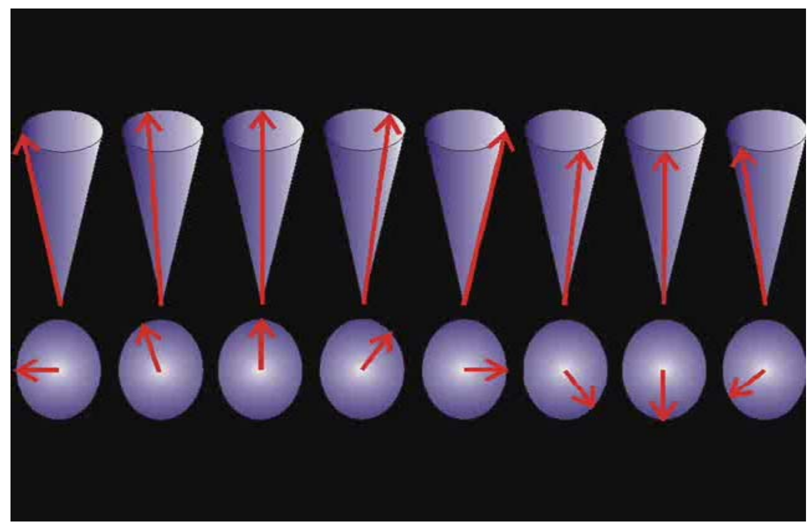
Magnetic excitations

A rigid model of magnetic moments fails to describe magnetic materials fully!

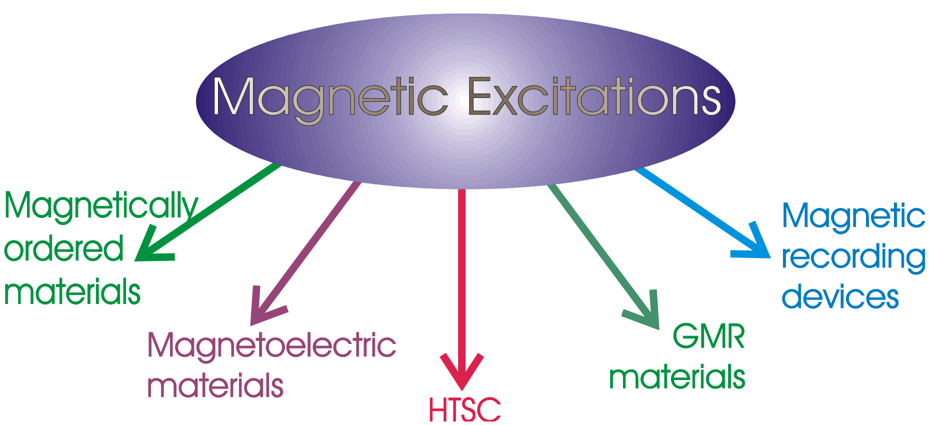
Normal excitations in a FM: spins of magnetic atoms interact strongly. Ground state: aligned spins. Excited state: a spin flips (high energy). A small amount of energy can create a much lower-energy excited state: spins precess around equilibrium direction: **spin-wave**!







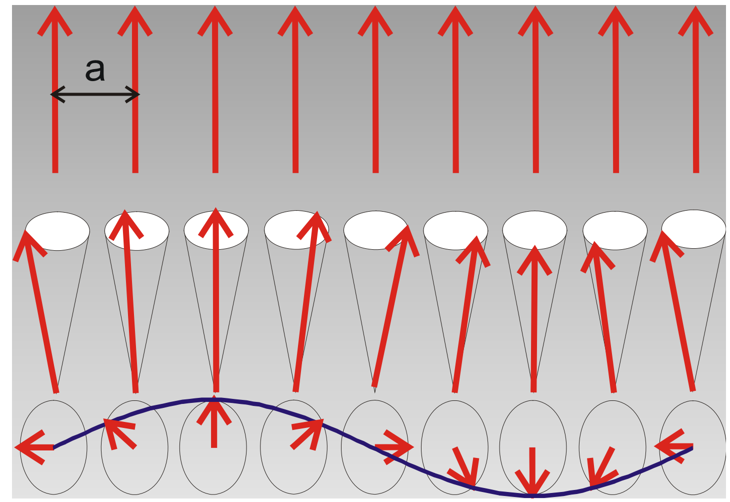
This concept can be extended to AF and itinerant systems.



Spin waves (magnons)

Magnetic materials: neighboring spins are usually coupled.

When one spin changes direction, it induces a wave-like disturbance of all neighbouring spins!



Example: spins interact via exchange interactions:

FM: $J_{ij} < 0$

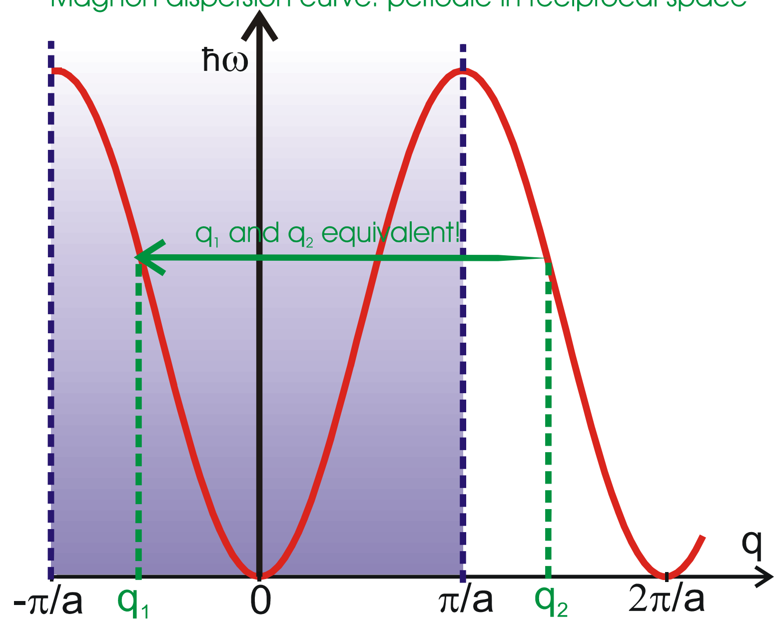
$$H = -\sum_{i,j} J_{ij}\, \mathbf{S}_i \cdot \mathbf{S}_j$$

J can be measured with neutrons.

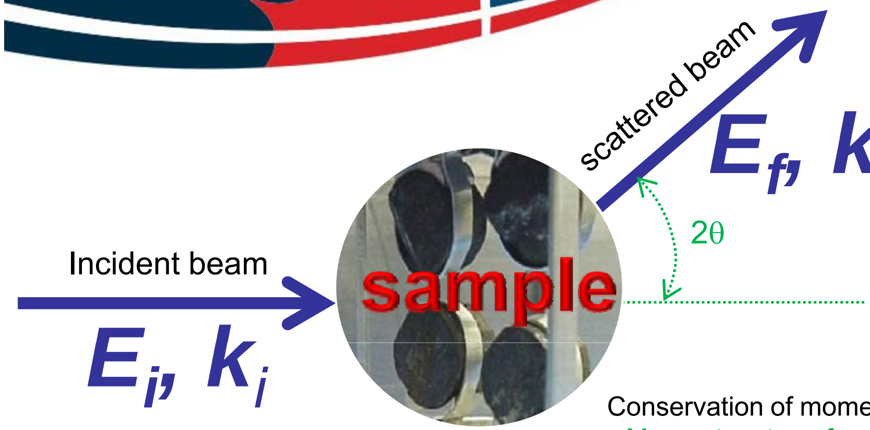
$$\omega(\mathbf{q}) = 2S\sum_{\mathbf{R}} J(\mathbf{R}) \sin^2\left(\frac{1}{2}\mathbf{q}.\mathbf{R}\right)$$

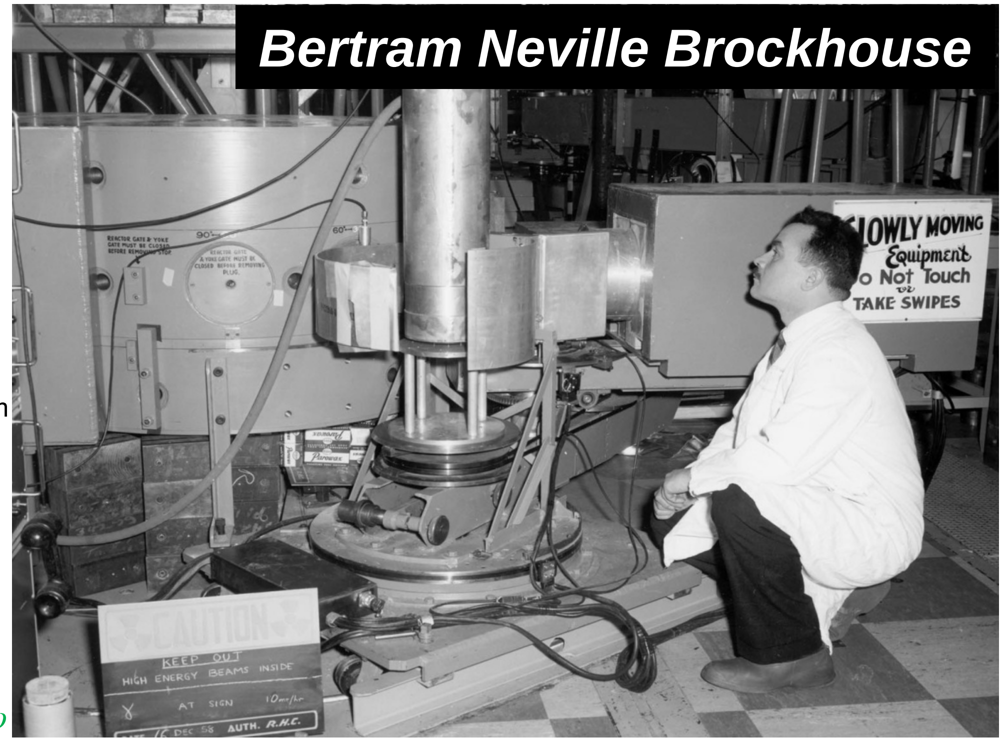
Quantum energy of excitation=magnon

Magnon dispersion curve: periodic in reciprocal space



How is it related to experiment?





Conservation of momentum

Momentum transfer= $\hbar\mathbf{Q}$

Scattering vector

$$\mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f$$

Energy transfer

$$E = E_i - E_f$$

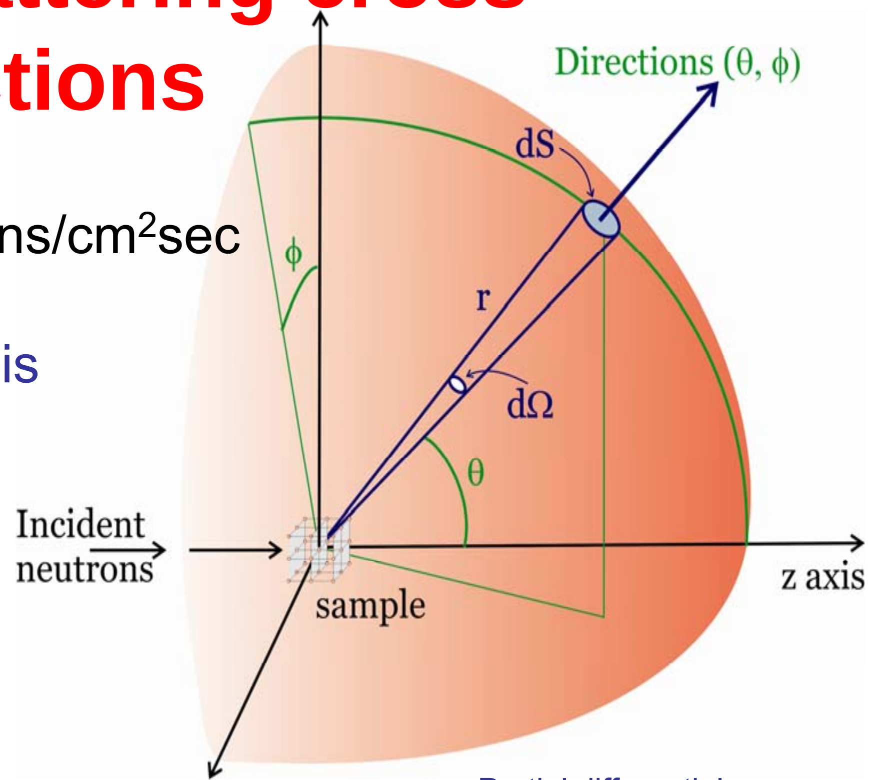
Energy transfer= $\hbar\omega$

Conservation of energy:

$$E_i + E_\alpha = E_f + E_\beta \rightarrow \Delta E_{\alpha\beta} = E$$

The **number of scattered neutrons** as a function of **Q** and ω is measured. The result is the scattering function S(**Q,** ω) depending only on the properties of the sample.

Scattering cross sections



Incident flux: Φ=number of incident neutrons/cm^{2}sec

Incident neutron beam directed along polar is scattered by the sample along (θ, ϕ).

Detector measures all the neutrons into solid angle dΩ in the direction of (θ, ϕ).

Differential cross-section:

$$\frac{d\sigma}{d\Omega} = \frac{\text{number of neutrons scattered per second into } \mathrm{d}\Omega}{\Phi \mathrm{d}\Omega}$$

Partial differential cross section (implies integration over all energies or no energy analysis).

Double differential cross-section:

$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{\text{number of neutrons scattered per second into } \mathrm{d}\Omega \text{ and } dE_f}{\Phi \mathrm{d}\Omega dE_f}$$

Double differential cross section (neutron flux into dΩ with final energy between E_f and E_f +dE_f)

Total cross section

Partial differential cross section (implies integration over all energies or no energy analysis)

$$\frac{d\sigma}{d\Omega} = \int_0^\infty \frac{d^2\sigma}{d\Omega dE_\mathbf{f}} dE_\mathbf{f}$$

Total number of scattered neutrons in all directions (units: barn=10^{-24} cm^2)

$$\sigma = \int_0^{4\pi} \frac{d\sigma}{d\Omega} d\Omega = \int_0^{4\pi} \int_0^\infty \frac{d^2\sigma}{d\Omega dE_\mathbf{f}} dE_\mathbf{f} d\Omega$$

In practice neutrons can also be absorbed by the sample, hence the total cross-section for neutrons (units: barn=10^{-24} cm^2)

$$\sigma_{\text{tot}} = \sigma_{\text{scat}} + \sigma_{\text{abs}}$$

Scattering by many nuclei

Measured **scattering intensity** is the sum of scattering from each individual nucleus!

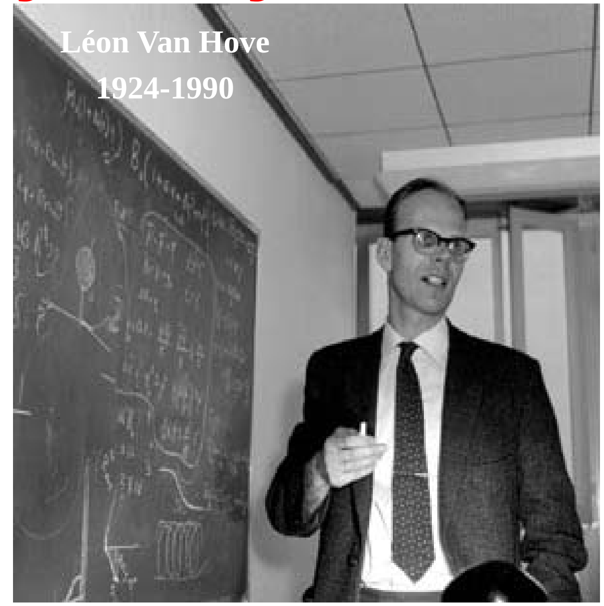
Pseudo-potential (Fermi): interaction between a neutron and a nucleus is replaced by a much weaker effective potential.

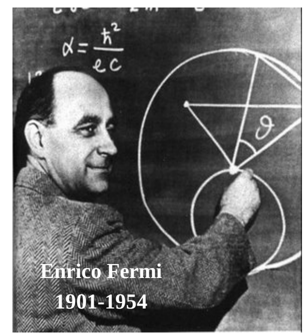
Perturbation approximation (Born): effective potential is weak enough to use perturbation in calculating scattering!

Scattering law (Van Hove): probability of a neutron wave $\mathbf{k}_i$, E_i being scattered by $V(\mathbf{r},t)$ into outgoing wave of $\mathbf{k}_f$, E_f is:

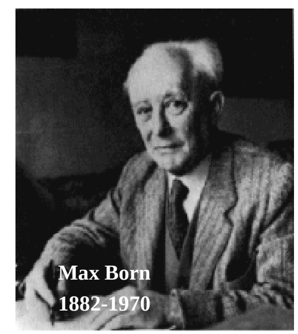
$$\left|\int V(\mathbf{r},t)\, e^{i\mathbf{Q}.\mathbf{r}}\, d\mathbf{r}\right|^2 \delta(\Delta E - \hbar\omega)$$

Integration is over the volume of the sample. ΔE is the change in energy of the sample due to scattering.

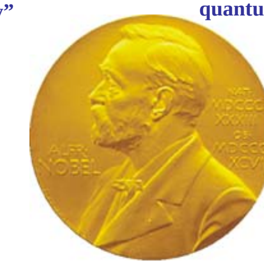




Nobel Prize 1938 for "his work on induced radioactivity"



Nobel Prize 1954 for "his fundamental research in quantum mechanics"



From Discovery to Innovation...

Scattering by many nuclei

Fermi pseudo-potential for an assembly of nuclei at positions $\mathbf{R}_j$ is:

$$V(\mathbf{r},t) = \frac{2\pi\hbar^2}{m}\sum_j b_j \delta(\mathbf{r} - \mathbf{R}_j)$$

m is neutron mass, δ is Dirac delta function=1 at position **r** and zero elsewhere, b_j are scattering lengths.

$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{k_f}{k_i}\frac{1}{2\pi\hbar}\left(\frac{m}{2\pi\hbar^2}\right)^2 \int_{-\infty}^{\infty}\left|\int V(\mathbf{r}',t)e^{-\mathbf{Q}.\mathbf{r}'}d\mathbf{r}'\right|^2 e^{i\Delta E t}e^{-i\omega t}dt$$

$$= \frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{j,j'} b_j b_{j'} \int_{-\infty}^{\infty} dt\, e^{-i\omega t}\left\langle e^{i\mathbf{Q}.\mathbf{R}_j(t)} e^{-i\mathbf{Q}.\mathbf{R}_{j'}(0)}\right\rangle$$

$$\mathbf{R}_j(t) = e^{iHt/\hbar}\mathbf{R}_j e^{-iHt/\hbar}$$

This is Heisenberg operator for the position of the jth nucleus, H is the Hamiltonian of the scattering system. Classically it can be regarded as the position of the jth nucleus.

Double sum over all of positions of nuclei in the sample. Angular brackets mean a thermal average at the temperature of the scattering system.

More on scattering by many nuclei

$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{j,j'} b_j b_{j'} \int_{-\infty}^{\infty} dt\, e^{-i\omega t} \left\langle e^{i\mathbf{Q}.\mathbf{R}_j(t)} e^{-i\mathbf{Q}.\mathbf{R}_{j'}(0)} \right\rangle$$

$$= \frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{j,j'} b_j b_{j'} \int_{-\infty}^{\infty} dt\, e^{-i\omega t} \int_{-\infty}^{\infty} \delta\left\langle (\mathbf{r} - [\mathbf{R}_{j'}(0) - \mathbf{R}_j(t)]) \right\rangle e^{-i\mathbf{Q}.\mathbf{r}} d\mathbf{r}$$

For $b_j = b_k$:

Only considering coherent scattering!

$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{\mathrm{N\,b}^2}{2\pi\hbar}\frac{k_f}{k_i} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathrm{G}(\mathbf{r},\mathrm{t})\, e^{-i\mathbf{r}.\mathbf{Q}} e^{-i\omega t}\, d\mathbf{r}dt$$

$$\mathrm{G}(\mathbf{r},t) = \frac{1}{\mathrm{N}}\sum_{j,j'} \delta(\mathbf{r} - (\mathbf{R}_{j'}(0) - \mathbf{R}_j(t)))$$

Fourier transform of time-dependent pair correlation function G(**r**,t)

Intensity is proportional to **Fourier transform** of **time-dependent pair correlation function** (probability of finding two atoms being a certain distance apart at a certain time). Scattering gives information as how correlations between pairs of nuclei evolves with time.

Dynamic structure factor S(Q,ω)

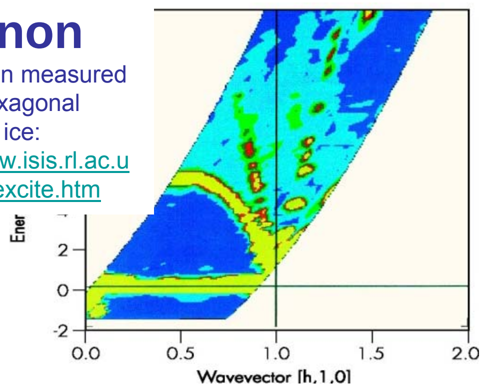
$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{\mathrm{N\,b}^2}{2\pi\hbar}\frac{k_f}{k_i}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\mathrm{G}(\mathbf{r},\mathrm{t})\,e^{-i\mathbf{r}.\mathbf{Q}}e^{-i\omega t}\;d\mathbf{r}dt$$

$$= \mathrm{N}\frac{k_f}{k_i}\mathrm{b}^2\,S(\mathbf{Q},\omega)$$

S(**Q**,ω) contains all the physics of system: neutron scattering probes dynamical processes over a length scale ~1/Q & over a time scale ~1/ω. S(**Q**,ω) can be calculated and compared with measurements to test theories.

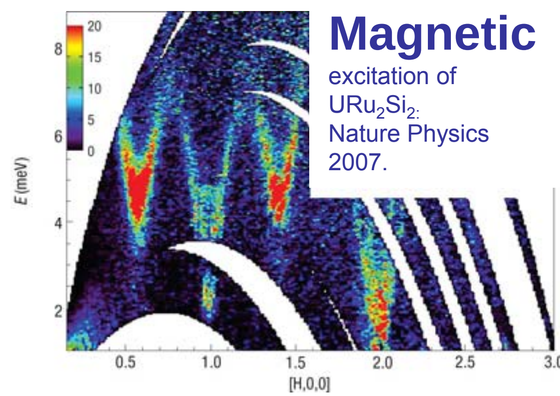
Phonon

dispersion measured in the hexagonal phase of ice: http://www.isis.rl.ac.uk/isis97/excite.htm



Magnetic

excitation of URu_2Si_2: Nature Physics 2007.



Fluctuation dissipation theorem

$$S(\mathbf{Q},\omega) = \frac{1}{1-e^{-\hbar\omega/k_BT}}\,\chi''(\mathbf{Q},\omega)$$

For ω both positive and negative.

Induced fluctuations due to an external perturbation ⟷ Spontaneous fluctuations in thermodynamic equilibrium

$\chi''(\mathbf{Q},\omega)$: imaginary part of dynamical susceptibility: basic excitation not complicated by thermal population of states, often calculated in theoretical modeling. $\mathbf{M}(\mathbf{Q},\omega)=\chi(\mathbf{Q},\omega)\ \mathbf{H}(\mathbf{Q},\omega)$: linear response due to magnetic perturbation varying in space and time.

What does it really mean?

Evolution of an externally induced perturbation is similar to that of a spontaneous fluctuation! Neutrons interact weakly with the system (a small perturbation) causing a linear response:

fluctuations in unperturbed system are observed!

Detailed balance

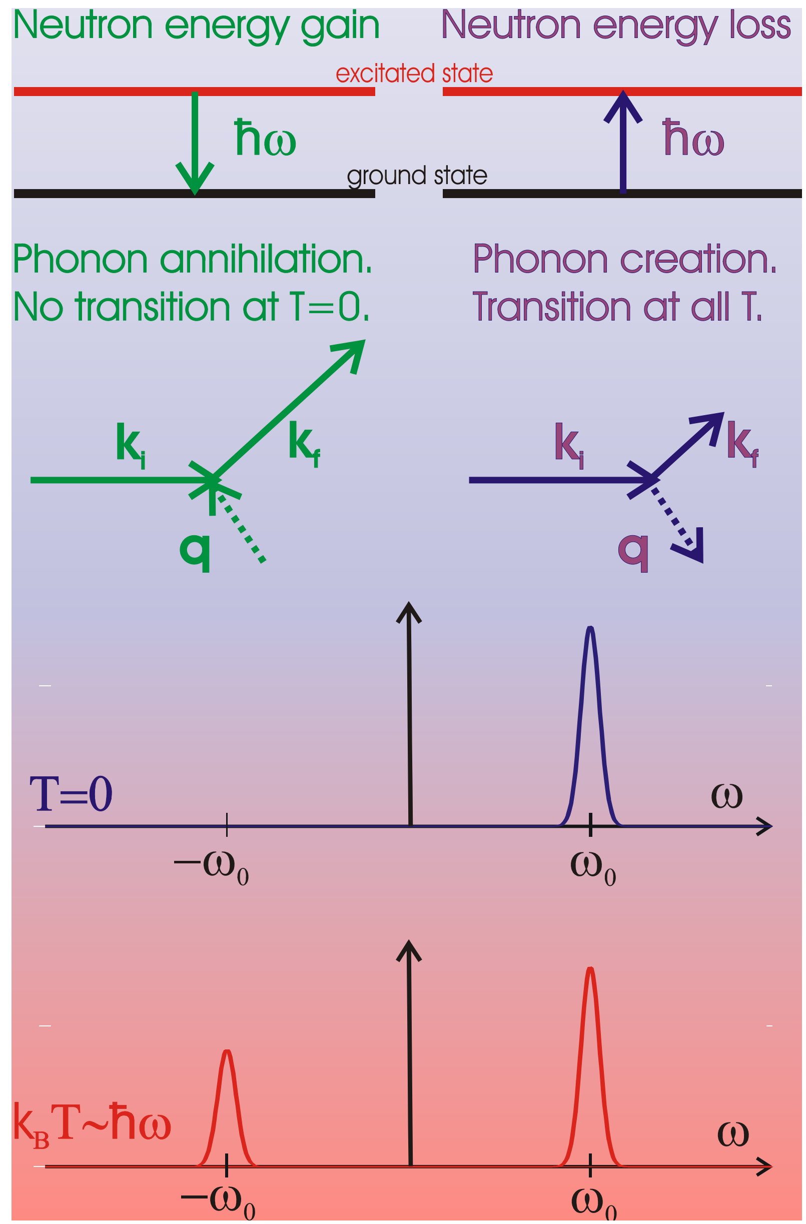
$$\frac{d^2\sigma}{d\Omega dE_f} = \mathrm{N}\frac{k_f}{k_i}\mathrm{b}^2\ S(\mathbf{Q},\omega)$$

$$S(-\mathbf{Q},-\omega) = e^{-\frac{\hbar\omega}{k_B T}}\ S(\mathbf{Q},\omega)$$

Neutron energy gain — Neutron energy loss

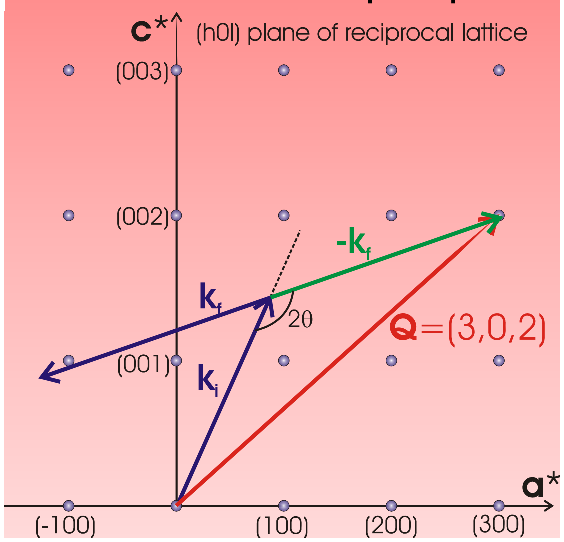
ω is assumed to be positive.

Probability of a transition in sample depends on statistical weight factor of the initial state: always lower for annihiling an excitation than creating one!

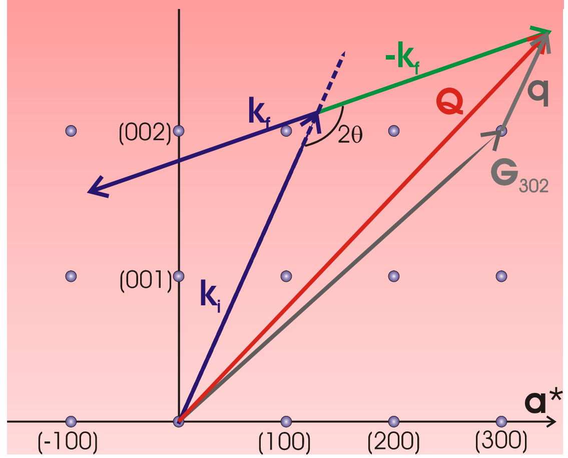


Scattering triangle: elastic vs. inelastic

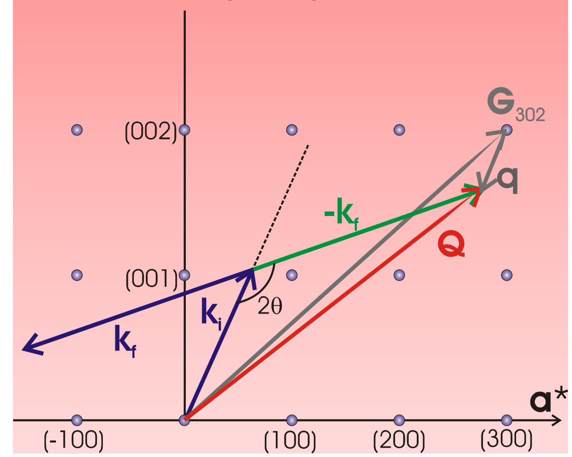
Elastic: $\mathbf{k}_i = \mathbf{k}_f$



Neutron Energy loss: $\mathbf{k}_f < \mathbf{k}_i$



Neutron Energy gain: $\mathbf{k}_f > \mathbf{k}_i$



Kinematic range that can be covered in a scattering event:

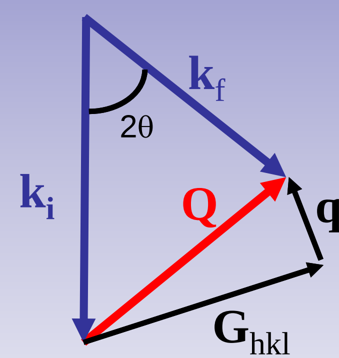
$$\frac{\hbar^2}{2m} Q^2 = E_i + E_f - 2\sqrt{E_i E_f}\cos 2\theta$$

$$\mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f = \mathbf{G}_{hkl} + \mathbf{q}$$

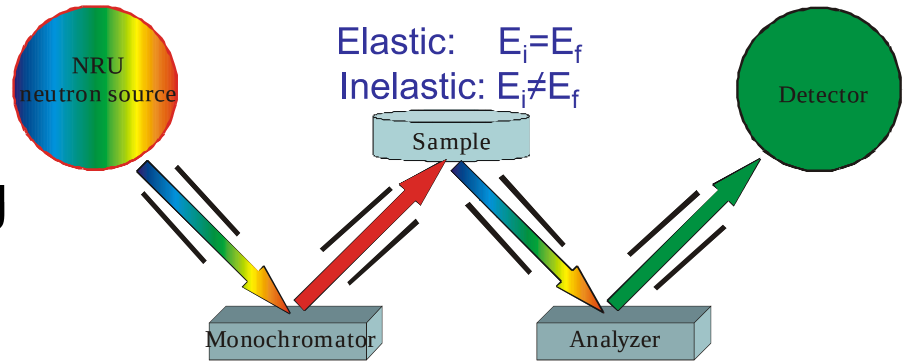
$$Q^2 = k_i^2 + k_f^2 - 2k_i k_f \cos 2\theta$$

$$E = E_i - E_f \rightarrow \frac{\hbar^2}{2m} Q^2 = 2E_f + E - 2\sqrt{E_f (E_f + E)}\cos 2\theta$$

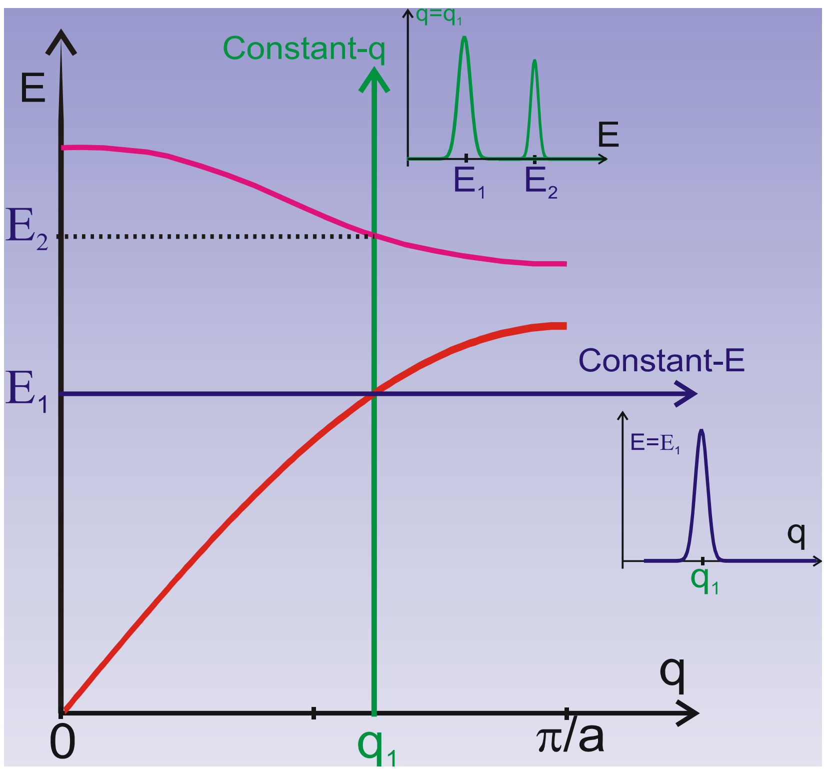
For a fixed final energy experiment

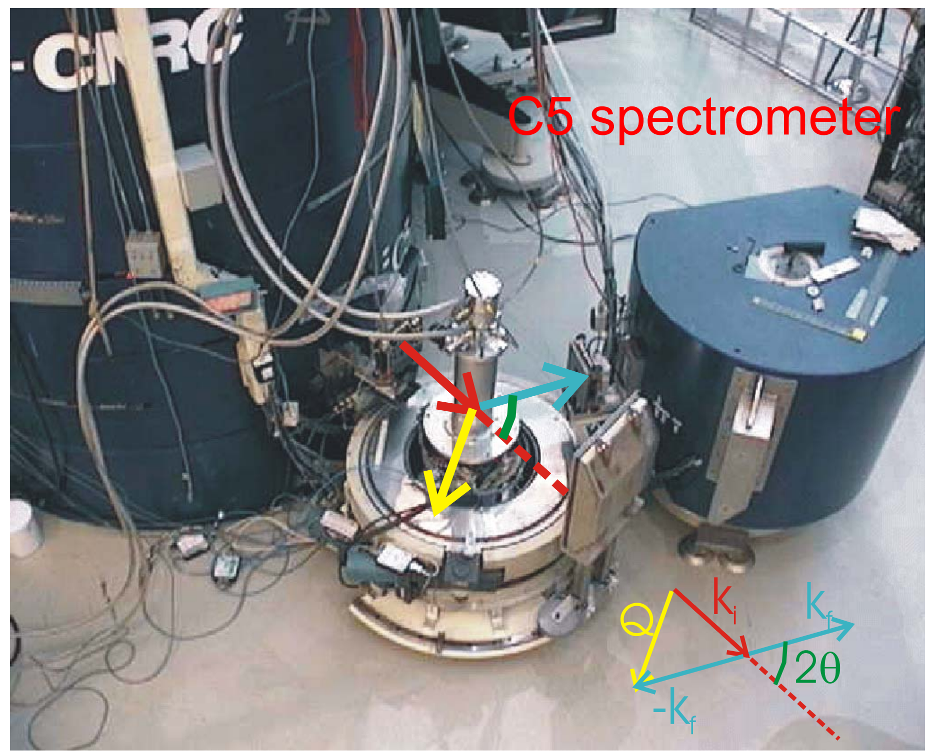


Triple-axis spectroscopy

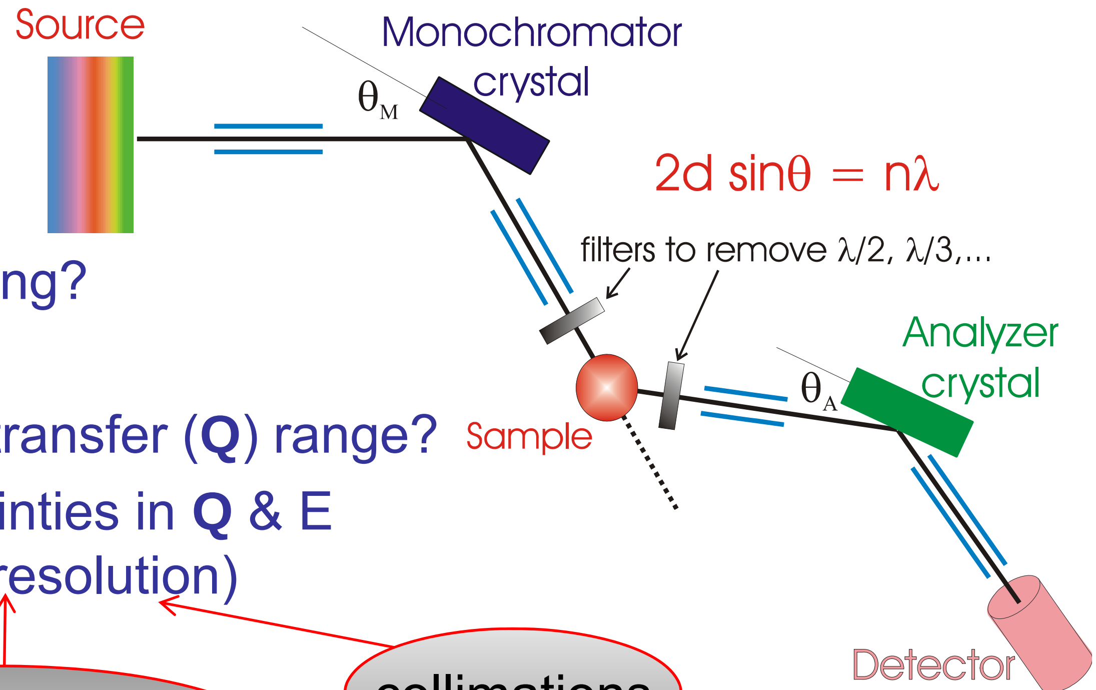


This techniques allows performing measurements point by point in **momentum- energy space**!





Triple-axis experiment



- Planning the experiment:
  1. Elastic or inelastic scattering?
  2. Magnetic scattering?
  3. Energy (E) & momentum transfer (**Q**) range?
  4. What resolution? (uncertainties in **Q** & E determine the instrument resolution)

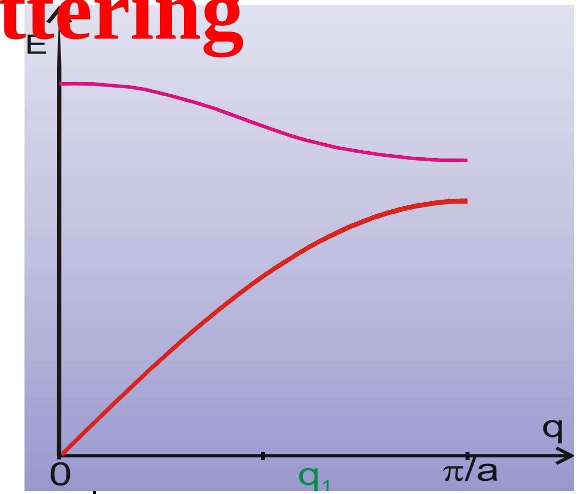
Final energy

Monochromator/analyzer mosaic

collimations

- What needs to be done:
  1. Determine the wavelengths of neutrons (wavelength resolution)
  2. Beam collimations (angular resolution)
  3. Detect neutrons (statistical process with uncertainty proportional to square root of the counts)

Phonon scattering



Sums are over all reciprocal lattice vectors and all the phonon modes.

$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{k_f}{k_i}\frac{(2\pi)^3}{V_c}\sum_{\mathbf{G}}\sum_{j\mathbf{q}}\left|F_j(\mathbf{q},\mathbf{Q})\right|^2 \times$$

$$\Big[\underbrace{n_j(\mathbf{q})\delta(\omega+\omega_j(\mathbf{q}))\delta(\mathbf{Q}+\mathbf{q}-\mathbf{G})}_{\text{Phonon annihilation}} + \underbrace{(n_j(\mathbf{q})+1)\delta(\omega-\omega_j(\mathbf{q}))\delta(\mathbf{Q}-\mathbf{q}-\mathbf{G})}_{\text{Phonon creation}}\Big]$$

Delta-functions mean that we only observe peaks only when:

$\hbar\omega = \pm\,\hbar\omega_{ph}$

$\hbar\mathbf{Q} = \hbar(\mathbf{q}_{ph} \pm \mathbf{G})$

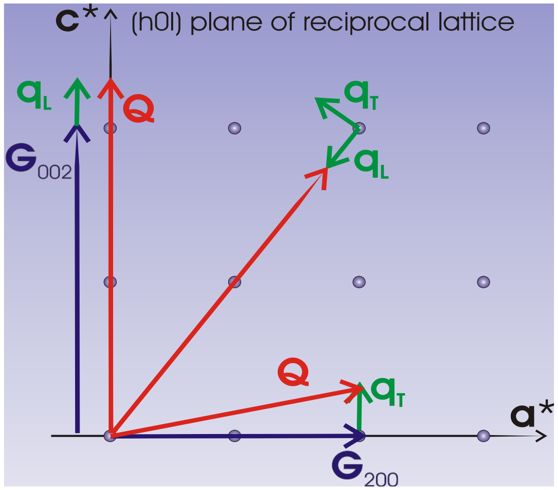
Phonon dynamic structure factor:

$$F_j(\mathbf{q},\mathbf{Q}) = \sum_l \sqrt{\frac{1}{2m_l\omega_j(\mathbf{q})}}\; b_l\,[\mathbf{Q}.\mathbf{e}_j(\mathbf{q})]\; e^{i\mathbf{Q}.\mathbf{r}_l}\; e^{-W_l(\mathbf{Q})}$$

Debye-Waller factor to describe attenuation due to thermal motion.

Intensity increases as Q^2, measure at higher zones!

Selection rule: separate transverse from longitudinal



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Phonon scattering: examples

PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Crystal Dynamics of Sodium at 90°K

A. D. B. Woods, B. N. Brockhouse,* R. H. March,** and A. T. Stewart†
Neutron Physics Branch, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

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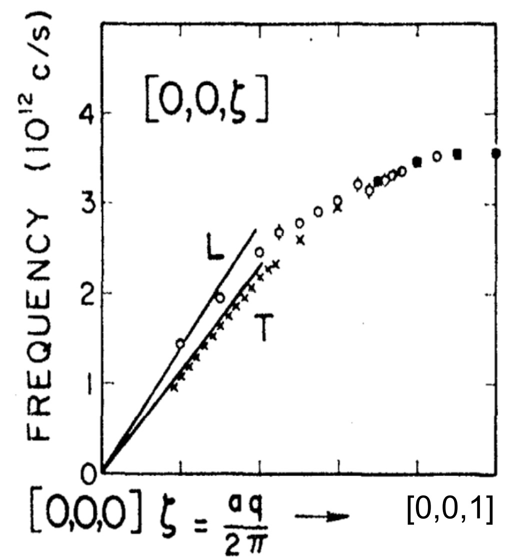
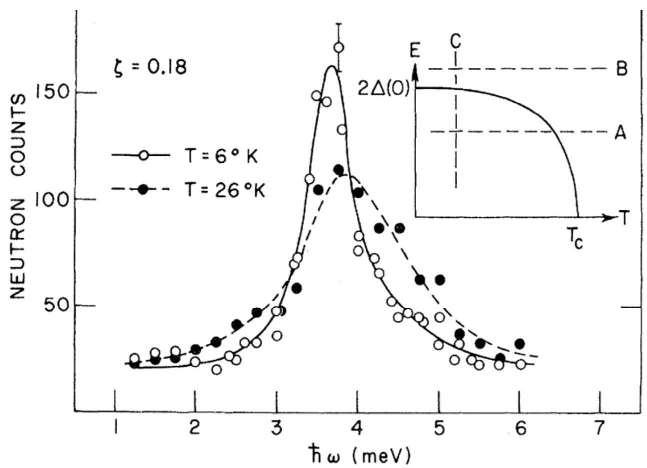
R. Bowers‡
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York

(Received June 4, 1962)

The frequency/wave vector dispersion relations for the lattice vibrations of sodium have been measured by neutron spectrometry along the symmetric lines [00ζ], [ζζ0], [ζζζ], [½ ½ ζ], and [ζζ1] and at several nonsymmetric points in the reduced zone. The measurements were made at 90°K using the triple-axis crystal spectrometer in the constant **Q** mode of operation. The results can be qualitatively described by a first- and second-neighbor force model but detailed analysis shows that fourth- and fifth-neighbor forces are probably significant. The calculated force constants for fifth neighbors are about 1 or 2% of those for first neighbors. Discontinuities in the slopes of the dispersion curves due to the Fermi surface (the Kohn effect) were not observed.

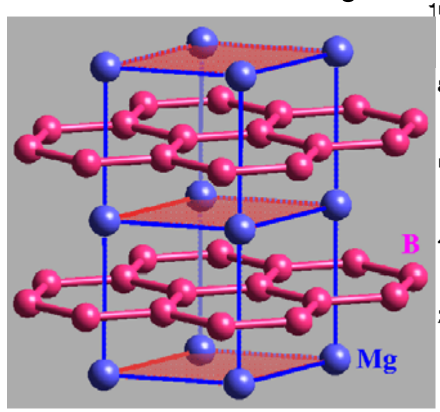


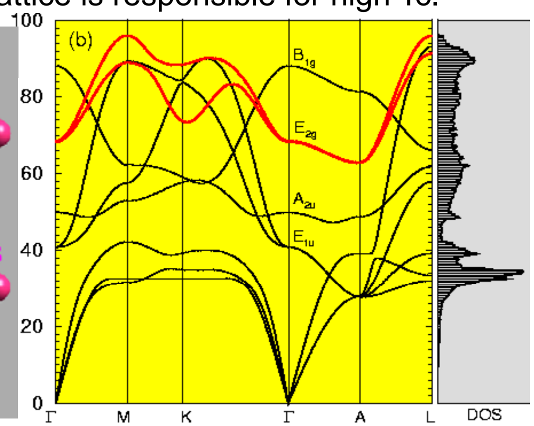
Axe, Shirane, s-wave superconductor: **Nb3Sn**



Phys. Rev. Lett. 30 (1973) 214.

Yildirim et al, Superconductivity in MgB2, a special type of vibration in the MgB2 lattice is responsible for high Tc.





http://www.ncnr.nist.gov/staff/taner/mgb2/

Magnon scattering

Magnetic diffraction: Lecture by Dominic tomorrow.

$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{k_f}{k_i}\left(\frac{g}{2}\gamma r_0\right)^2 \left|F(\mathbf{Q})\right|^2 e^{-2W(Q)} \sum_{\alpha\beta}\left(\delta_{\alpha\beta} - \hat{\mathbf{Q}}_\alpha \hat{\mathbf{Q}}_\beta\right) S^{\alpha\beta}(\mathbf{Q},\omega)$$

|F(**Q**|: Magnetic form factor due to intra-atomic interference, Fourier transform of spin density distribution on atom decreases with increasing Q.

Magnetic scattering function: time and spatial Fourier transform of spin-spin correlation function.

For a FM:

$$S(\mathbf{Q},\omega) = S\sum_{\mathbf{G},\mathbf{q}}\left[\underbrace{n_j(\mathbf{q})\delta(\omega+\omega_j(\mathbf{q}))\delta(\mathbf{Q}+\mathbf{q}-\mathbf{G})}+\underbrace{(n_j(\mathbf{q})+1)\delta(\omega-\omega_j(\mathbf{q}))\delta(\mathbf{Q}-\mathbf{q}-\mathbf{G})}\right]$$

How to separate from phonons?

Use differences from phonon scattering: intensity decreases with Q and no Q^2 dependence! Usually also decreases with T unlike phonons.

$$\sum_{\alpha\beta}\left(\delta_{\alpha\beta} - \hat{\mathbf{Q}}_\alpha \hat{\mathbf{Q}}_\beta\right) S^{\alpha\beta}(\mathbf{Q},\omega)$$

Neutrons scatter from **m**⊥ perpendicular component of atomic magnetic moment to **Q**

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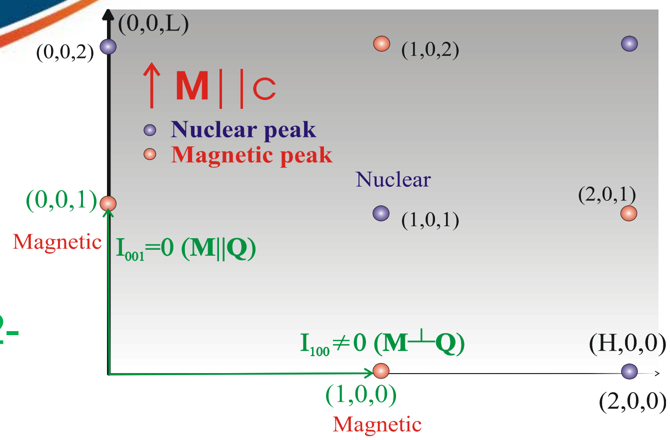
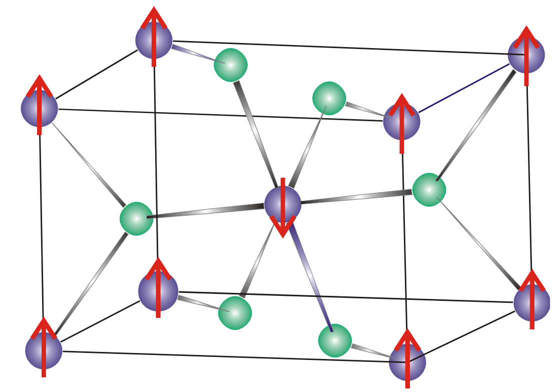
Magnons in MnF_2

Tetragonal ($P4_2/mnm$): a=4.873, c=3.130 Å

Mn: (2a) (0, 0, 0) ; (1/2,1/2,1/2)

F: (4f) (x,x,0); (-x,-x,0); (1/2+x,1/2-x,1/2); (1/2-x,1/2+x,1/2); x=0.3





NNN coupling, J_2, through fluorine ligands

NN coupling, J_1, much weaker & FM

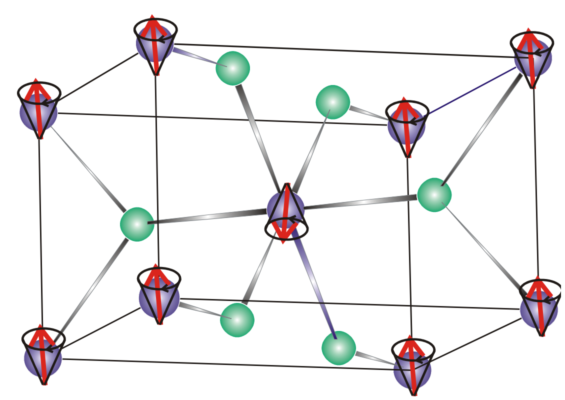
Single-ion anisotropy

$$H = \frac{1}{2} J_2 \sum_{\mathbf{r},\mathbf{d}_2} \mathbf{S}_{\mathbf{r}} . \mathbf{S}_{\mathbf{r}+\mathbf{d}_2} - \frac{1}{2} J_1 \sum_{\mathbf{r},\mathbf{d}_1} \mathbf{S}_{\mathbf{r}} . \mathbf{S}_{\mathbf{r}+\mathbf{d}_1} - D \sum_{\mathbf{r}} (\mathbf{S}_{\mathbf{r},\mathbf{z}})^2$$

$$\hbar\omega_{\mathbf{q}} = \hbar\omega_{\mathbf{2}} \sqrt{(1+\zeta_{\mathbf{q}})^2 - \gamma_{\mathbf{q}}^2]}$$

$$\zeta_{\mathbf{q}} = \frac{D + 2\hbar\omega_{\mathbf{1}} \sin^2(\frac{1}{2} q_z c)}{2\hbar\omega_{\mathbf{2}}} \ \textbf{with}\ \hbar\omega_{\mathbf{i}} = 2Sz_i J_i \ (\mathbf{z_1} = 2, \mathbf{z_2} = 8)$$

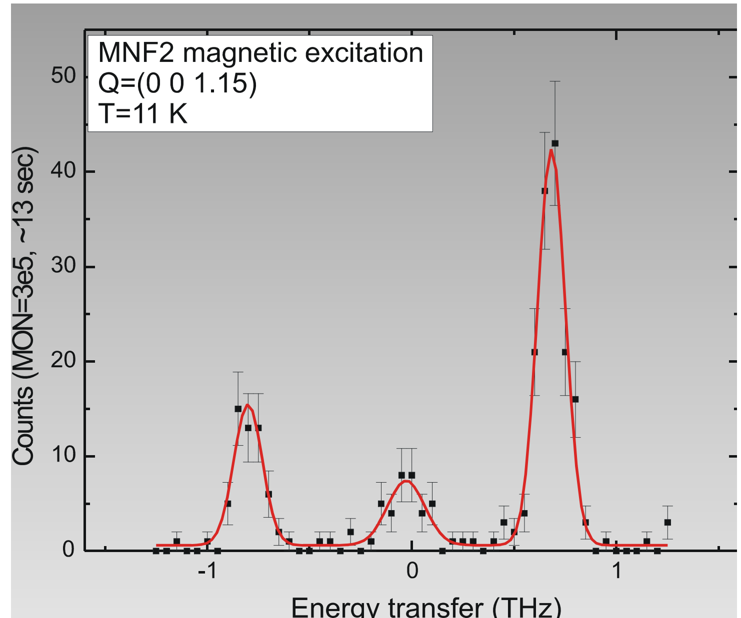
$$\gamma_{\mathbf{q}} = \cos(\frac{1}{2} q_x a) \cos(\frac{1}{2} q_y a) \cos(\frac{1}{2} q_z c)$$

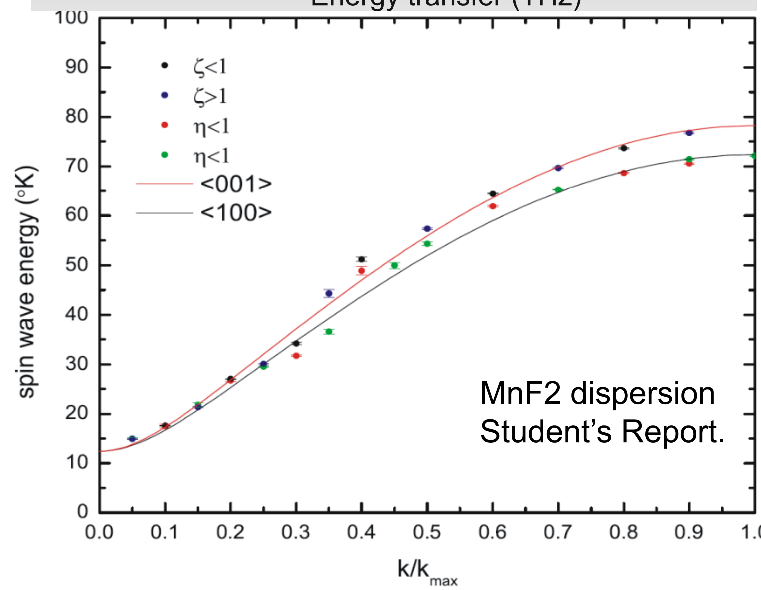


Observation of magnons

N5 spectrometer

McGill Condensed Matter Graduate Course with Prof. Ryan and students, March 2009.





More on inelastic scattering

… look for lots more inelastic examples in talks by Maikel Rheinstaedter & Bruce Gaulin.

Final word!

Hope to have convinced you (and more so by the end of Summer School) that **neutron scattering** is a powerful probe:

- used to directly study fundamental structural & magnetic correlations (both static and dynamic) in condensed matter! and hence to enhance our understanding of microscopic origin of physical properties of materials.

References and further readings

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- http://neutron.nrc-cnrc.gc.ca/home_e.html.