Inelastic neutron scattering

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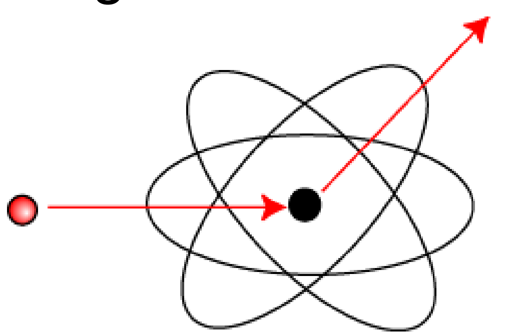
Outline

I. **Interaction of the neutron**
   A. Nuclear
   B. Magnetic
II. **General inelastic scattering**

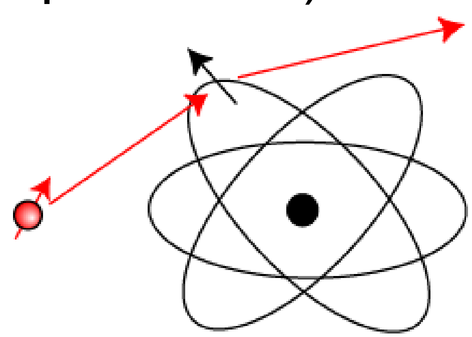
III. **Nuclear inelastic scattering**
   A. Correlation functions
   B. Examples
IV. **Magnetic inelastic scattering**
   A. Correlation functions
   B. Examples

Neutron interaction with matter

- **Properties of the neutron**
  - Mass $m_n = 1.675 \times 10^{-27}$ kg
  - Charge 0
  - Spin-1/2, magnetic moment $\mu_n = -1.913\ \mu_N$
- **Neutrons interact with…**
  - Nucleus
    - Crystal structure/excitations (eg. phonons)
  - Unpaired e^- via dipole scattering
    - Magnetic structure/excitations (eg. spin waves)



Nuclear scattering



Magnetic dipole scattering

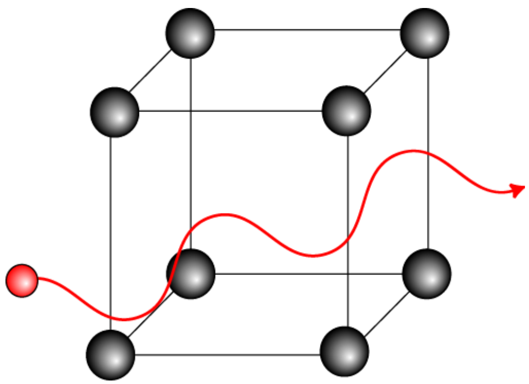
Wavelength-energy relations

- **Neutron as a wave …**
  - Energy (E), velocity (v), wavenumber (k), wavelength (λ)

$$k = \frac{m_n \mathrm{v}}{\hbar} = \frac{2\pi}{\lambda}$$

$$E = \frac{\hbar^2 k^2}{2m_n} = \frac{\hbar^2}{2m_n}\left(\frac{2\pi}{\lambda}\right)^2 = \frac{81.81\,\mathrm{meV}\cdot\text{Å}^2}{\lambda^2}$$

$$E = k_B T = \left(0.08617\,\mathrm{meV}\cdot\mathrm{K}^{-1}\right)T$$



λ ~ interatomic spacing → E ~ excitations in condensed matter

	Energy (meV)	Temperature (K)	Wavelength (Å)
Cold	0.1 – 10	1 – 120	4 – 30
Thermal	5 – 100	60 – 1000	1 – 4
Hot	100 – 500	1000 – 6000	0.4 – 1

Dynamical (time) scales

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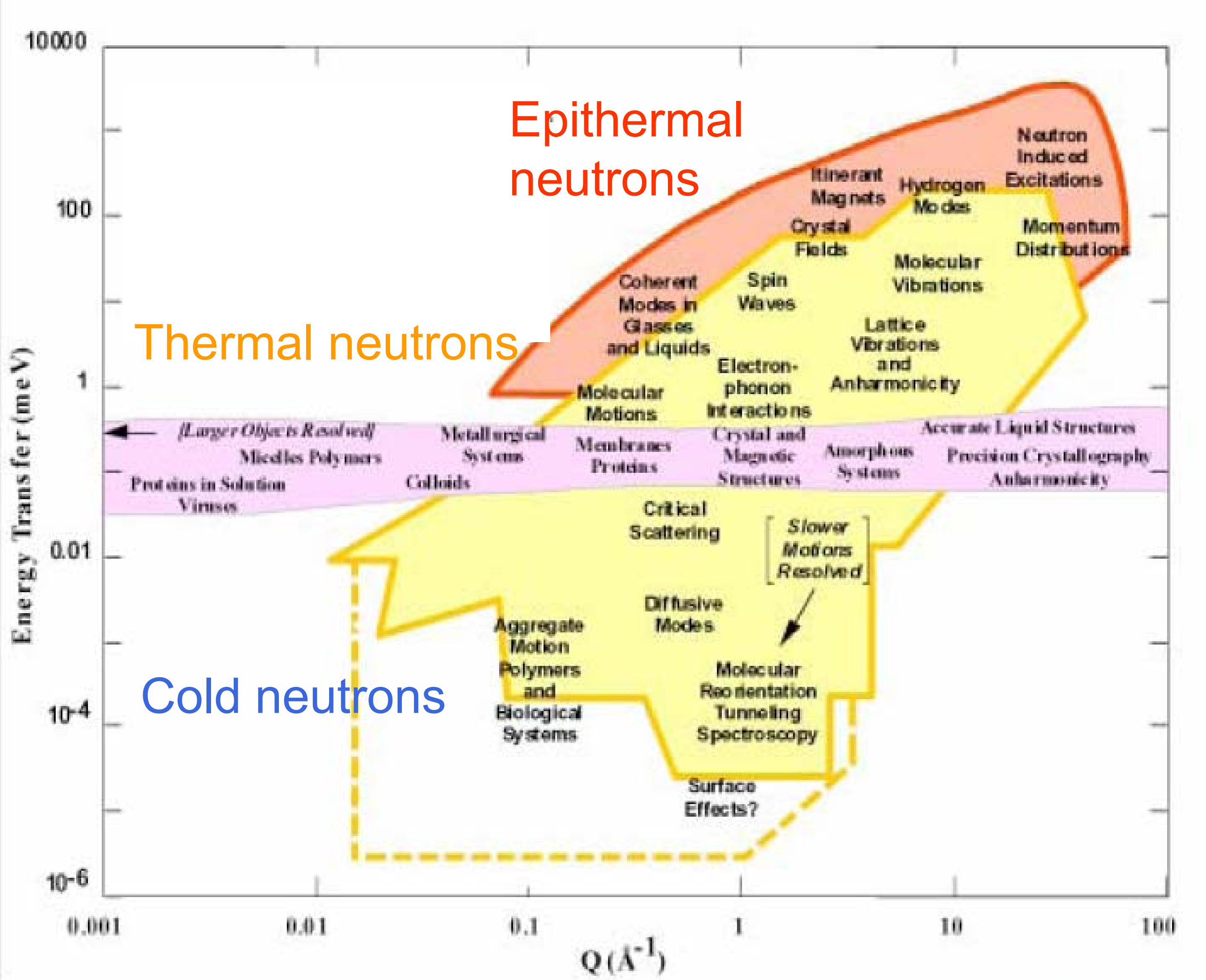
Faster processes

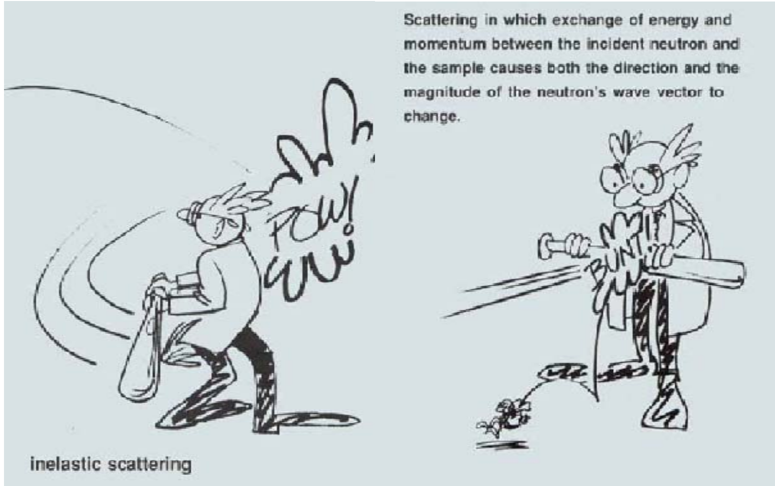


Elastic scattering

Shorter length scales

Inelastic scattering

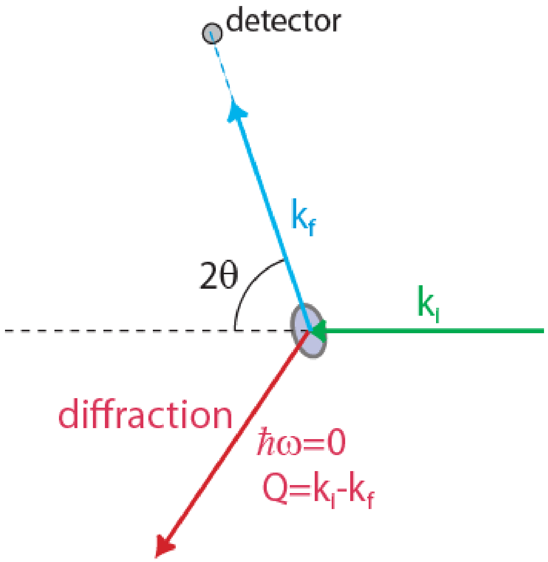
- Scattering process that changes the energy of the neutron



- Conservation of energy and momentum

$$h\omega = E_i - E_f \qquad \mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f$$

- Scattering triangle



Elastic scattering

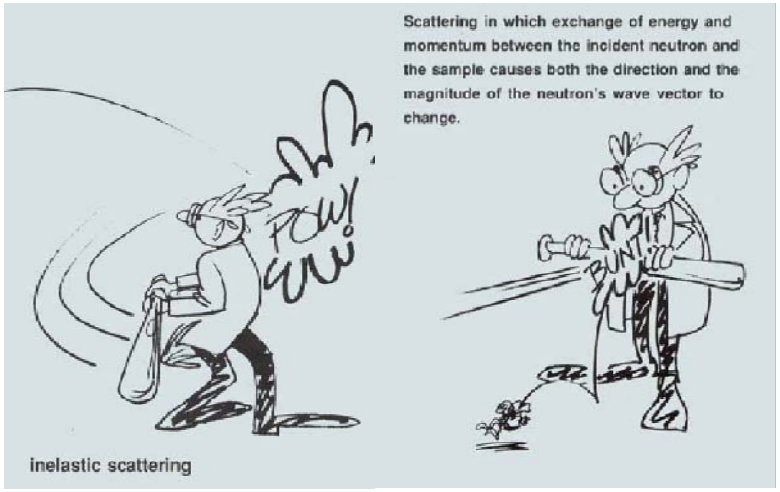
$$h\omega = 0$$

$$|\mathbf{k}_i| = |\mathbf{k}_f|$$

$$Q = 2k_i \sin\theta$$

Inelastic scattering

- Scattering process that changes the energy of the neutron



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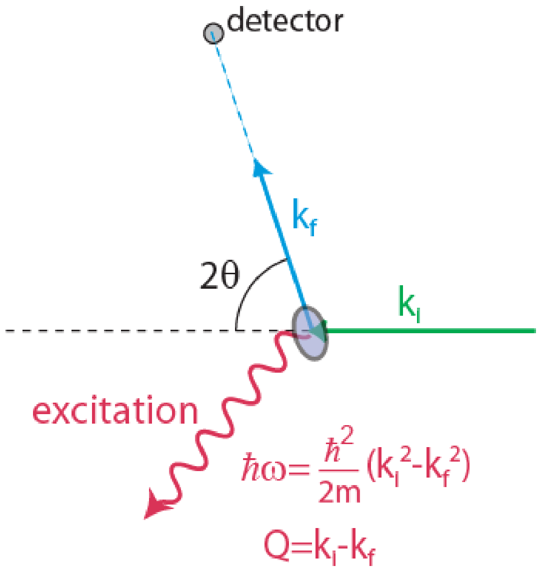

Inelastic scattering

$$h\omega > 0$$

$$|\mathbf{k}_i| \neq |\mathbf{k}_f|$$

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

Nuclear correlation functions

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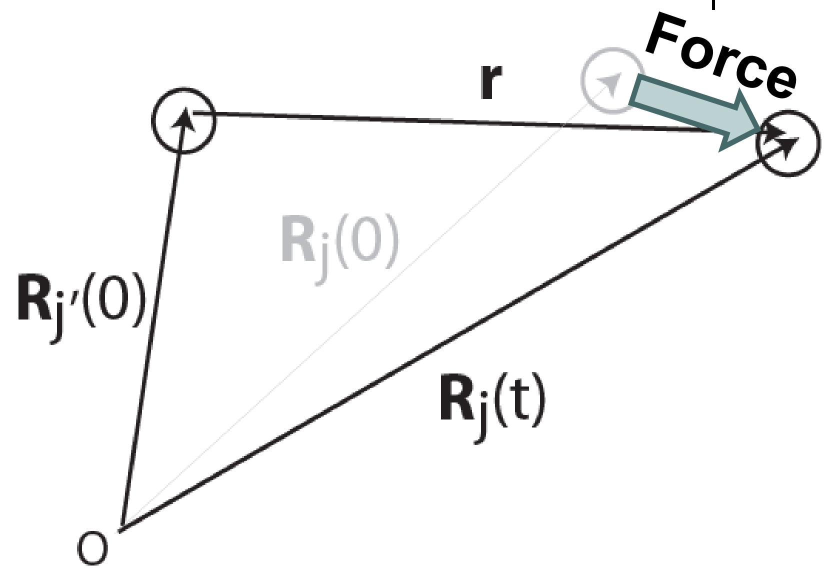

Pair correlation function

$$G(\mathbf{r},t)=\frac{1}{N}\int\sum_{jj'}\delta\left(\mathbf{r}'-\mathbf{R}_{j'}(0)\right)\delta\left(\mathbf{r}'+\mathbf{r}-\mathbf{R}_j(t)\right)d\mathbf{r}'$$

Intermediate function

$$I(\mathbf{Q},t)=\int G(\mathbf{r},t)e^{i\mathbf{Q}\cdot\mathbf{r}}d\mathbf{r}=\frac{1}{N}\sum_{jj'}\exp\left(-i\mathbf{Q}\cdot\mathbf{R}_{j'}(0)\right)\exp\left(i\mathbf{Q}\cdot\mathbf{R}_j(t)\right)$$

Scattering function

$$S(\mathbf{Q},\omega)=\frac{1}{2\pi\hbar}\int I(\mathbf{Q},t)e^{-i\omega t}dt$$

Differential scattering cross-section

$$\frac{d^2\sigma}{d\Omega dE_f}=\frac{\sigma_{scat}}{4\pi}\frac{k_f}{k_i}NS(\mathbf{Q},\omega)$$

Nuclear (lattice) excitations

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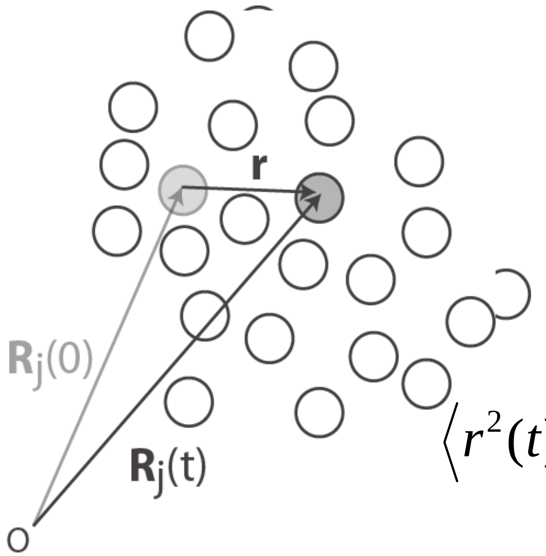
Neutron scattering measures simultaneously the wavevector and energy of **collective excitations** → dispersion relation, $\omega(\mathbf{q})$
In addition, **local excitations** can of course be observed

- **Commonly studied excitations**
  - Phonons
  - Librations and vibrations in molecules
  - Diffusion
  - Collective modes in glasses and liquids
- **Excitations can tell us about**
  - Interatomic potentials & bonding
  - Phase transitions & critical phenomena (soft modes)
  - Fluid dynamics
  - Momentum distributions & superfluids (eg. He)
  - Interactions (eg. electron-phonon coupling)

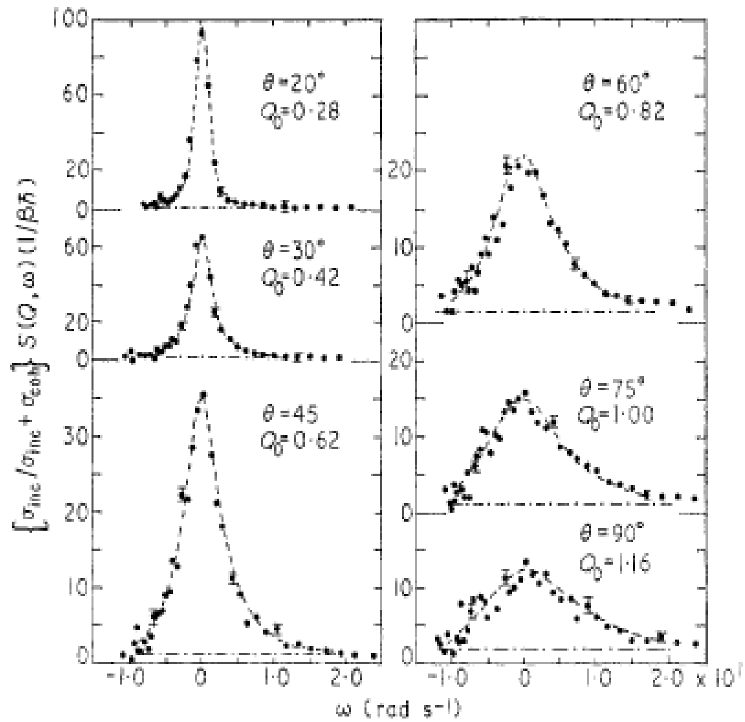
Atomic diffusion

For long times compared to the collision time, atom diffuses



$$\langle r^2(t)\rangle \approx 6Dt$$

Liquid Na



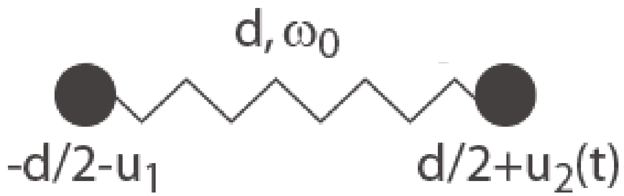
Cocking, *J. Phys. C* **2**, 2047 (1969)..

Auto-correlation function

$$G_s(r,t) = \left\{6\pi\langle r^2(t)\rangle\right\}^{-3/2} \exp\left(-\frac{r^2}{6\langle r^2(t)\rangle}\right)$$

$$S(Q,\omega) = \frac{1}{\pi\hbar}\exp\left(\frac{\hbar\omega}{2k_BT}\right)\frac{DQ^2}{\omega^2 + (DQ^2)^2}$$

Diatomic molecule



$$R_1(0) = -\frac{d}{2} - u(0)$$
$$R_2(t) = \frac{d}{2} + u(t)$$

$$u(t) = \sqrt{\frac{\hbar}{2M\omega_0}}\left[\hat{a}e^{-i\omega_0 t} + \hat{a}^{+}e^{i\omega_0 t}\right]$$

$$S(Q,\omega) = \frac{1}{2\pi\hbar N}\int_{-\infty}^{\infty} dt e^{-i\omega t}\sum_{jj'}\left\langle \exp\left(-iQR_{j'}(0)\right)\exp\left(iQR_j(t)\right)\right\rangle$$

$$S(Q,\omega) = \frac{1}{2\pi\hbar}e^{-Q^2\langle u^2\rangle}\int_{-\infty}^{\infty} dt e^{-i\omega t}\left[e^{Q^2\langle u(0)u(t)\rangle} + \cos(Qd)e^{-Q^2\langle u(0)u(t)\rangle}\right]$$

SHO correlation functions

$$\langle u^2\rangle = \frac{\hbar}{2M\omega_0}\coth(\hbar\omega_0\beta)$$

$$\langle u(0)u(t)\rangle = \frac{\hbar}{2M\omega_0}\left[\left(1+\frac{1}{e^{\hbar\omega_0\beta}-1}\right)e^{i\omega_0 t} + \frac{1}{e^{\hbar\omega_0\beta}-1}e^{-i\omega_0 t}\right] = \frac{\hbar}{2M\omega_0}\frac{\cosh\omega_0(it+\hbar\beta/2)}{\sinh(\hbar\omega_0\beta/2)}$$

$$e^{y\cosh x} = \sum_{n=-\infty}^{\infty} I_n(y)e^{nx} \qquad y = \frac{\hbar Q^2}{2M\omega_0}\operatorname{csch}\left(\frac{1}{2}\hbar\omega_0\beta\right)$$

Diatomic molecule

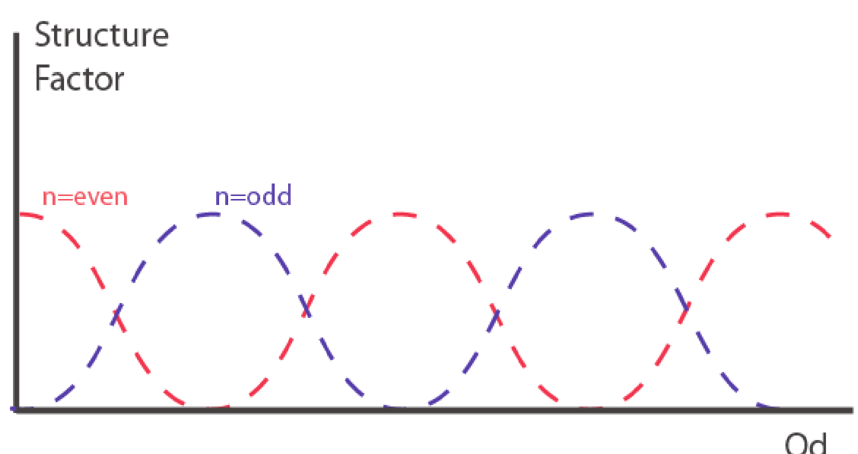
$$S(Q,\omega)=\frac{1}{\hbar}e^{-Q^2\langle u^2\rangle}e^{\hbar\omega\beta/2}\sum_{n=-\infty}^{\infty}\left[1+(-1)^n\cos(Qd)\right]I_n(y)\,\delta(\omega-n\omega_0)$$

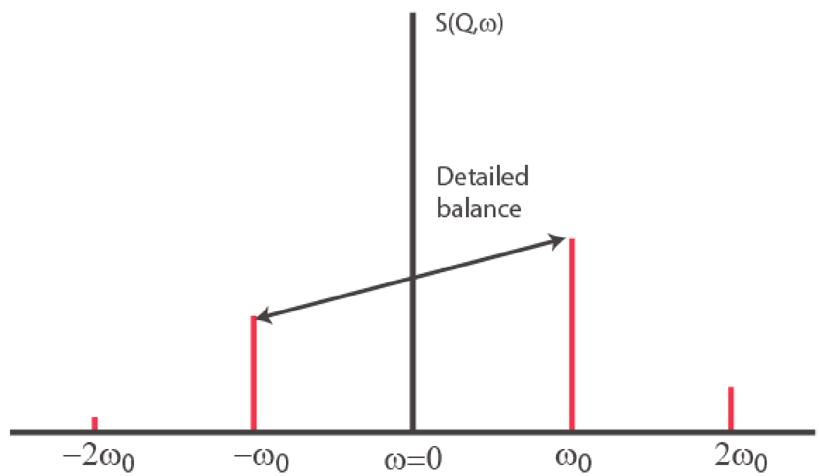
Debye-Waller — Detailed balance — Structure factor — Form factor — Excitation energy

Small-amplitude approximation, y small

$$S(Q,\omega)\approx\frac{1}{\hbar}e^{-Q^2\langle u^2\rangle}\left\{\left[1+\cos(Qd)\right]\delta(\omega)+\frac{Q^2}{2M\omega_0}\left[1-\cos(Qd)\right]\left[\left(\frac{1}{2}\pm\frac{1}{2}+n(\omega_0)\right)\delta(\omega\mp\omega_0)\right]+\dots\right\}$$

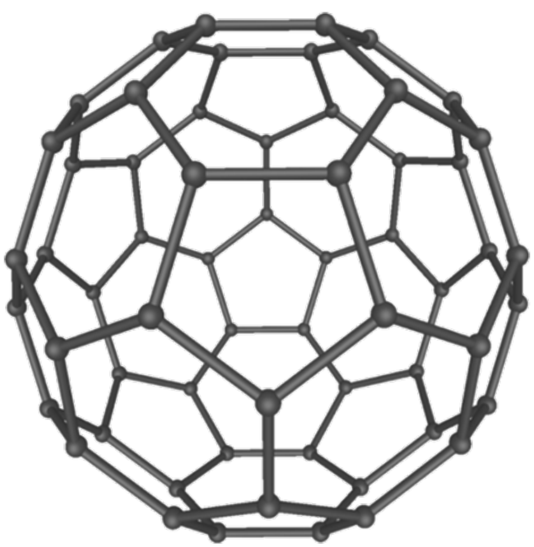
Elastic scattering — One quantum — Multi-quanta



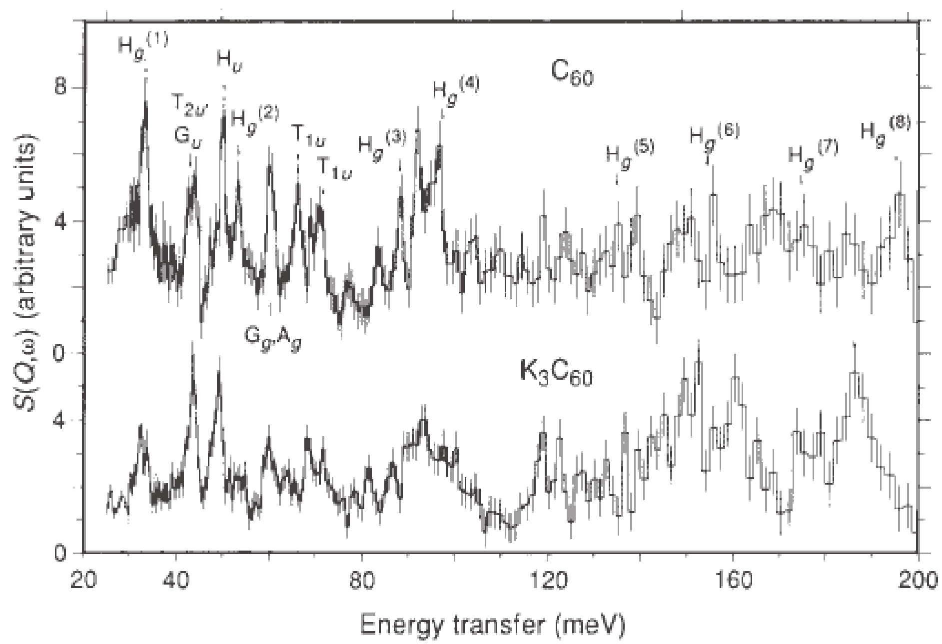


Molecular vibrations

- Large molecule, many normal modes
- Harmonic vibrations can determine interatomic potentials



C60 molecule



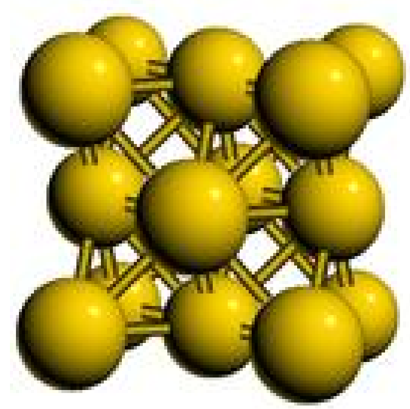
Prassides *et al., Nature* **354**, 462 (1991).

Phonons

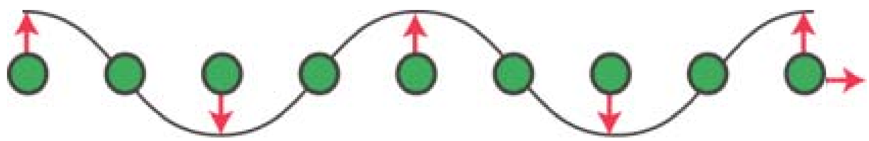
- Normal modes in periodic crystal → wavevector

$$\mathbf{u}(l,t) = \frac{1}{\sqrt{NM}} \sum_{j\mathbf{q}} \varepsilon_j(\mathbf{q}) \exp(i\mathbf{q}\cdot\mathbf{l}) \hat{B}(\mathbf{q}j,t)$$

- Energy of phonon depends on **q** and polarization

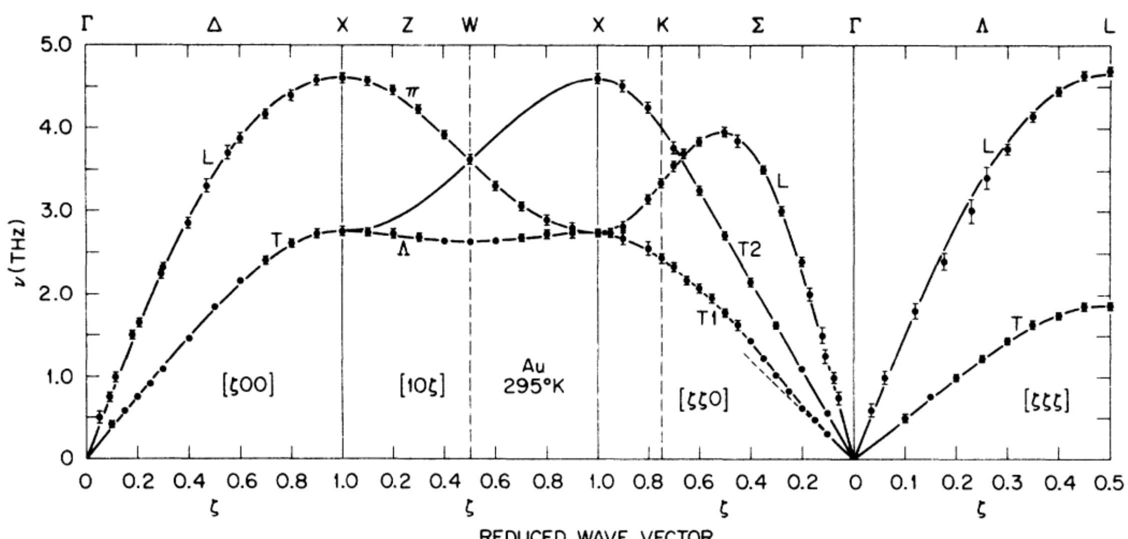


FCC structure

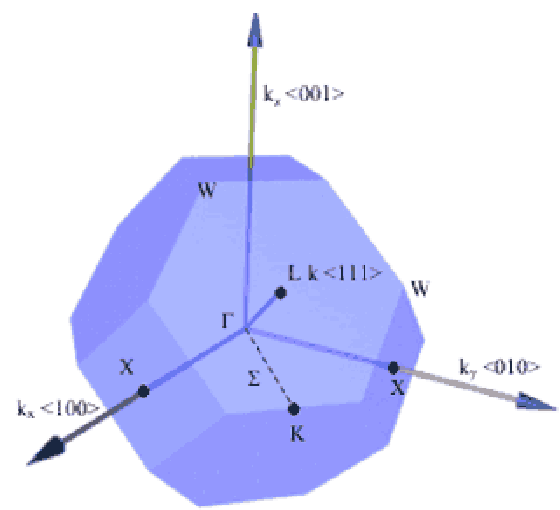


Longitudinal mode

Transverse mode



Lynn, *et al*., *Phys. Rev. B* **8**, 3493 (1973).

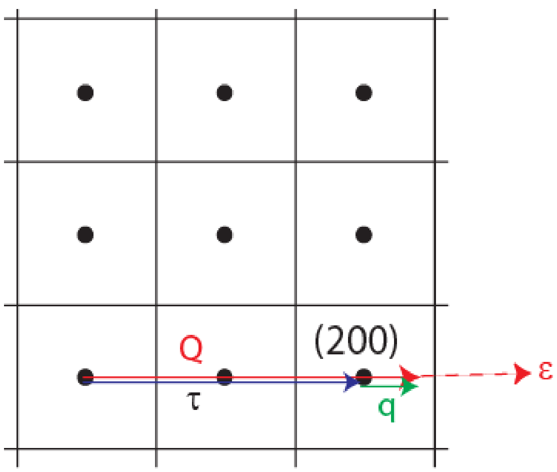


FCC Brillouin zone

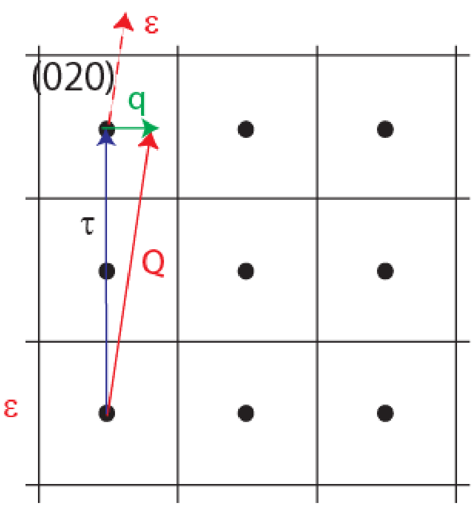
Phonon intensities

Structure (polarization) factor

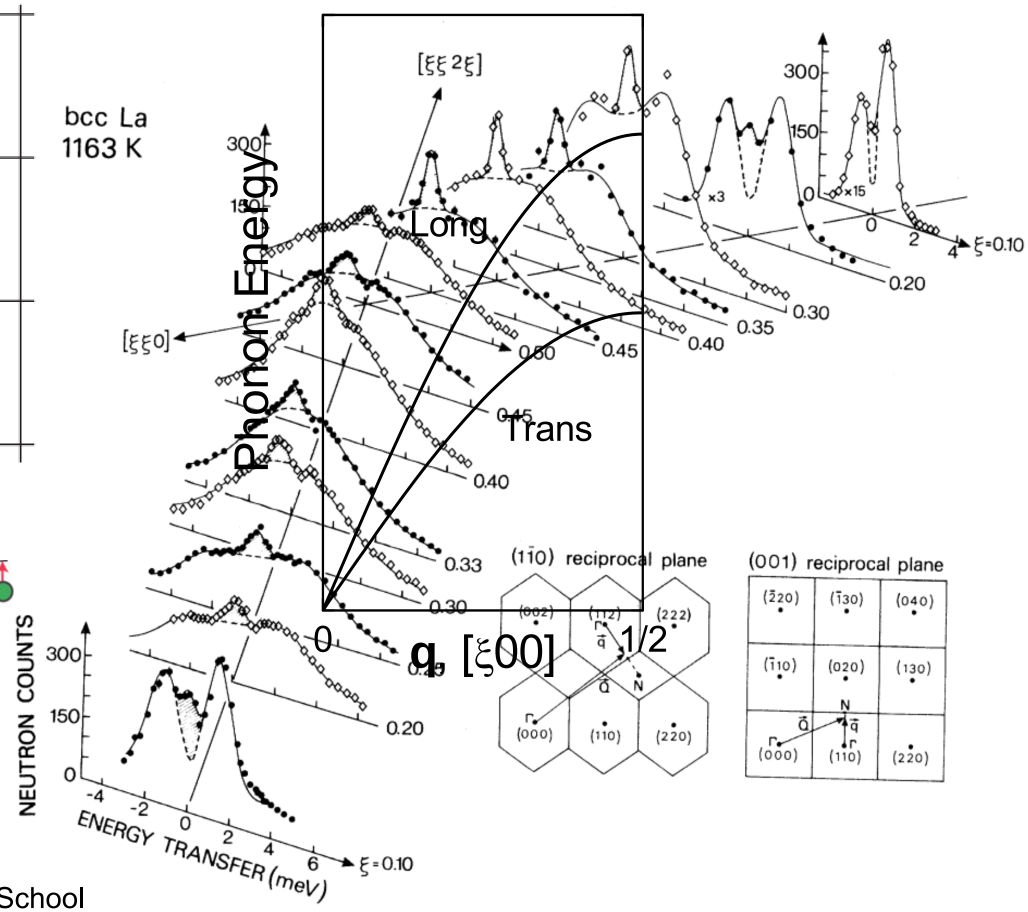
$$S_{1+}(\mathbf{Q},\omega)=\frac{1}{2NM}e^{-Q^2\langle u^2\rangle}\sum_{j\mathbf{q}}\frac{\left|\mathbf{Q}\cdot\boldsymbol{\varepsilon}_j(\mathbf{q})\right|^2}{\omega_j(\mathbf{q})}(1+n(\omega))\delta(\mathbf{Q}-\mathbf{q}-\boldsymbol{\tau})\delta(\omega-\omega_j(\mathbf{q}))$$



Longitudinal scan, **q** || ε

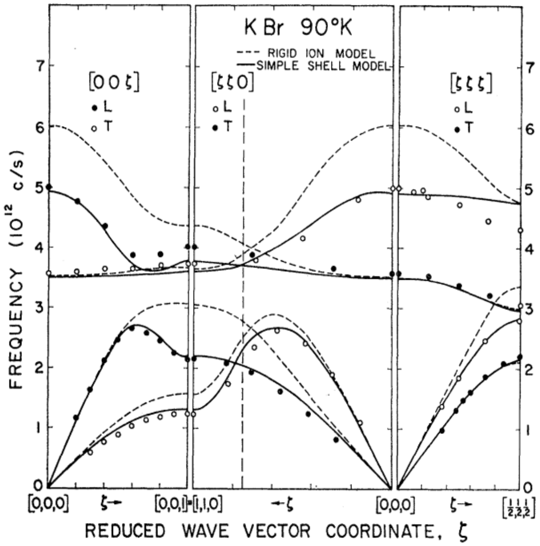


Transverse scan, **q** ⊥ ε

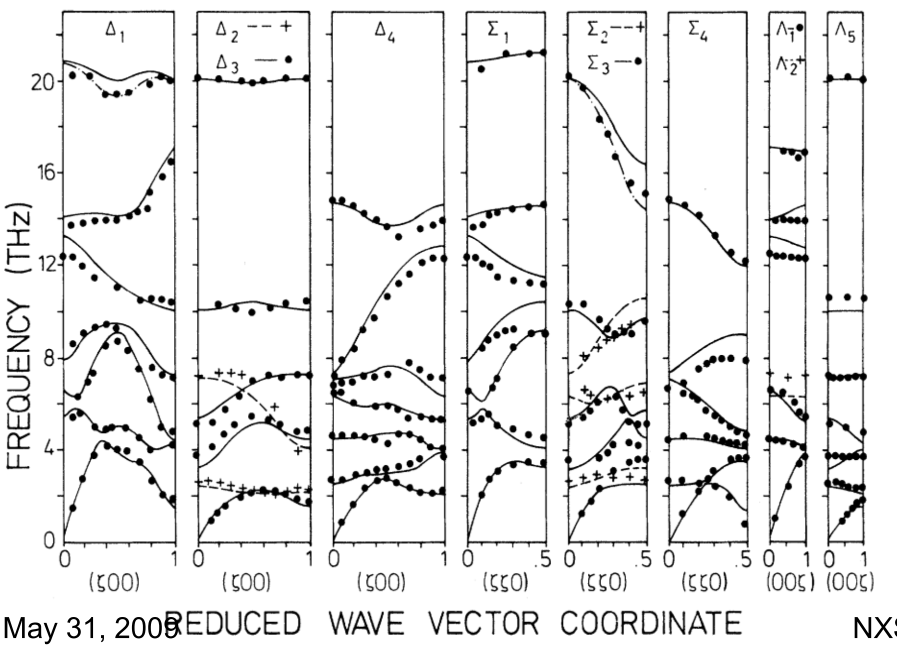


Guthoff *et al.*, *Phys. Rev. B* **47**, 2563 (1993).

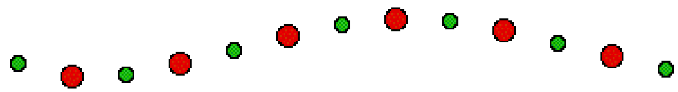
More complicated structures



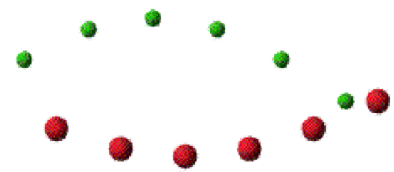
Woods, *et al., Phys. Rev*. **131**, 1025 (1963).



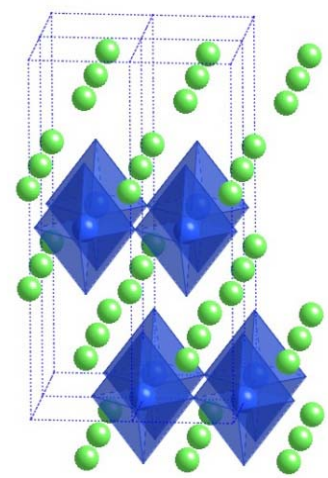
Chaplot, *et al., Phys. Rev*. B **52**, 7230(1995).



Acoustic phonon



Optical phonon



La_2CuO_4

Spin correlation functions

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$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{k_f}{k_i}\left[\frac{1}{2}\gamma r_0 g F(Q)\right]^2 \sum_{\alpha\beta}\left(\delta_{\alpha\beta} - \hat{Q}_\alpha \hat{Q}_\beta\right)\sum_{jj'} e^{i\mathbf{Q}\cdot(\mathbf{R}_{j'}-\mathbf{R}_j)} \frac{1}{2\pi\hbar}\int dt e^{-i\omega t}\left\langle S_j^\alpha(0) S_{j'}^\beta(t)\right\rangle$$

Scattering cross-section — Dipole interaction — Spin-spin correlation function

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right|_{inel} = \frac{k_f}{k_i}\left[\frac{1}{2}\gamma r_0 g F(Q)\right]^2 \sum_{\alpha\beta}\left(\delta_{\alpha\beta} - \hat{Q}_\alpha \hat{Q}_\beta\right)\left(1 - e^{\hbar\omega/kT}\right)^{-1} \frac{1}{\pi (g\mu_B)^2} \mathrm{Im}\left\{\chi^{\alpha\beta}(\mathbf{Q},\omega)\right\}$$

The cross-section is proportional to the magnetic susceptibility,
i.e. it is the response of the system to spatially & time varying magnetic field

Spin excitations

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- **Spin excitations**
  - Spin waves in ordered magnets
  - Paramagnetic & quantum spin fluctuations
  - Crystal-field & spin-orbit excitations
- **Magnetic inelastic scattering can tell us about**
  - Exchange interactions
  - Single-ion and exchange anisotropy (determine Hamiltonian)
  - Phase transitions & critical phenomena
  - Quantum critical scaling of magnetic fluctuations
  - Other electronic energy scales (eg. CF & SO)
  - Interactions (eg. spin-phonon coupling)

Paramagnetic scattering

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$$\left\langle S_j^{\alpha} S_{j'}^{\beta} \right\rangle = 0 \; (j \neq j')$$

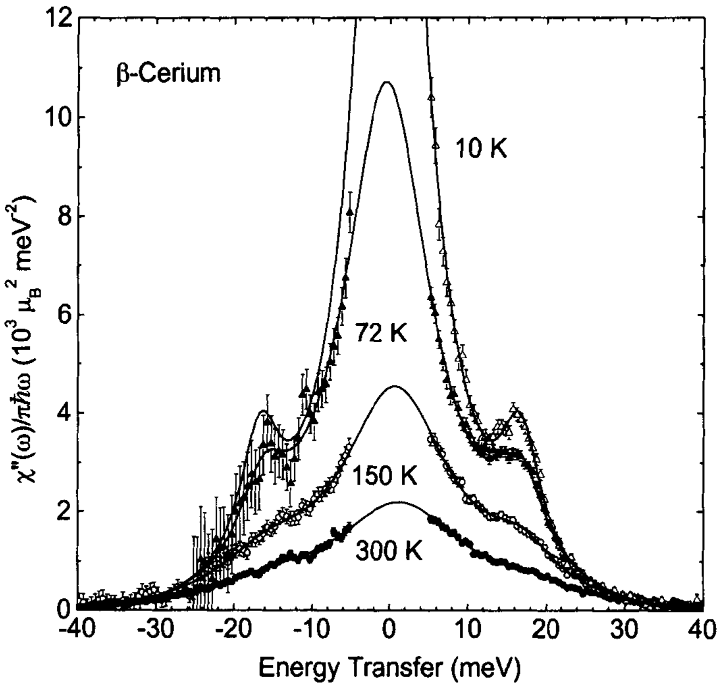
Single ion scattering

$$\left\langle S_j^z(0) S_j^z(t) \right\rangle = \left\langle \left(S_j^z\right)^2 \right\rangle e^{-\Gamma t} = \frac{1}{3}\left\langle \left(\mathbf{S}_j\right)^2 \right\rangle e^{-\Gamma t} = \frac{1}{3} S(S+1) e^{-\Gamma t}$$

$$\frac{\operatorname{Im}\{\chi^{zz}(0,\omega)\}}{\pi \hbar\omega} = \frac{g^2 S(S+1)\mu_B^2}{3k_B T} \frac{1}{\pi} \frac{\Gamma}{\Gamma^2 + (\hbar\omega)^2}$$

- Inverse width, 1/Γ, gives relaxation time
- Note crystal field excitation

$$\chi_0 = \int_{-\infty}^{\infty} \frac{\operatorname{Im}\{\chi^{zz}(0,\omega)\}}{\pi \hbar\omega} d\omega = \frac{g^2 S(S+1)\mu_B^2}{3k_B T}$$



McQueeney *et al., Phil. Mag.* B **81**, 675 (2001).

Spin waves

$$H = -\sum_{<i,j>} J_{ij} \mathbf{S}_{\mathrm{i}} \cdot \mathbf{S}_{\mathrm{j}}$$

Heisenberg Hamiltonian

Linear spin wave theory

$$S^z \approx S$$

$$S^{\pm} = S^x \pm i S^y$$

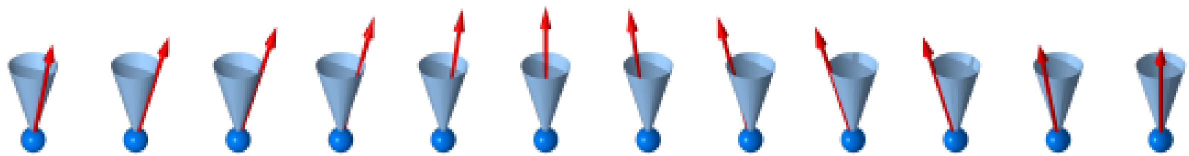
$$S_j^+(t) = \frac{1}{N} \sum_{\mathbf{q}} e^{i\mathbf{Q}\cdot\mathbf{R}_j} S_{\mathbf{q}}^+(t)$$

$$\left\langle S_j^{\alpha}(0) S_{j'}^{\beta}(t) \right\rangle = \left\langle S_j^-(0) S_{j'}^+(t) \right\rangle$$

For a simple ferromagnet

$$\left\langle S_{\mathbf{q}}^-(0) S_{\mathbf{q}}^+(t) \right\rangle = \frac{S}{2N} \left(1 - e^{-\hbar\omega/kT}\right)^{-1} e^{i\omega(\mathbf{q})t}$$

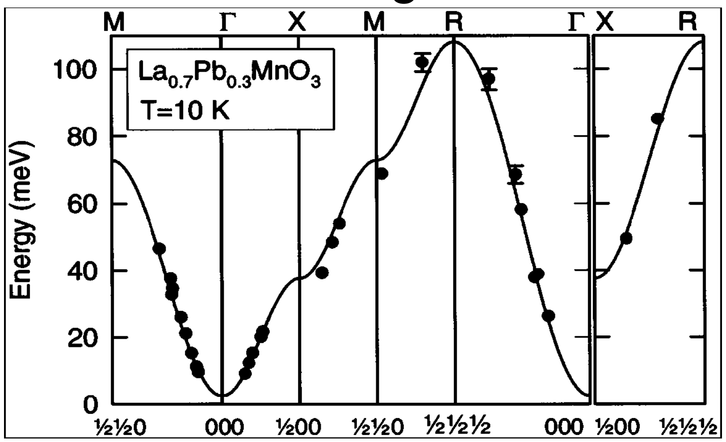
$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{1}{2}\left(1 + \hat{Q}_z^2\right) \frac{k_f}{k_i} \left[\frac{1}{2} g r_0 F(Q)\right]^2 \frac{S}{1 - e^{-\hbar\omega/kT}} \sum_{\mathbf{q}} \delta(\mathbf{Q} - \mathbf{q} - \boldsymbol{\tau}) \delta(\omega - \omega(\mathbf{q}))$$



Linear spin waves

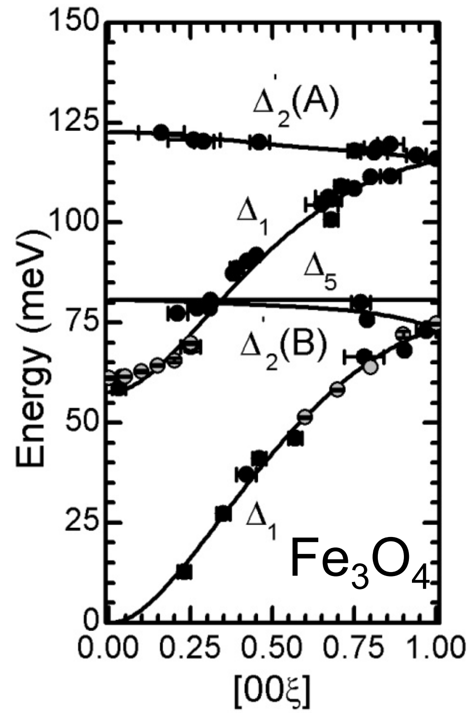
Spin waves

Ferromagnetic



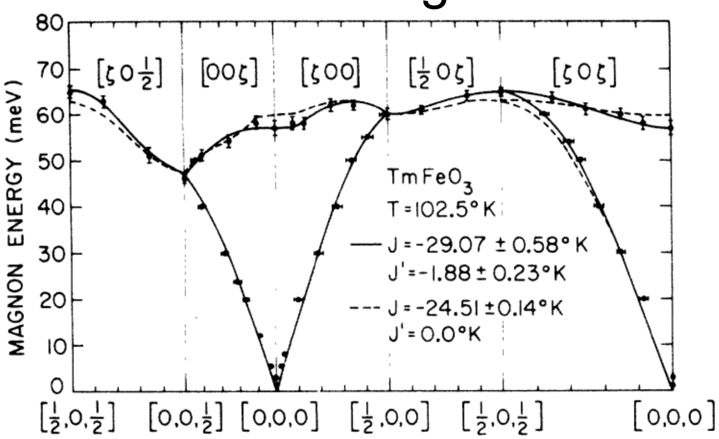
Perring *et al., Phys. Rev*. Lett. **77**, 711 (1996).

Ferrimagnetic



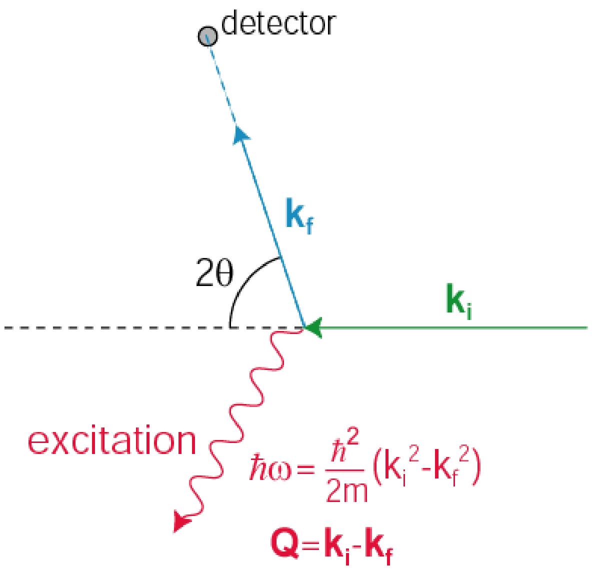
McQueeney *et al., Phys. Rev*. Lett. **99**, 246401 (2007).

Antiferromagnetic

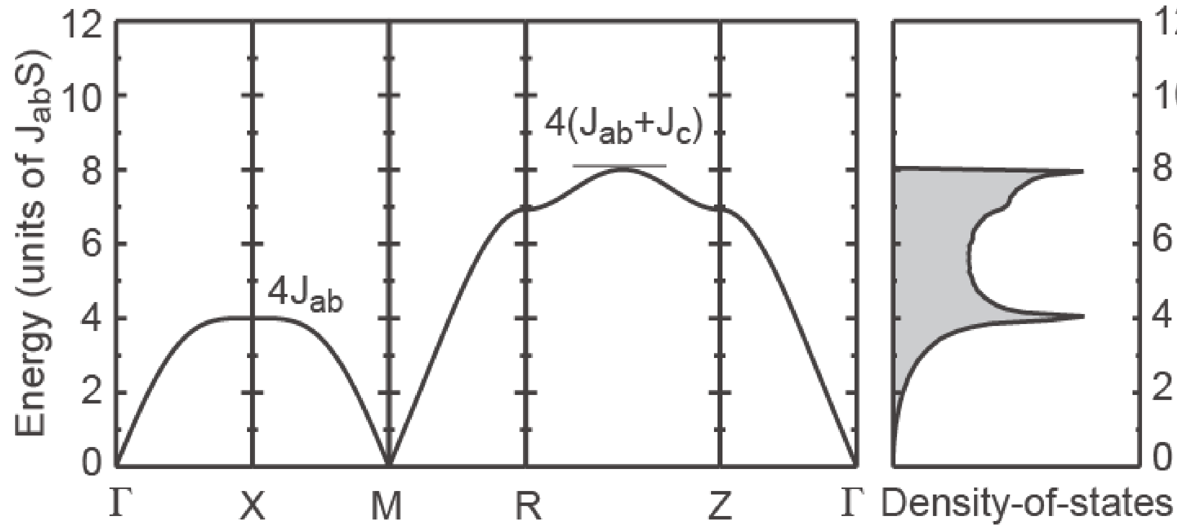


Shapiro *et al., Phys. Rev*. B **10**, 2014 (1974).

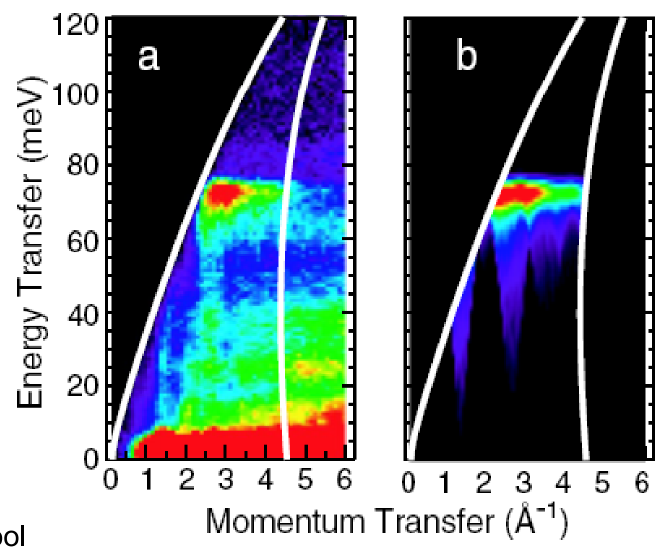
Scattering experiments



Single-crystal



Powder S(|**Q**|,ω)

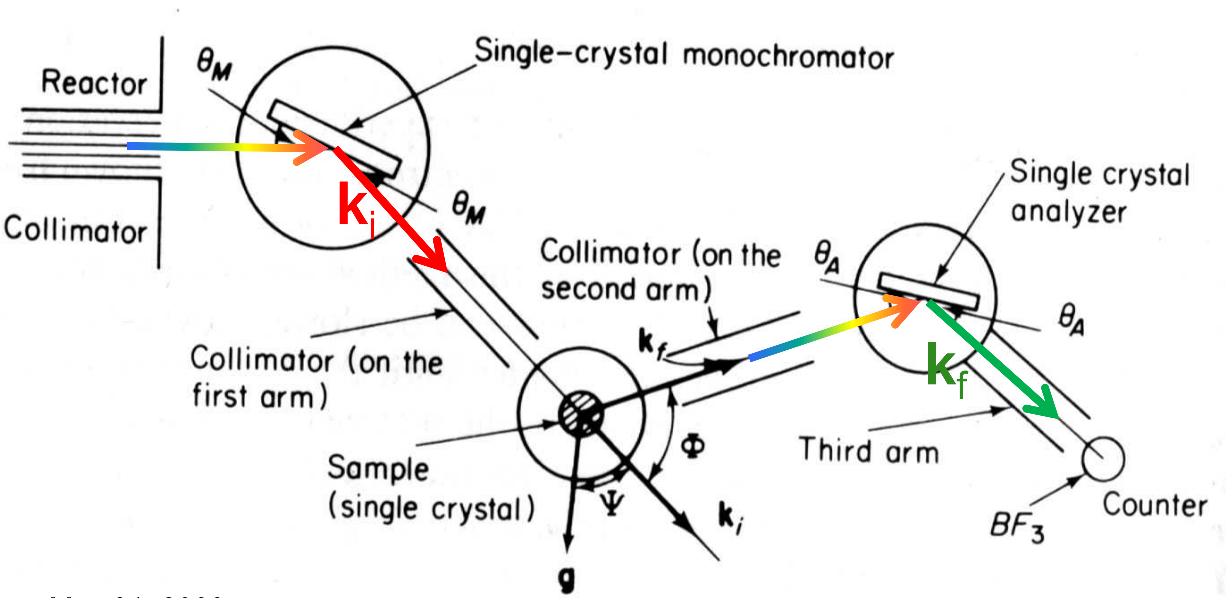


Instrument and sample (powder or single-crystal) determine how (**Q**,ω) space is sampled

Triple-axis instruments

High flux isotope reactor - ORNL

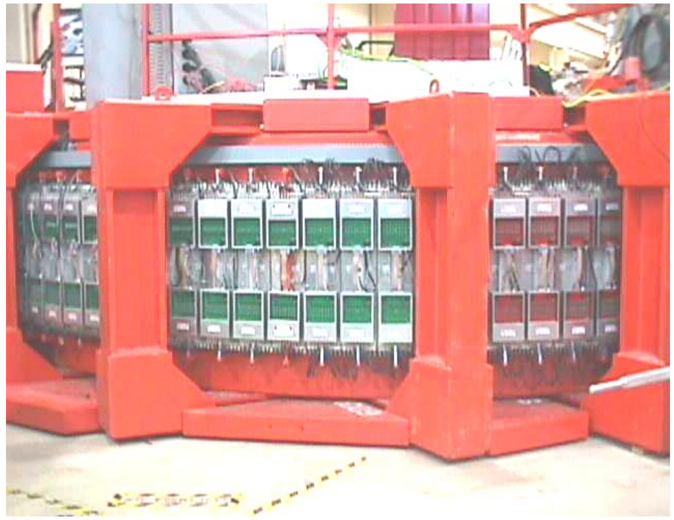
HB-1A 3-axis spectrometer



- Hardware flexibility
- Constant-**Q** (or E) scans
- Ideally suited for single-xtals

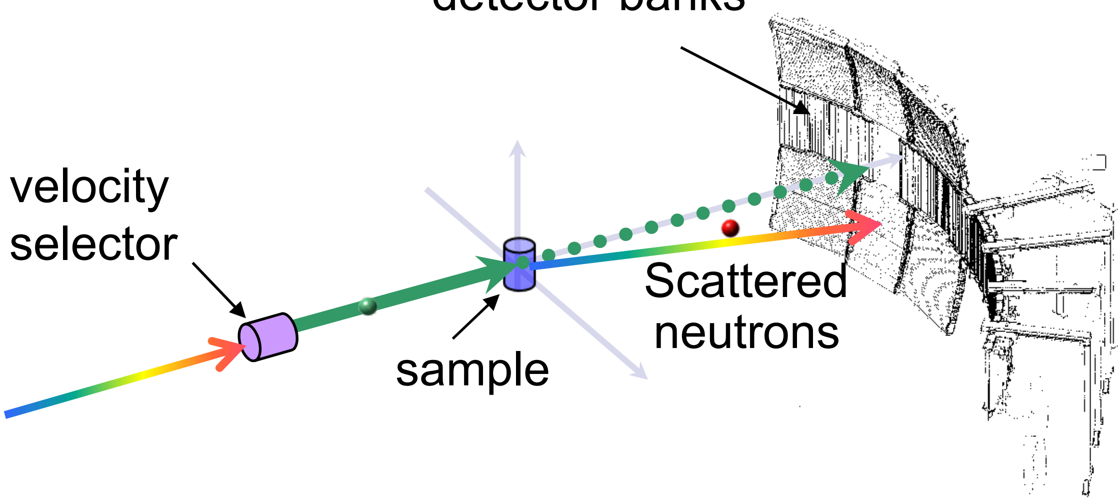
Time-of-flight methods

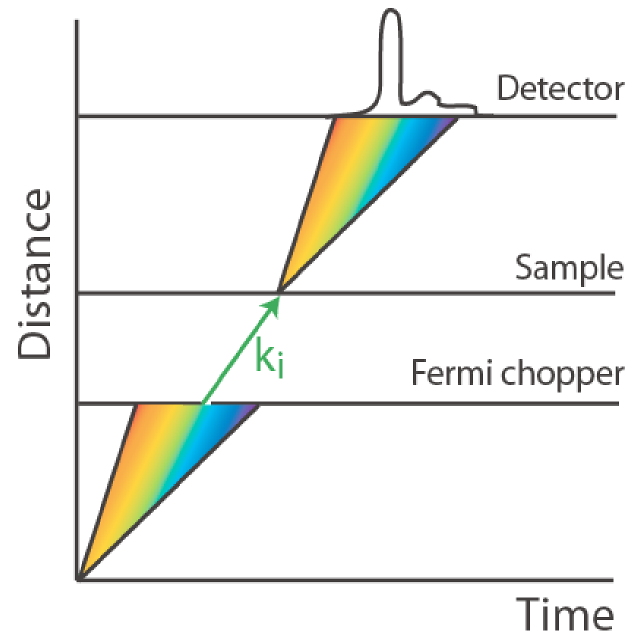
Spallation neutron source



Pharos – Lujan Center

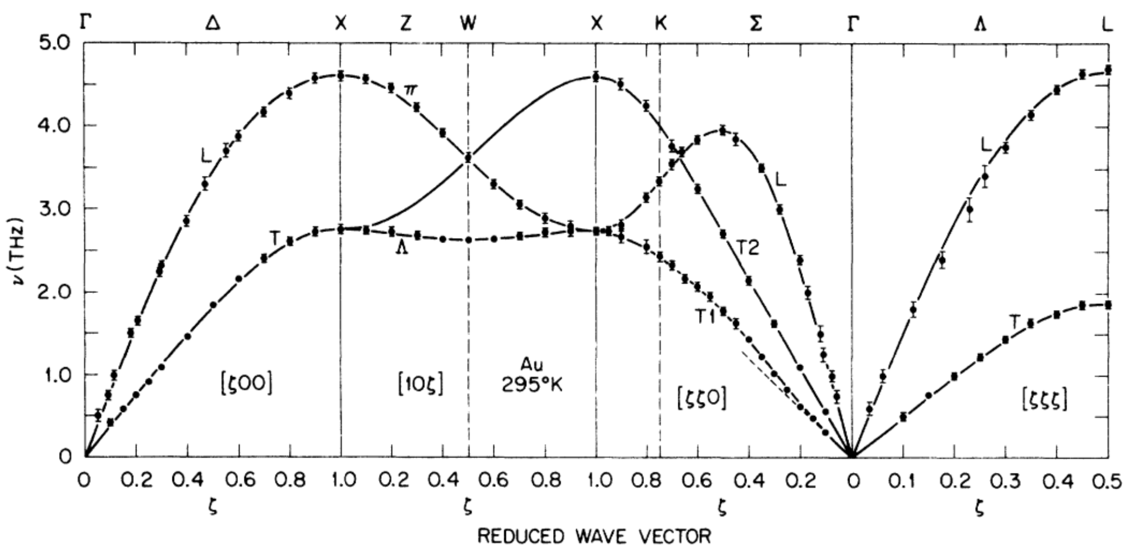
- Hardware inflexible
- Effective for powders
- Complicated **Q**,E-scans a challenge for single-xtals



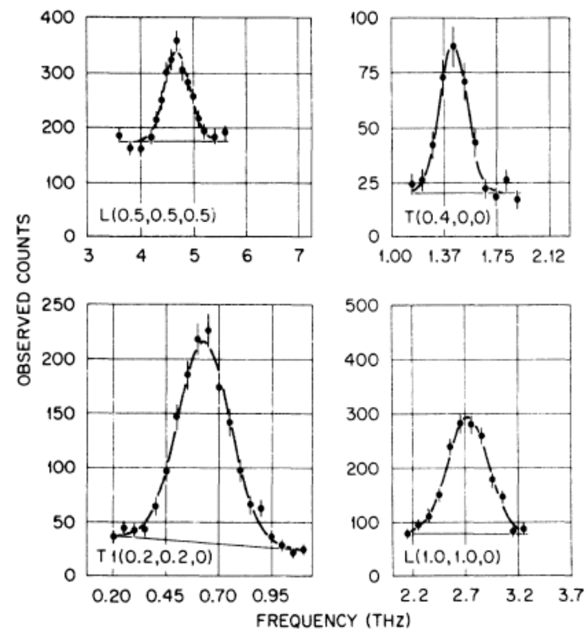


INS data

- Intensities as a function of **Q** and ω



Lynn, *et a*l., *Phys. Rev. B* **8**, 3493 (1973).



Reciprocal space

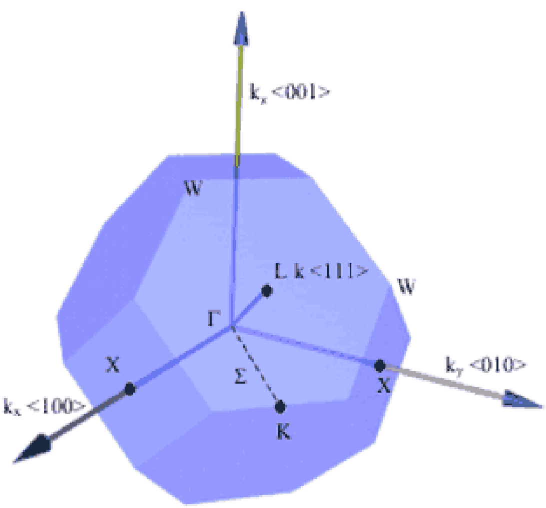
$$\mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f$$

$$h\omega = E_i - E_f$$

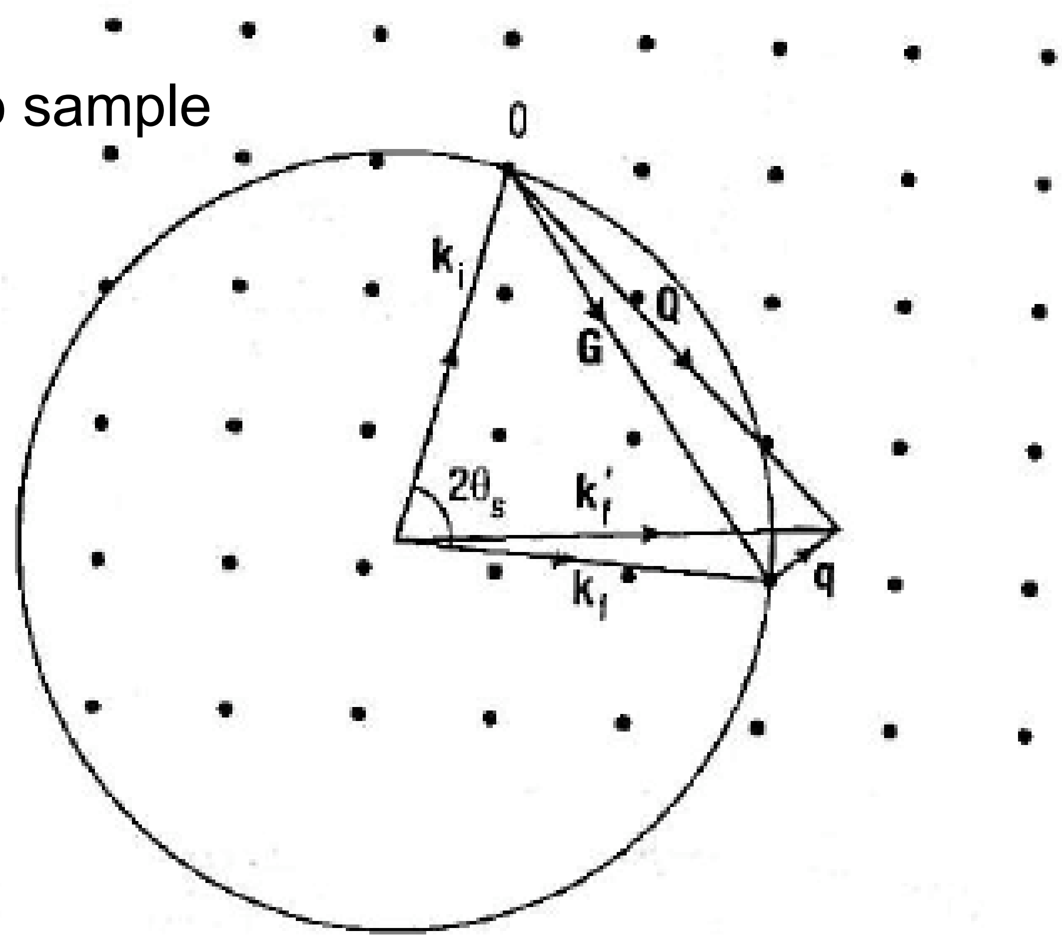
Momentum/energy transferred to sample

$$\mathbf{q} = \mathbf{Q} - \tau$$

Wavevector in 1st Brillouin zone



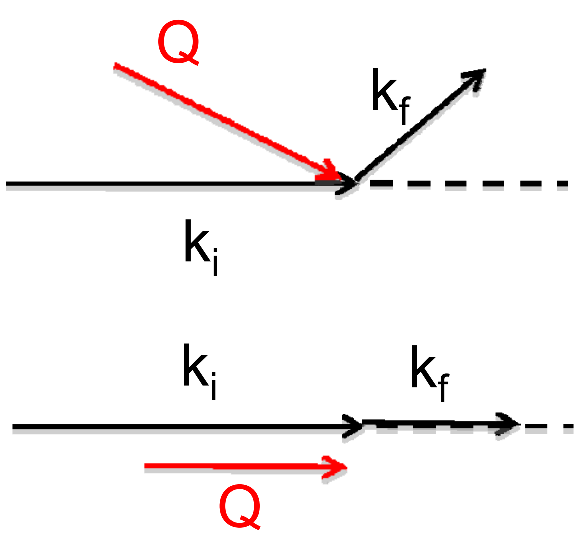
FCC Brillouin zone



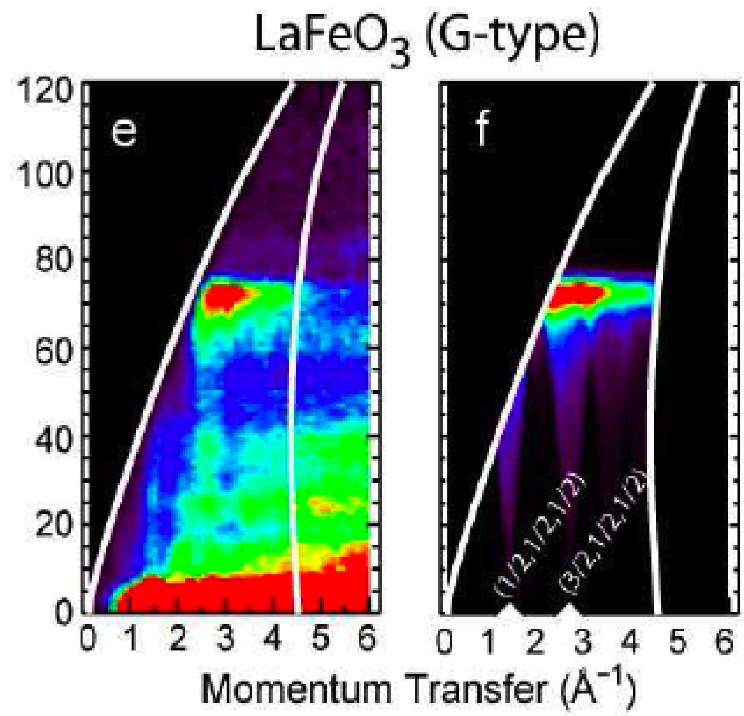
Scattering triangle

Kinematic limitations

- **Many combinations of k_i,k_f for same Q,ω**
  - Only certain configurations are used (eg. E_f-fixed)
- **Cannot "close triangle" for certain Q,ω due to kinematics**



Minimum accessible Q

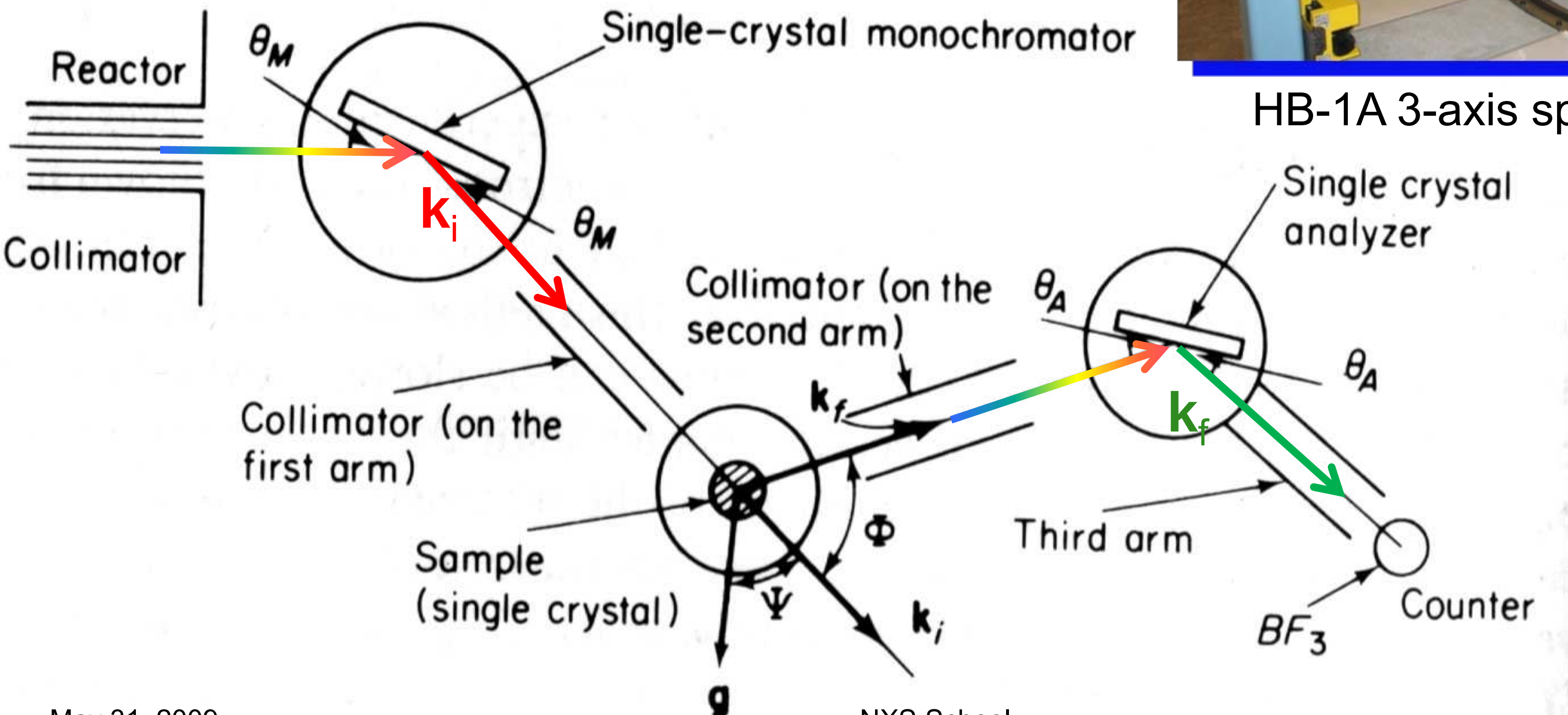


Kinematic limits, E_i=160 meV

Triple-axis instruments

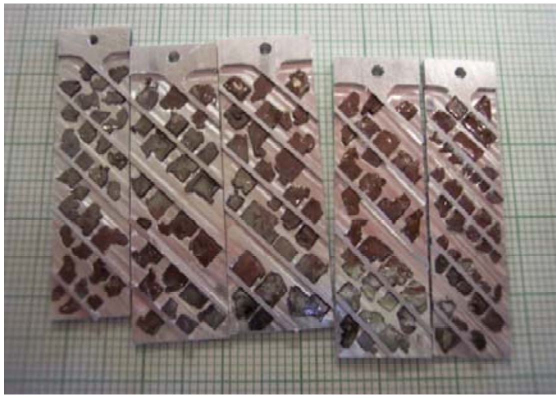
- **Workhorse INS instrument**
  - $\mathbf{k}_i,\mathbf{k}_f$ defined by Bragg scattering
  - Sample goniometer
  - Detector
  - Resolution/collimators

HB-1A 3-axis spectrometer



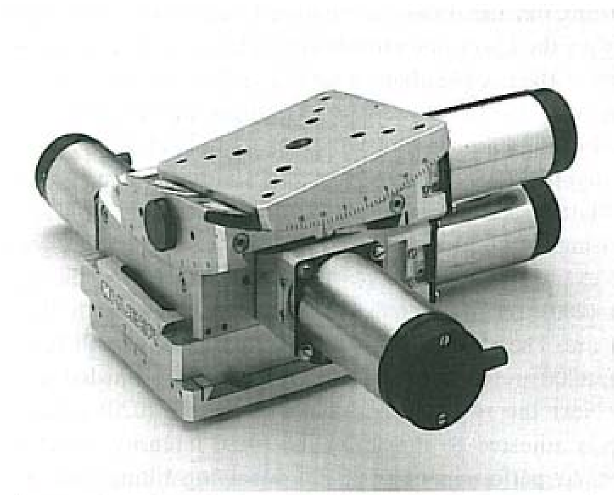
Samples

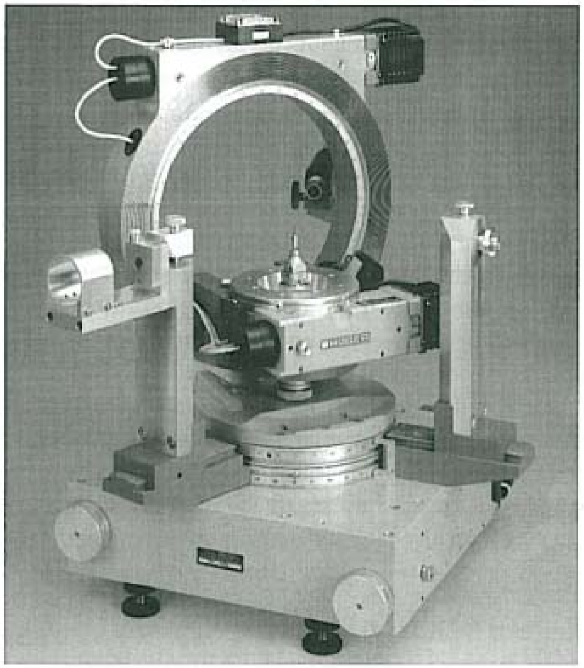
- **Samples need to be BIG**
  - ~ gram or cc
  - Counting times are long (mins/pt)



Co-aligned $CaFe_2As_2$ crystals

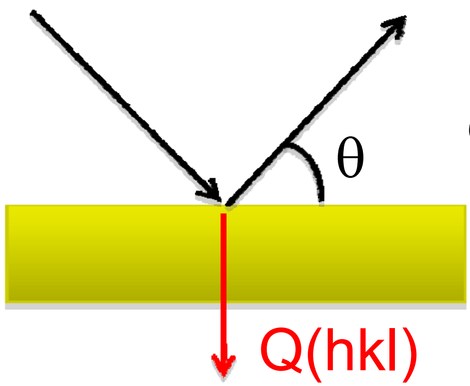
- **Sample rotation**
- **Sample tilt**





Monochromators

- **Selects the incident wavevector**



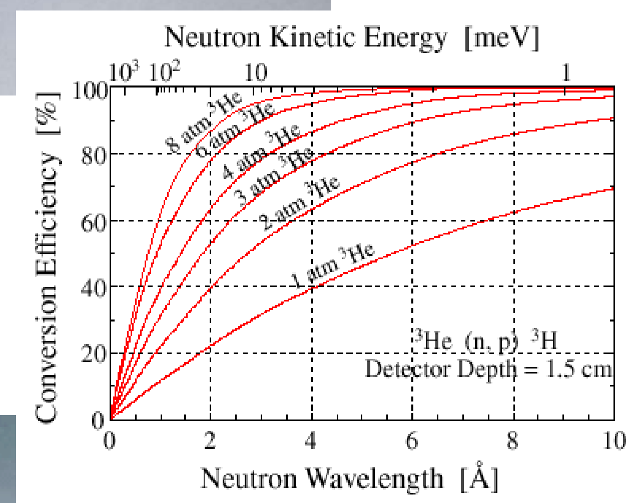
$$Q(hkl) = \frac{2\pi}{d(hkl)} = 2k_i \sin\theta$$

- Reflectivity
- focusing
- high-order contamination eg. $\lambda/2$ PG(004)

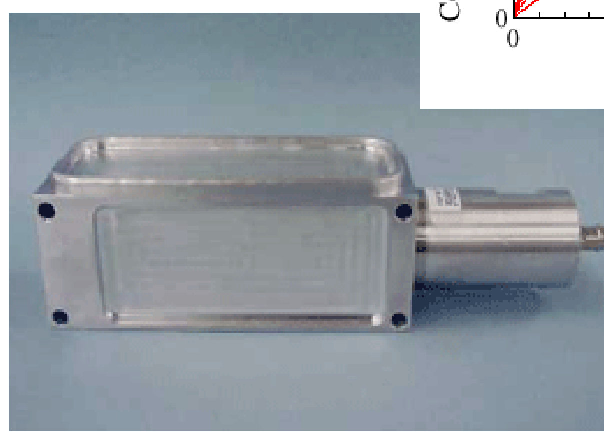
Mono	d(hkl)	uses
PG(002)	3.353	General
Be(002)	1.790	High k_i
Si(111)	3.135	No $\lambda/2$

Detectors

- **Gas Detectors**
- n + ^{3}He → ^{3}H + p + 0.764 MeV
- Ionization of gas
- e$^-$ drift to high voltage anode
- High efficiency

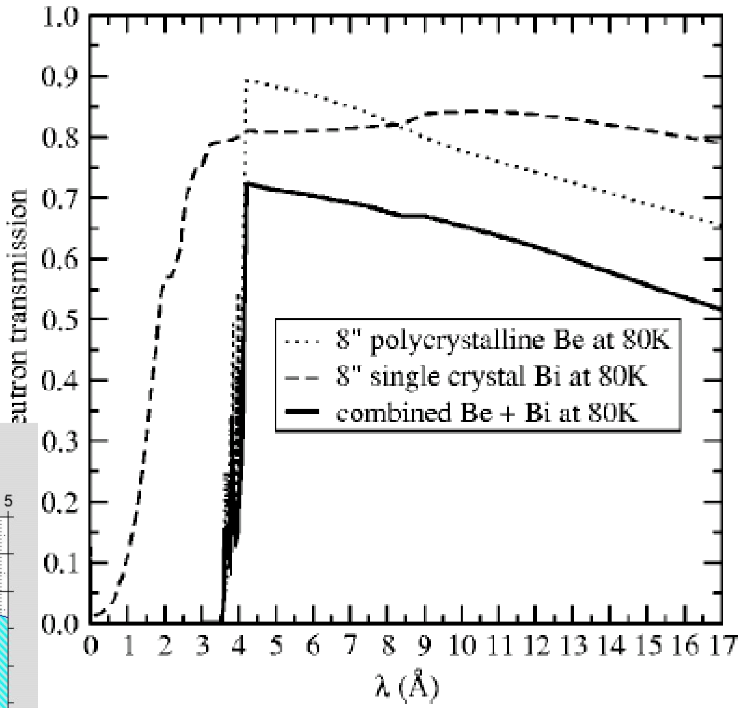


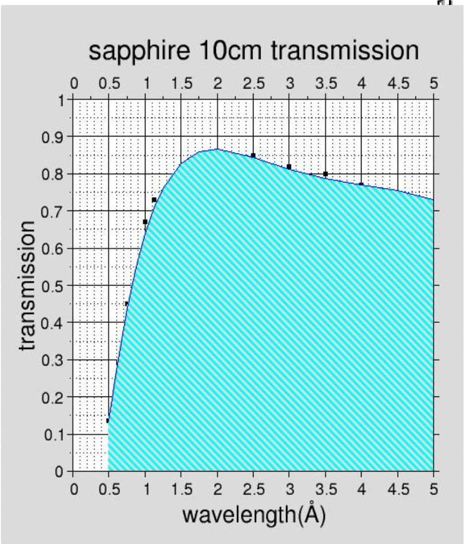
- **Beam monitors**
- Low efficiency detectors for measuring beam flux



Other triple-axis stuff

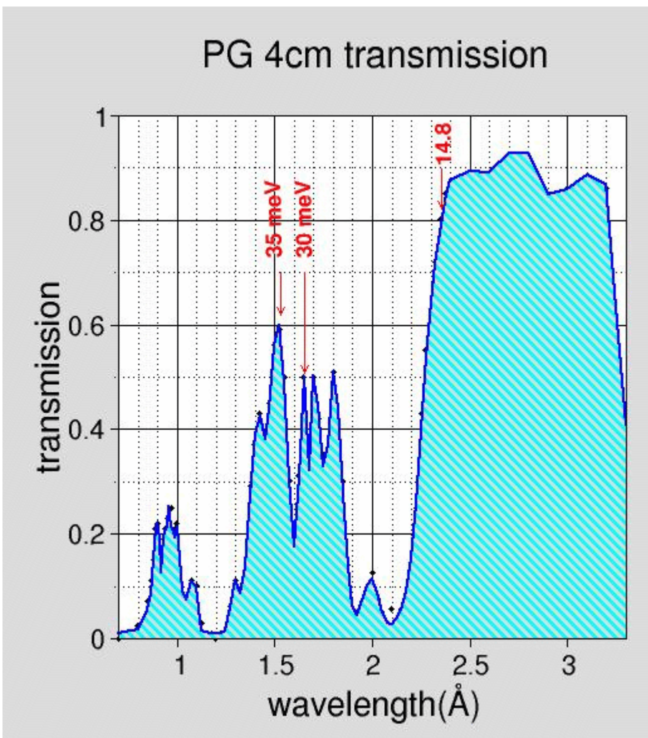
- **Soller Collimators**
  - Define beam divergence
  - Q,ω resolution function
- **Filters**
  - Xtal Sapphire: fast neutron background
  - Poly Be: low-energy (5 meV) band pass
  - PG: higher order contamination
- **Masks**
  - Beam definition
  - Background reduction

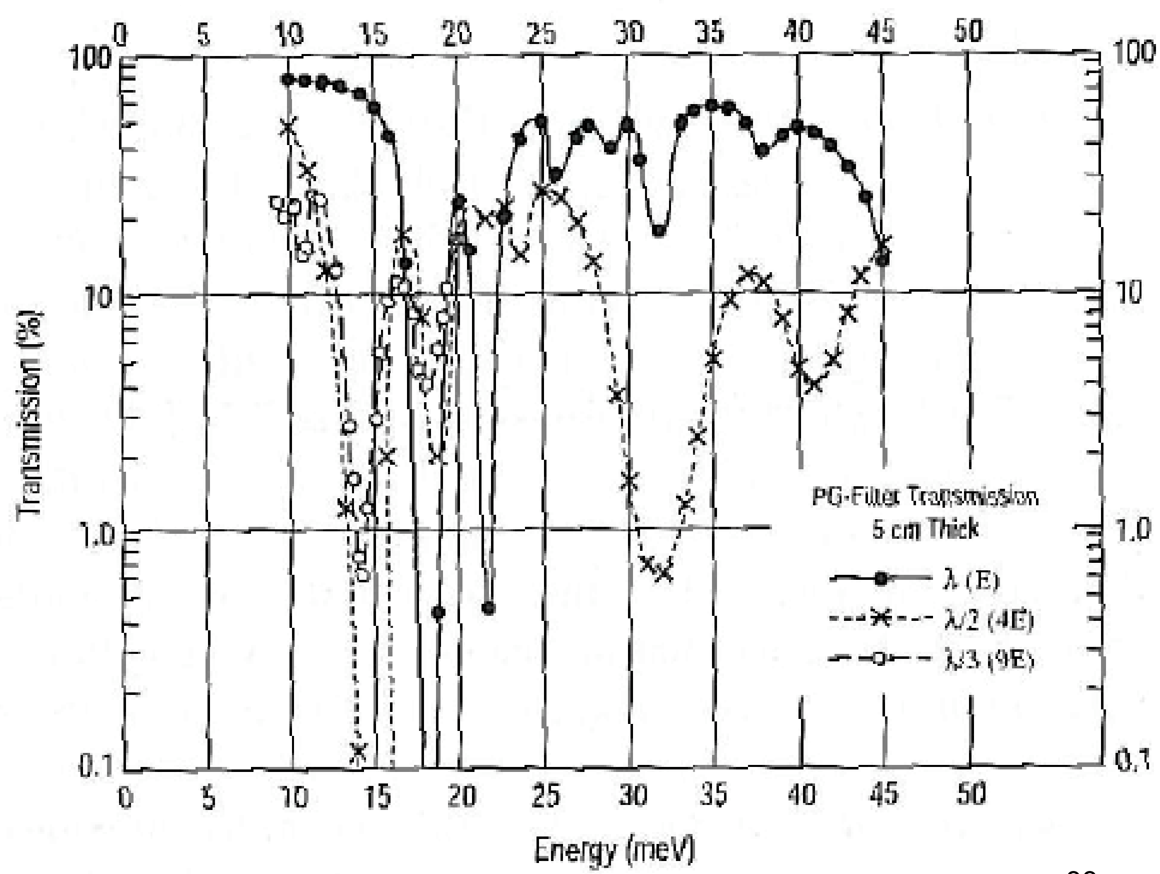




PG filter

- **Magic numbers**
  - Best filter for rejection of λ/2 contamination
  - E_f = 13.7, 14.7, 30.5, 41 meV



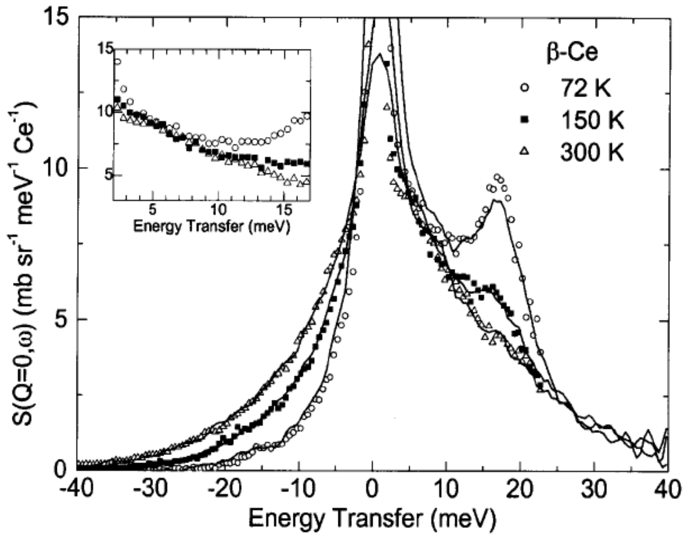


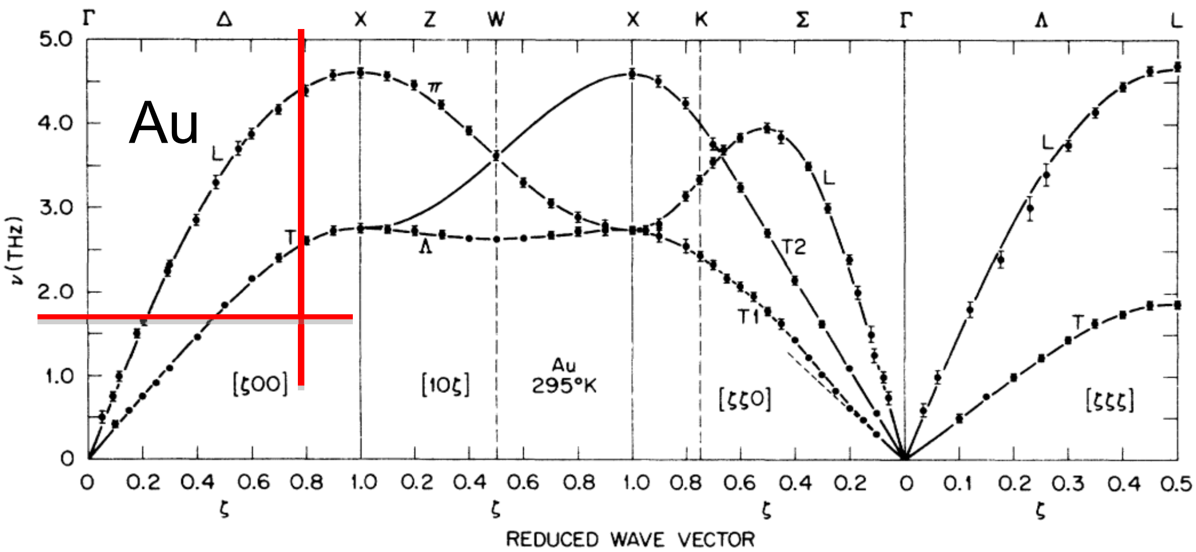
Sample environment

- **Temperature, field, pressure**
- **Heavy duty for large sample environment**
  - CCR
  - He cryostats
  - SC magnets
  - …

Acquiring data

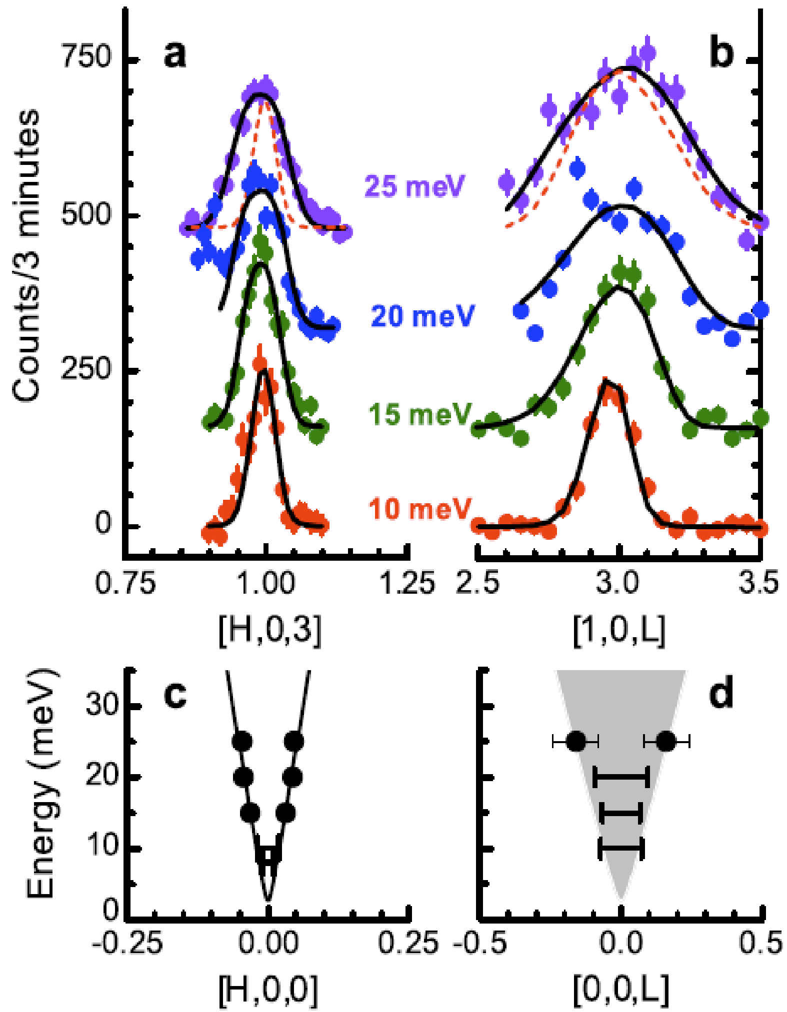
- **Energy gain, energy loss**
  - Detailed balance
- **Constant-Q scans**
  - Most common
- **Constant-ω scans**
  - Used for steep dispersions

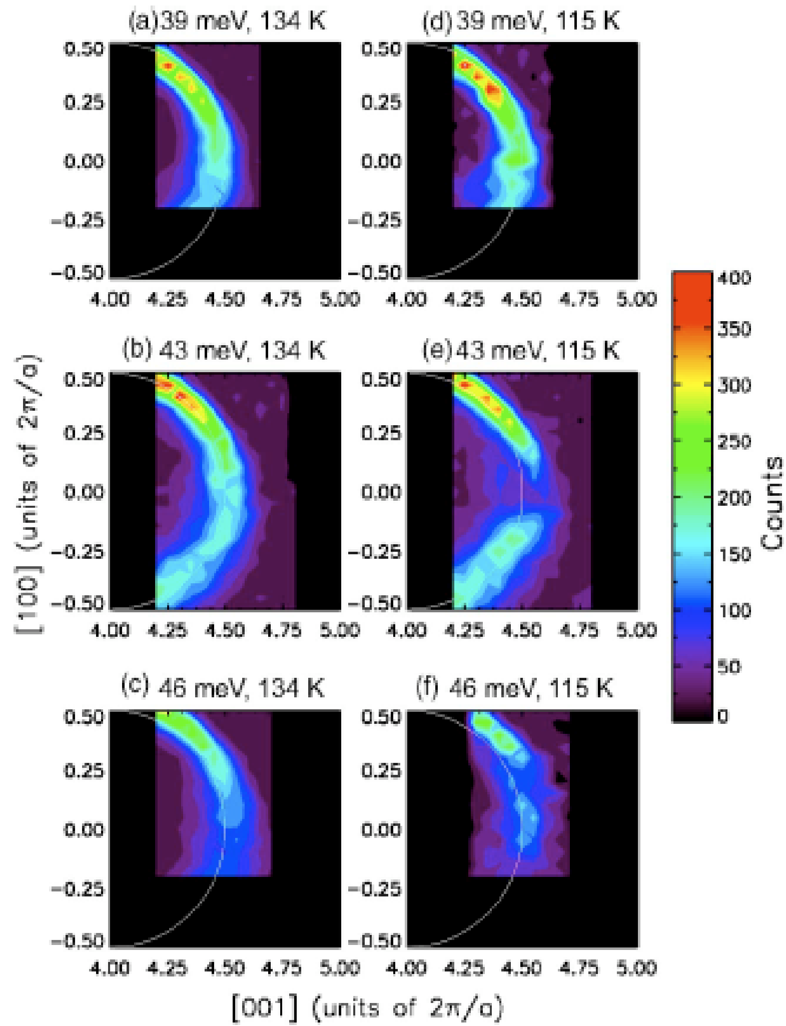




Lynn, *et al.*, *Phys. Rev. B* **8**, 3493 (1973).

Constant-ω scans

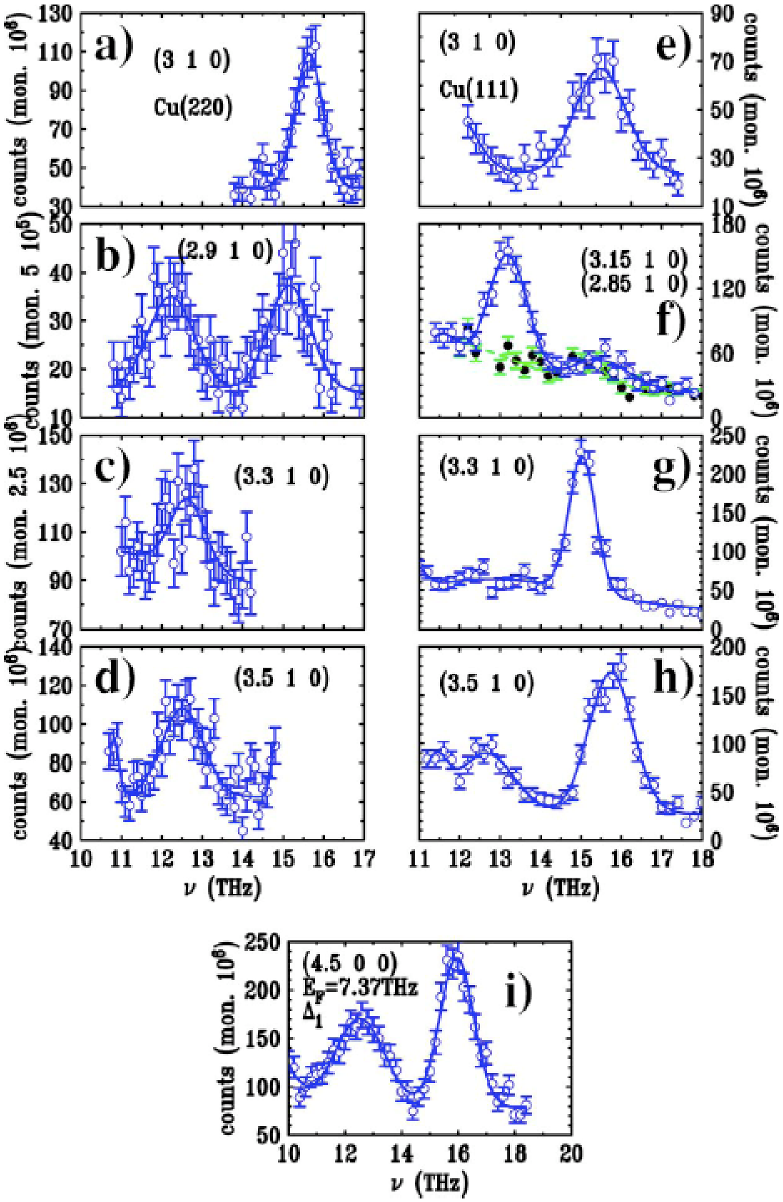


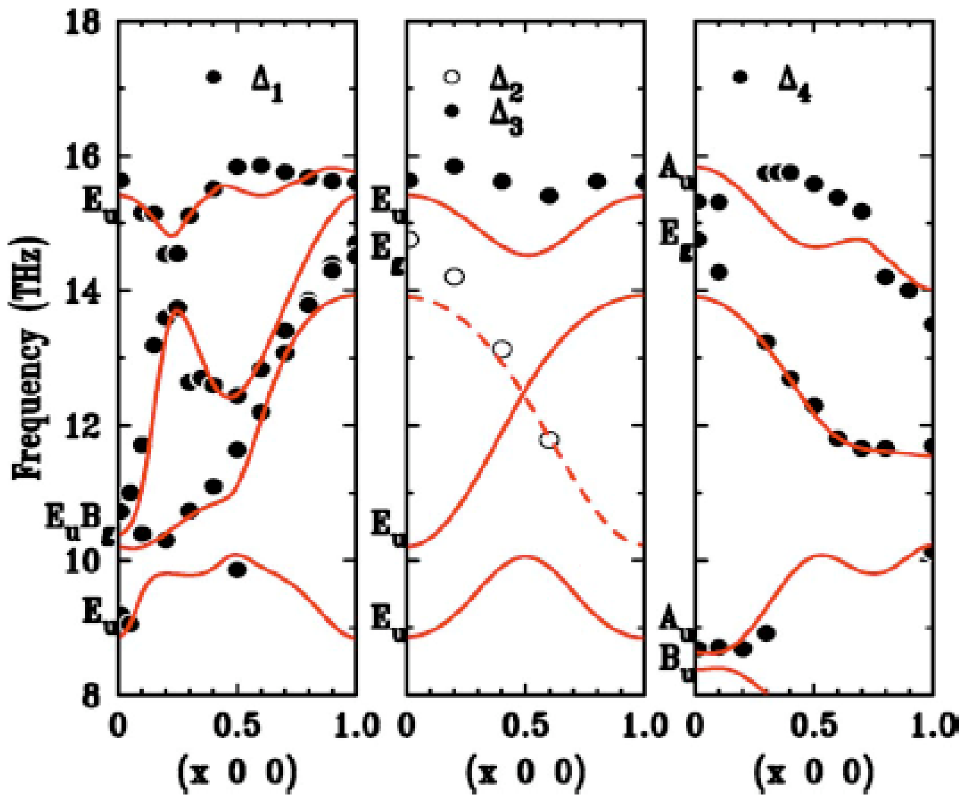


Steep AF spin waves in $CaFe_2As_2$
McQueeney et al, PRL 101, 227205 (2008)

Slice of spin wave cone in Fe_3O_4
McQueeney et al, PRB 73, 174409 (2006)

Constant-Q scans

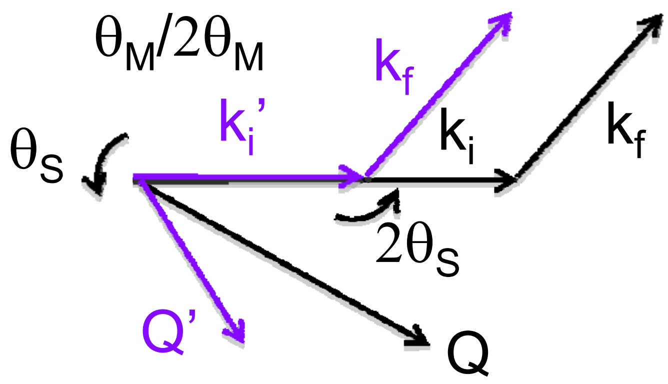




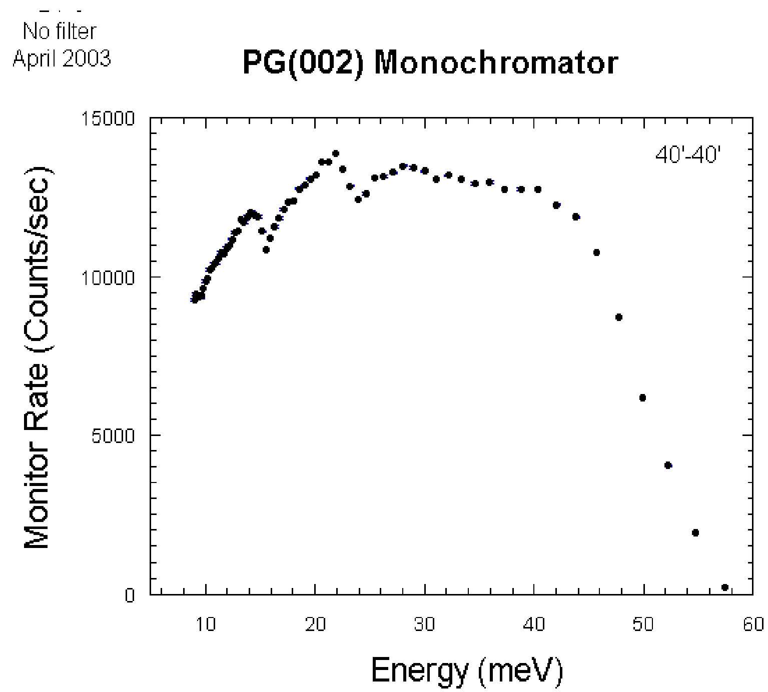
Optical phonons in $Nd_{0.85}Ce_{0.15}CuO_4$
Braden, et al, PRB, 72 184517 (2005).

Configurations

- **E_f-fixed mode**
  - Mono moves during ω-scan
  - Beam monitor accounts for variations in incident flux
- **E_i-fixed mode**
  - Analyzer moves during ω-scan
  - Useful for expts requiring low background
  - Analysis more complicated
- **Magic numbers**
  - λ/2 contamination
  - E_i or E_f = 13.7, 14.7, 30.5, 41 meV



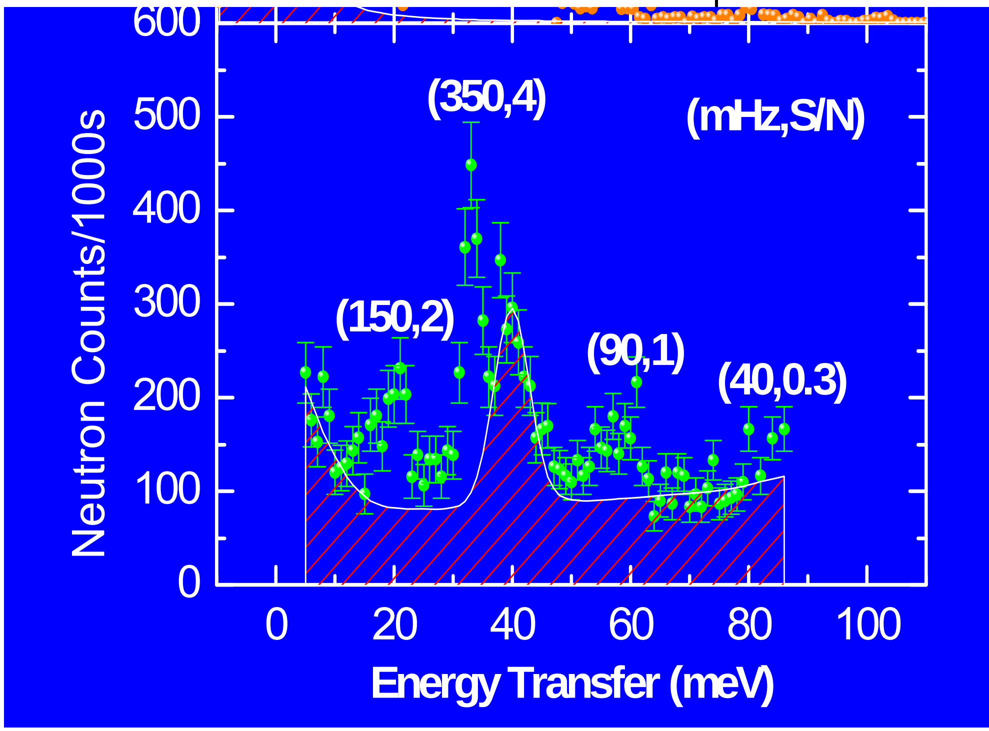
Fixed-E_f mode



Spurions

AMES LABORATORY

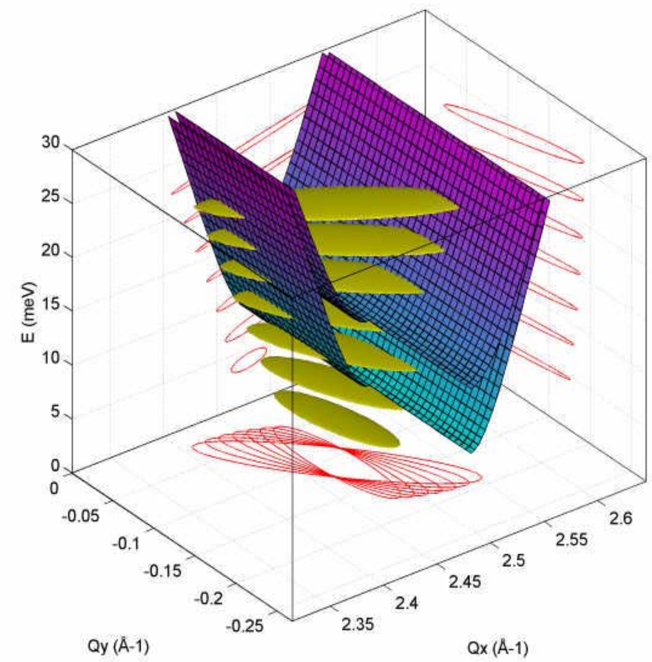
- **Bragg – incoherent – Bragg**
  - Eg. $k_i - 2k_f$
    - $\hbar\omega$ = 41.1 meV
    - E_f = 13.7 meV
      E_i = 54.8 meV
      $4E_f$ = 54.8 meV
    - Incoherent elastic scattering visible from analyzer $\lambda/2$



- **incoherent – Bragg – Bragg**
  - Sample 2θ in Bragg condition for k_f-k_f
  - Even for inelastic config, weak incoherent from mono

Resolution

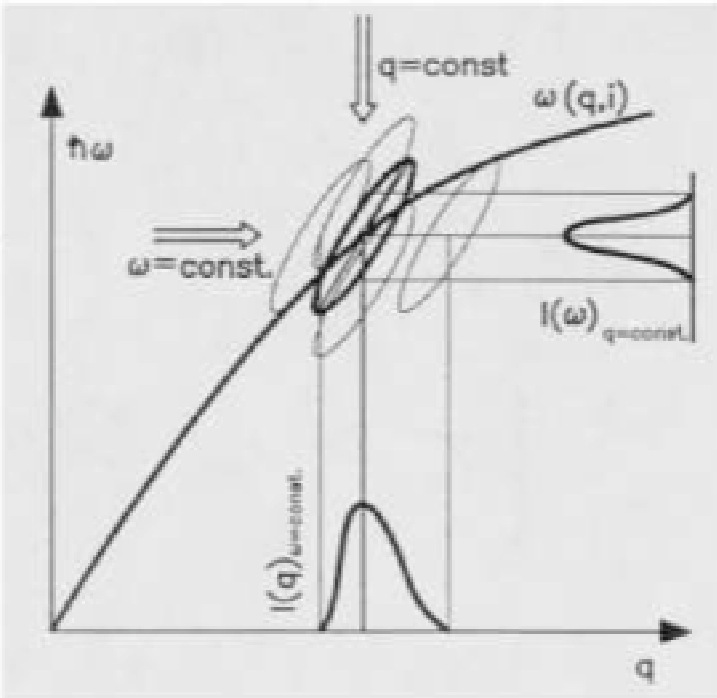
- **Resolution ellipsoid**
  - Beam divergences
  - Collimations/distances
  - Crystal mosaics/sizes/angles

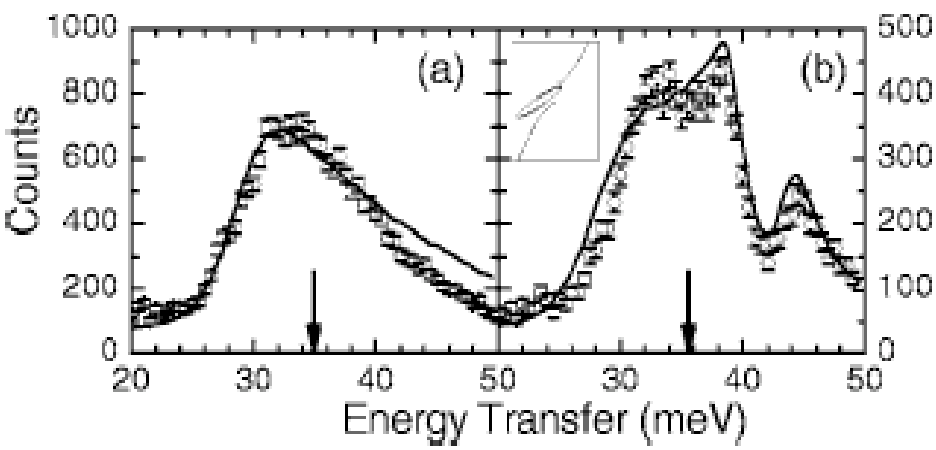


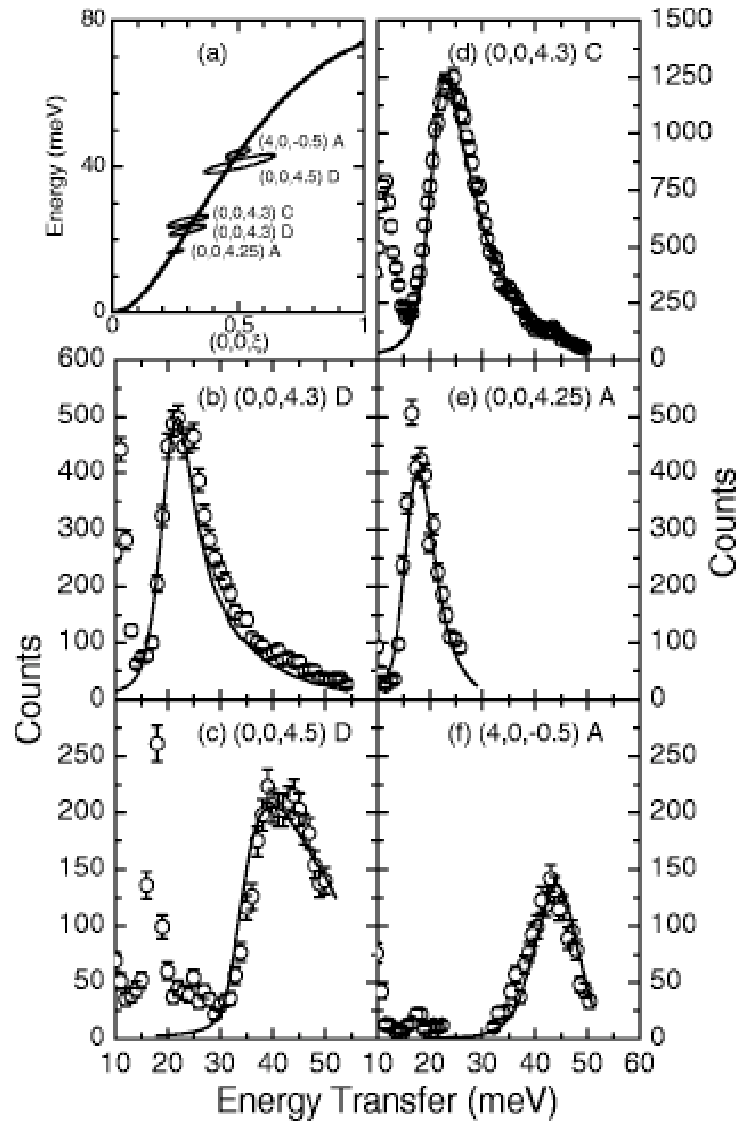
- **Resolution convolutions**

$$I(\mathbf{Q}_0,\omega_0) = \int S(\mathbf{Q}_0,\omega_0) R(\mathbf{Q}-\mathbf{Q}_0,\omega-\omega_0)\, d\mathbf{Q}\, d\omega$$

Resolution effects

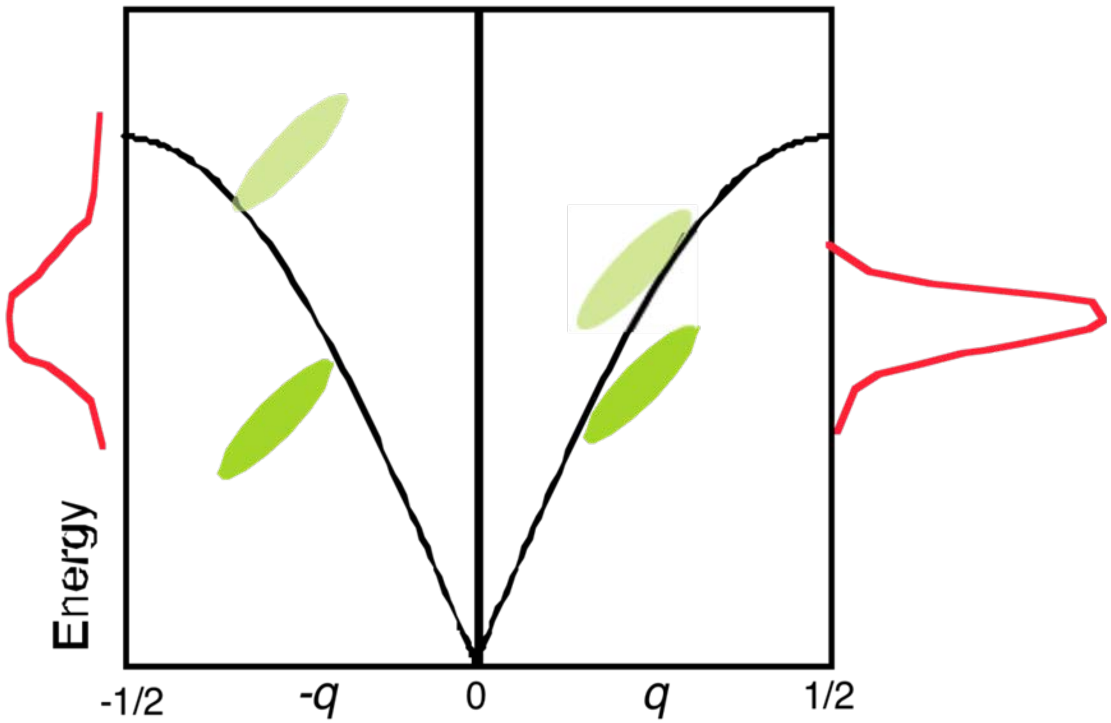






Resolution focusing

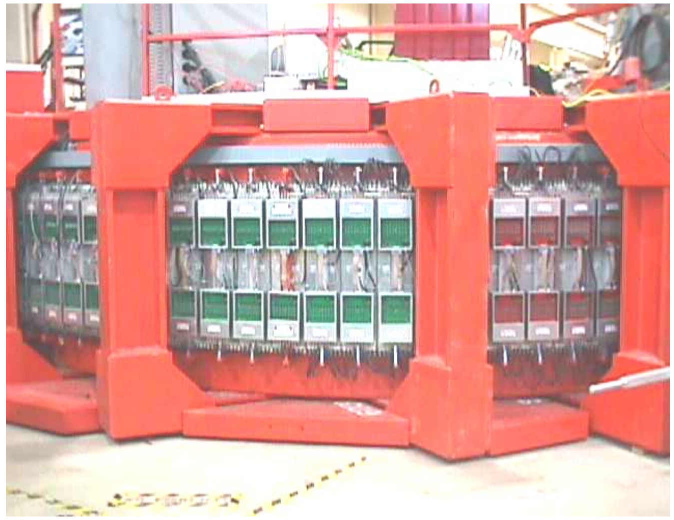
- Optimizing peak intensity
- Match slope of resolution to dispersion



Time-of-flight methods

AMES LABORATORY

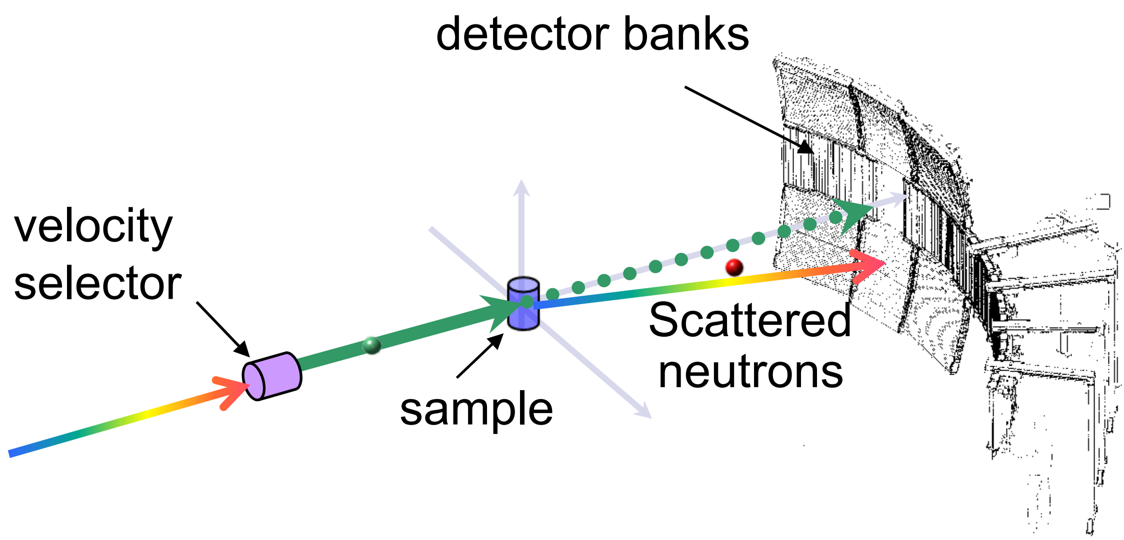
Spallation neutron source

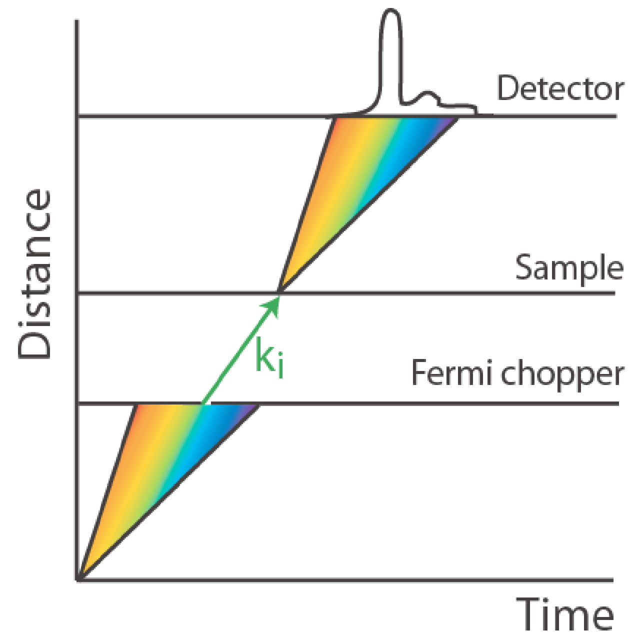


Pharos – Lujan Center

- Effectively utilizes time structure of pulsed neutron groups

$$t = \frac{d}{v} = \left(\frac{m}{h} d\right)\lambda$$

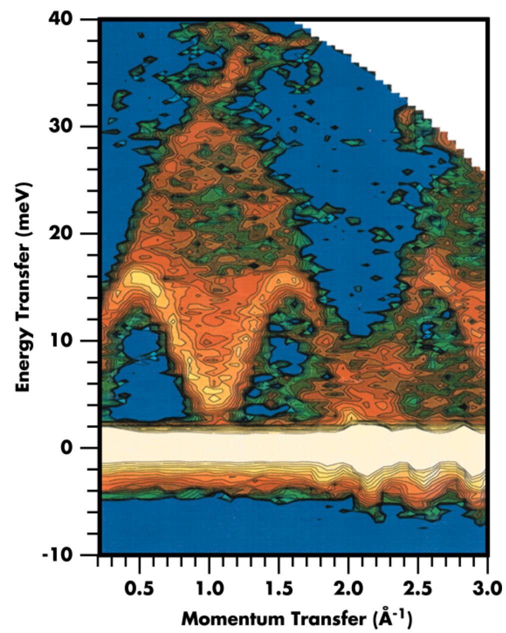


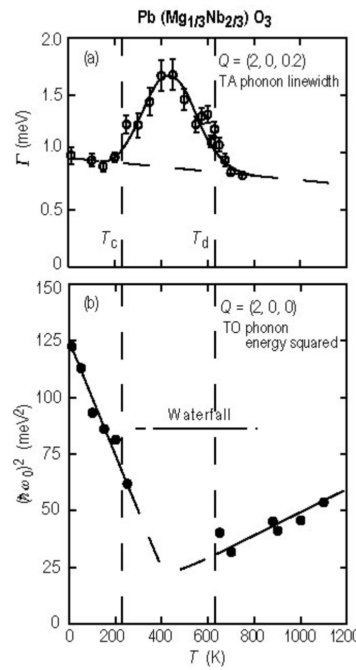


TOF vs. 3-axis

- epithermal (up to 2 eV)
- Total spectra (esp. powder samples)
- Absolute normalization
- Low-dimensional systems
- Hardware inflexible
- Software intensive

- High flux of thermal neutrons
- Focused studies in Q,ω (soft modes, gaps, etc.)
- Three-dimensional systems
- Hardware intensive
- Software inflexible





Fermi Choppers

- Body radius ~ 5 cm
- Curved absorbing slats
  - B or Gd coated
  - ~mm slit size
- f = 600 Hz (max)
- Acts like shutter, $\Delta t \sim \mu s$

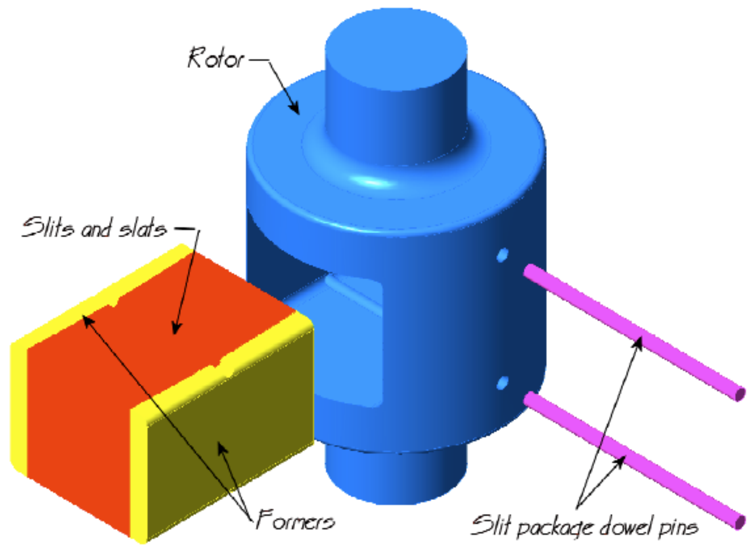
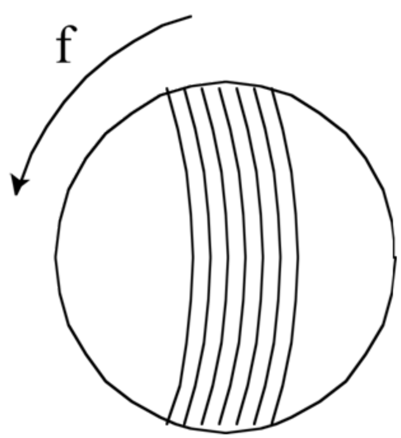
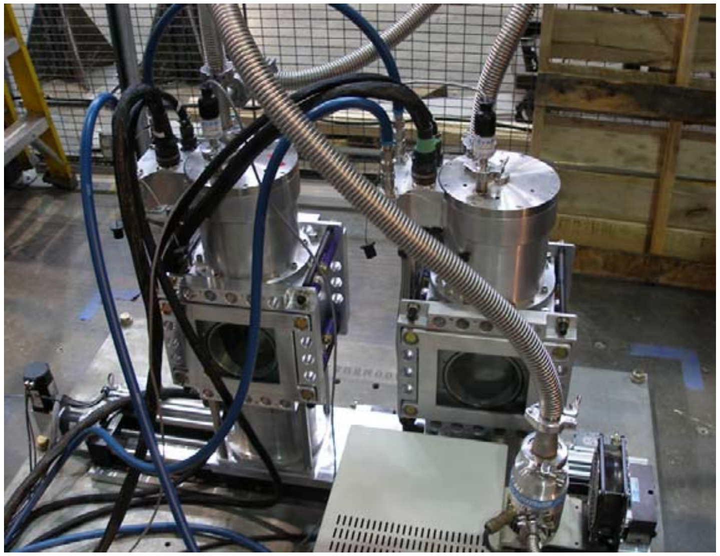


Figure 1. ISIS MAPS chopper and slit package assembly – exploded view

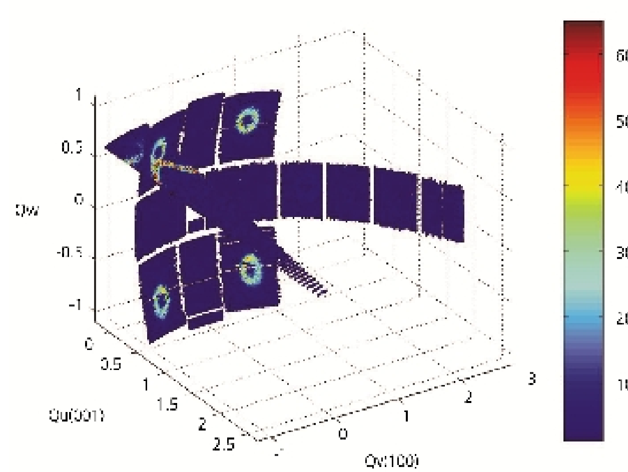




Position sensitive detectors

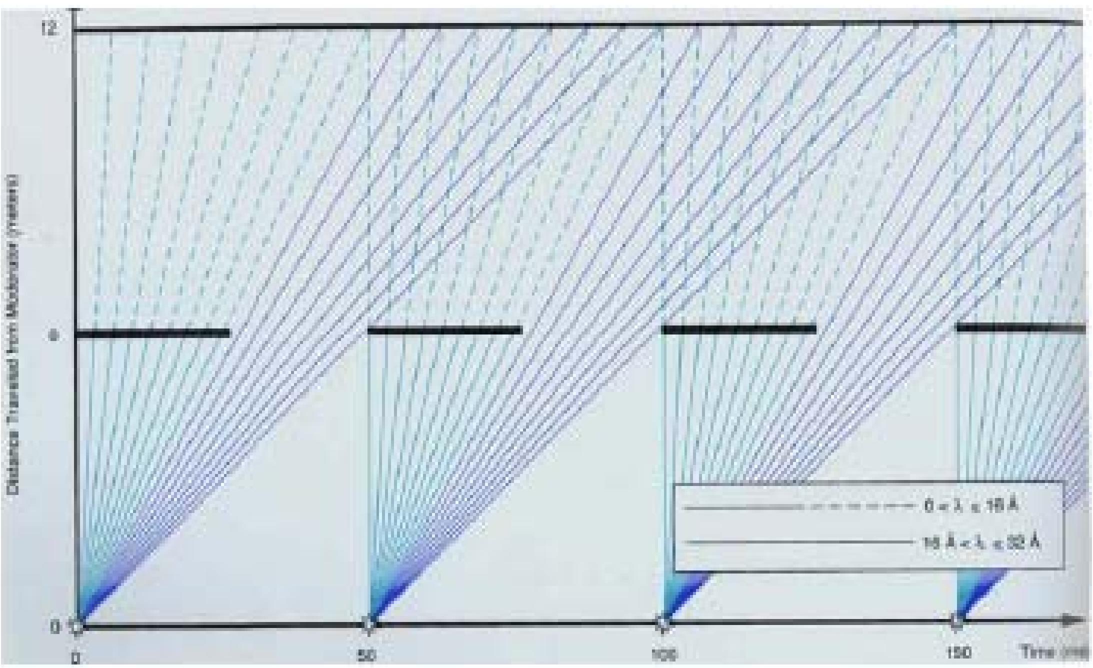
- ^3He tubes (usu. 1 meter)
- Charge division
- Position resolution ~ cm
- Time resolution ~ 10 ns

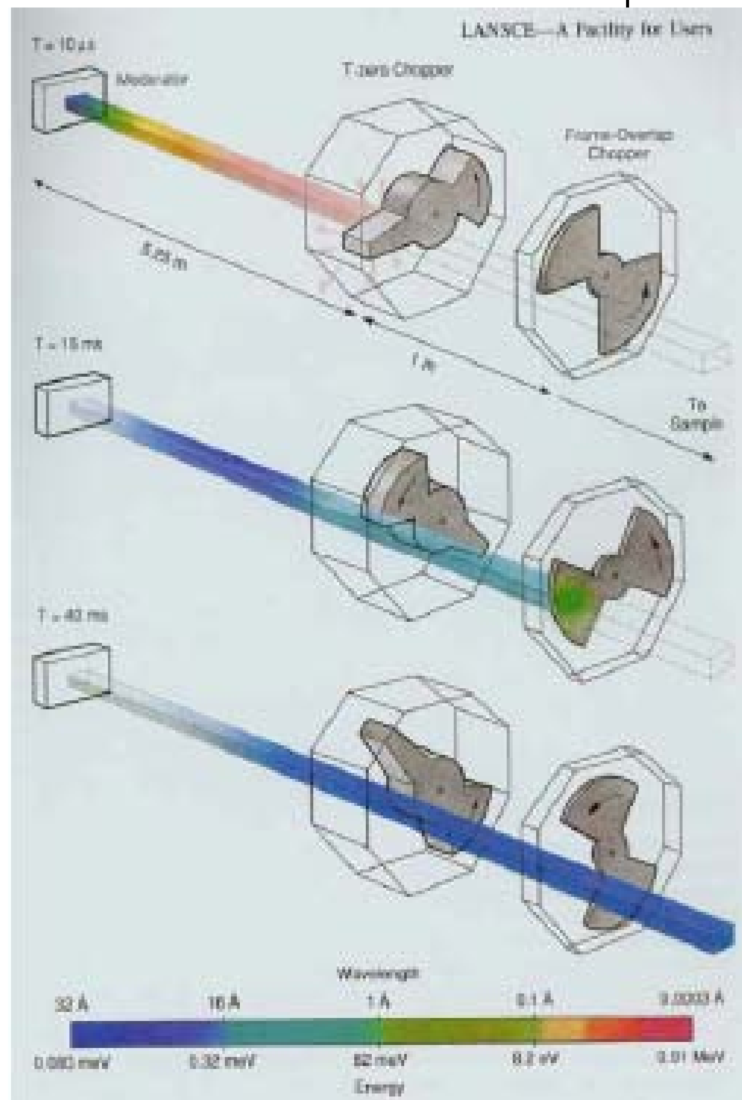
MAPS detector bank



T-zero chopper

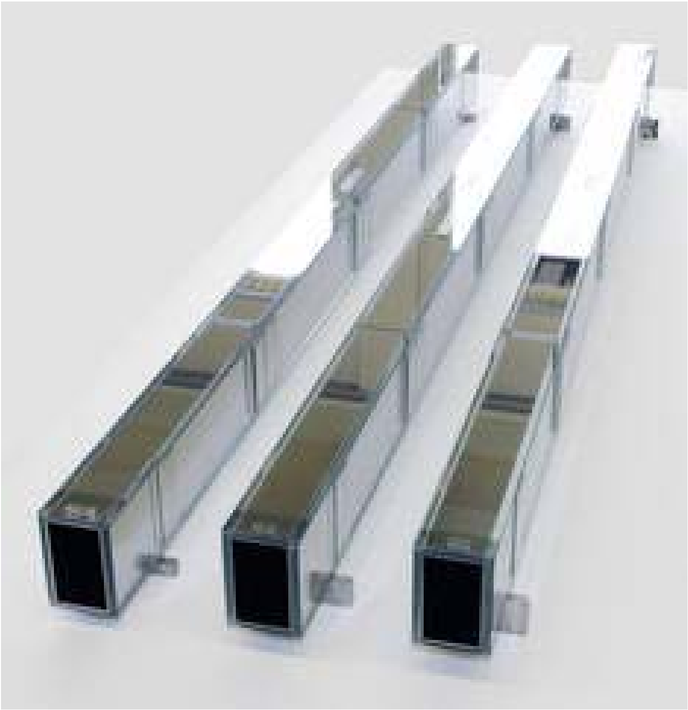
- **Background suppression**
- **Blocks fast neutron flash**





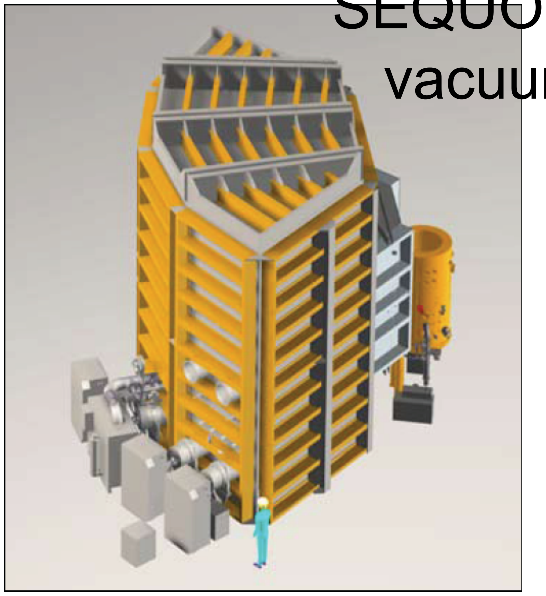
Guides

- **Transport beam over long distances**
- **Background reduction**
- **Total external reflection**
  - Ni coated glass
  - Ni/Ti multilayers (supermirror)



Size matters

- **Length = resolution**
  - Instruments ~ 20 – 40 m long
  - E-resolution ~ 2-4% E_i
- **More detectors**
  - SEQUOIA – 1600 tubes, 144000 pixels
  - Solid angle coverage 1.6 steradians
- **Huge data sets**
- 0.1 – 1 GB

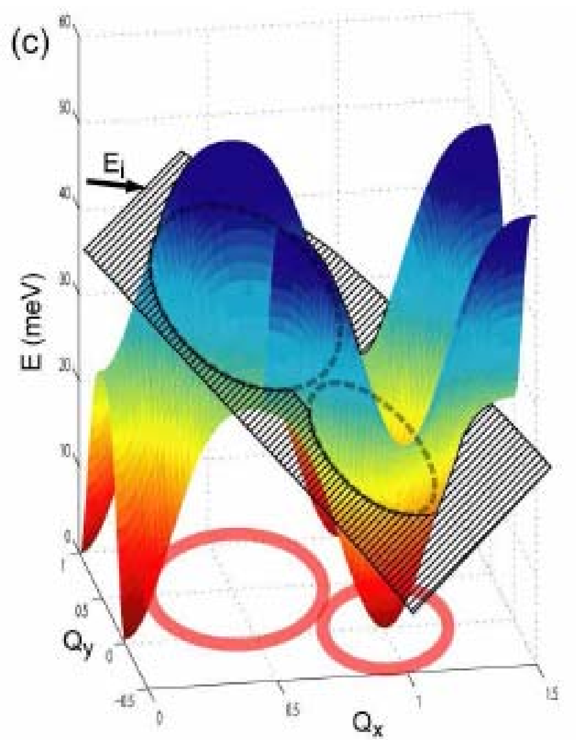


SEQUOIA detector vacuum vessel

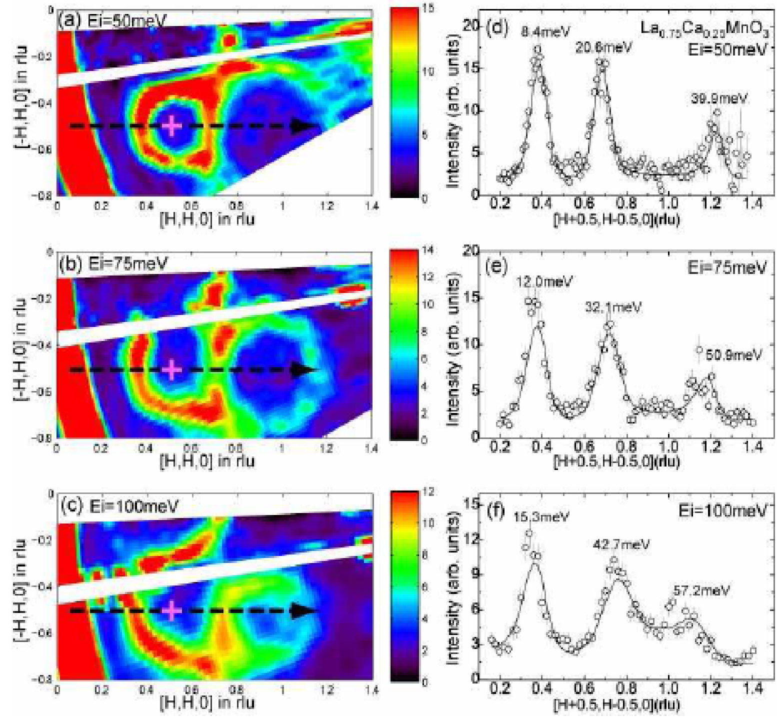
Data visualization

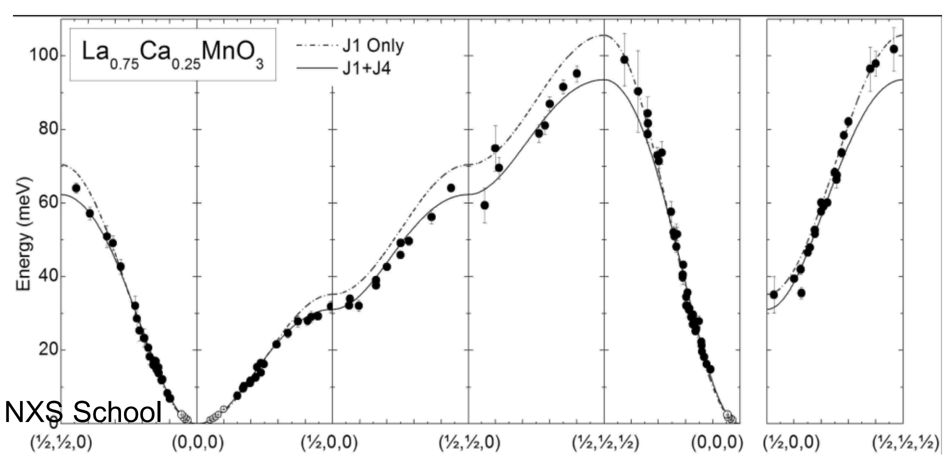
- Large, complex data from spallation sources
- Measure S(**Q**,ω) – 4D function

$La_{1-x}Ca_xMnO_3$

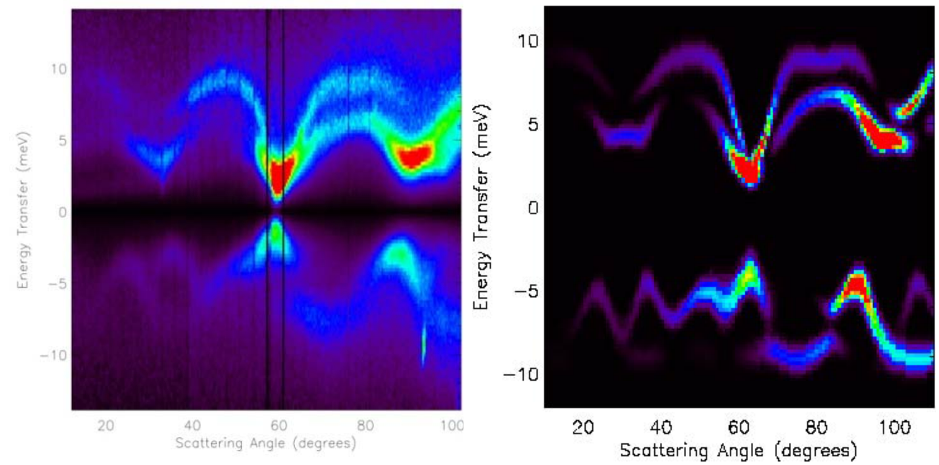


Ye *et al.*, *Phys. Rev. B*, **75** 144408 (2007).

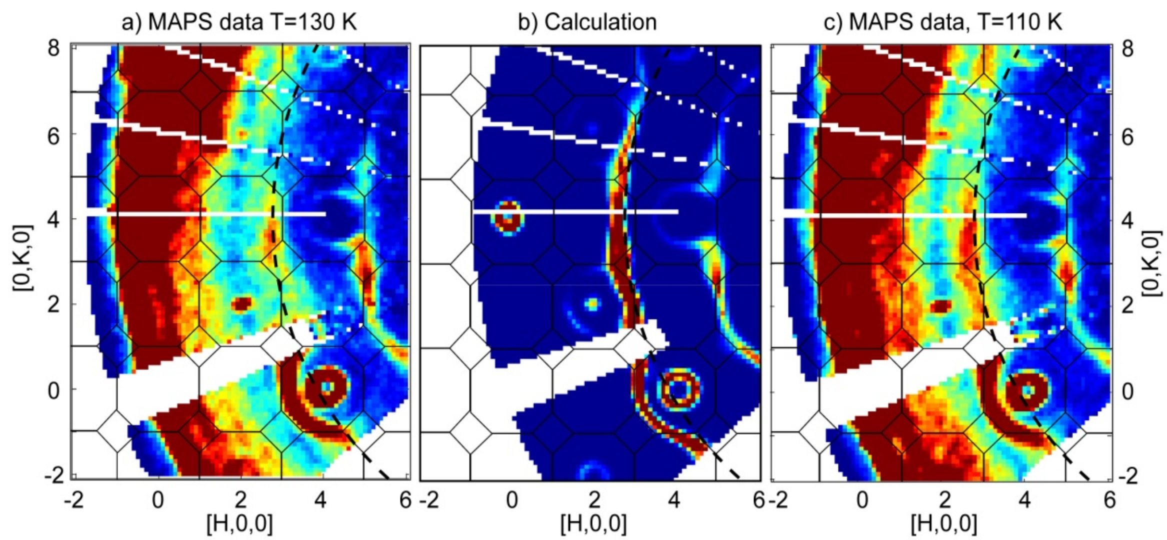




Computation



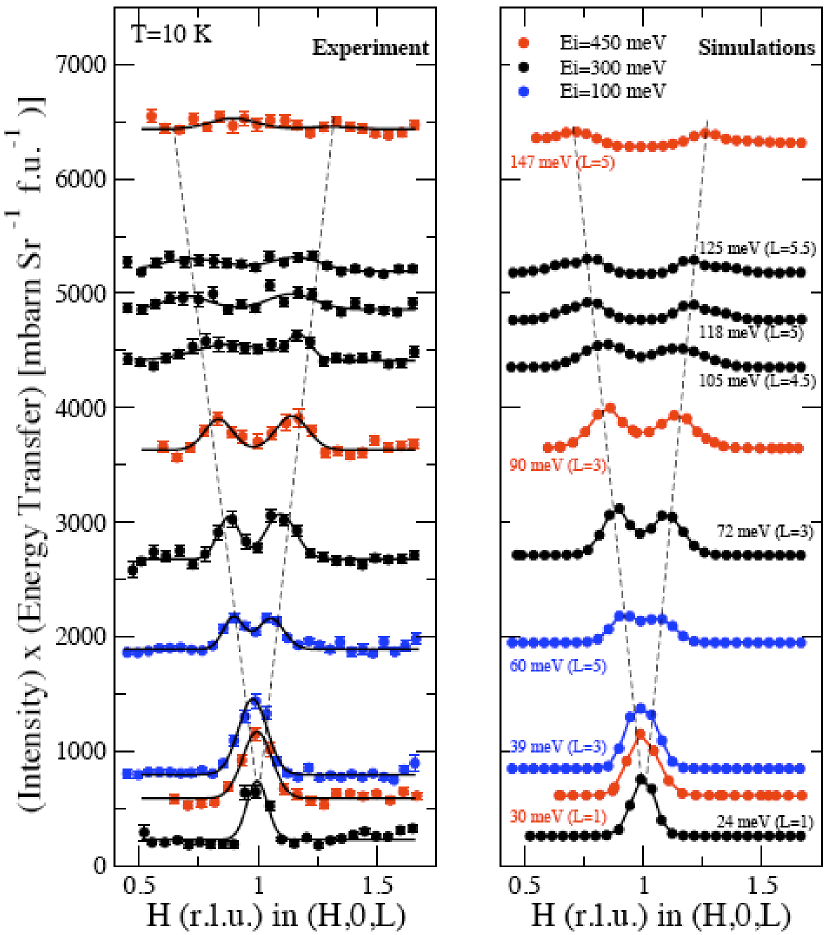
Pb phonons



Fe_3O_4 spin waves

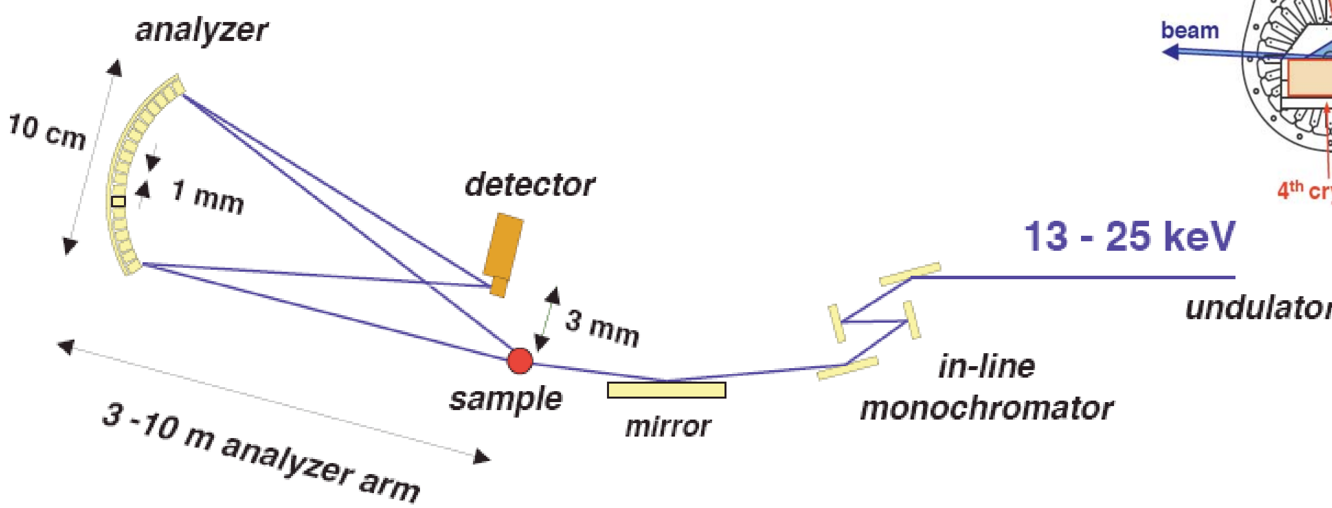
Absolute normalization

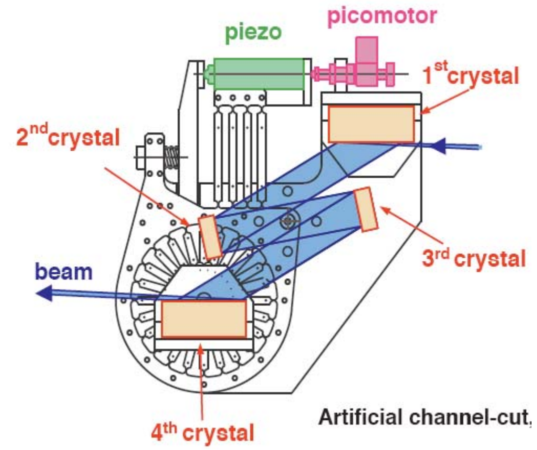
- **Absolute normalization**
  - Using incoherent scattering from vanadium
  - $\sigma/4\pi$ = 404 mbarns/Sr

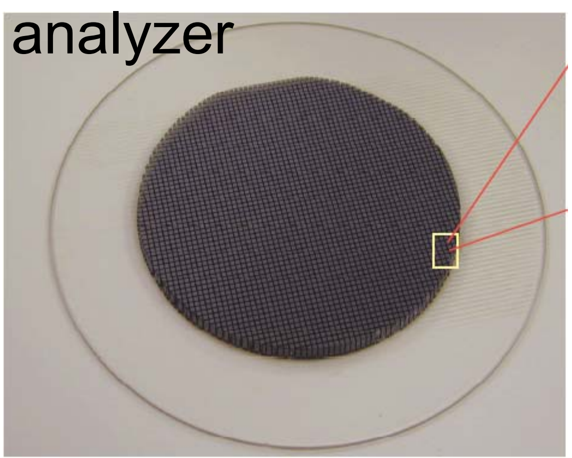


Inelastic x-ray scattering

- Ei=20 keV, need 1 meV resolution
- $\Delta E/E_i \sim 10^{-7}$!!!







ϕ-scan of monochromator

1 meV $\Rightarrow$ μrad

T-scan of monochromator

1 meV $\Rightarrow$ 0.02 K

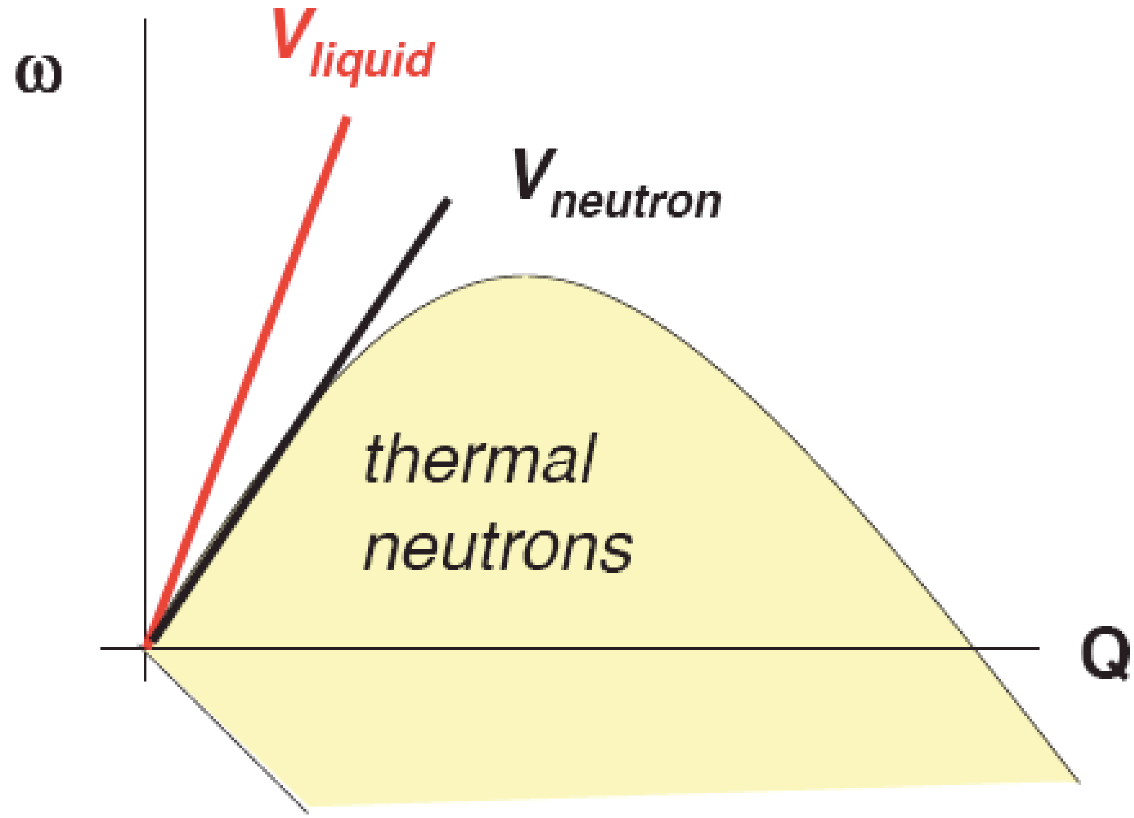
Sector-3, APS

Kinematics

- Essentially elastic scattering
- No kinematic limits

$$Q \approx 2k_i \sin\theta$$

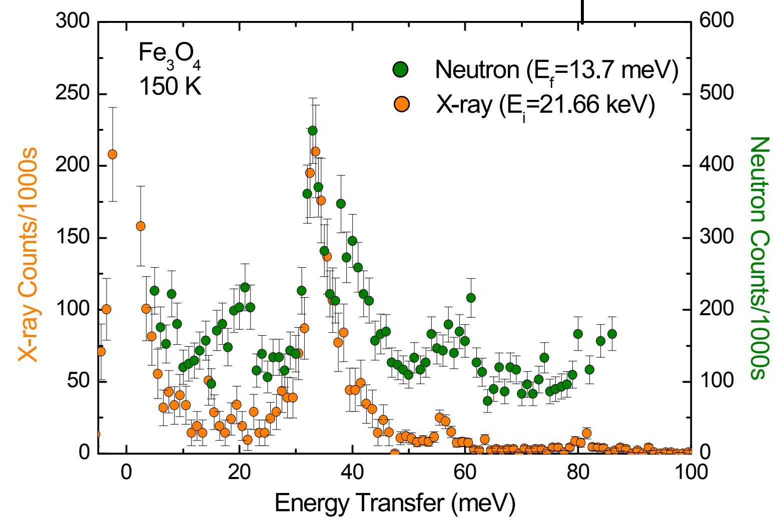
$$h\omega = hc(k_i - k_f)$$

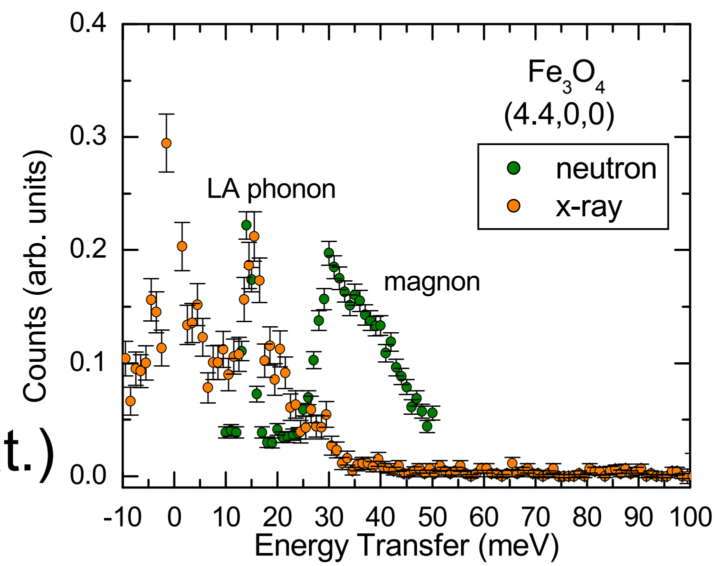


IXS vs. INS

- SAMPLE SIZE

- **IXS**
  - Simple scattering geometry ($k_i \approx k_f$)
  - Resolution function simpler
    (most angles fixed, E-scans only)
  - No spurions
    (high-order refs. keV, no incoherent scat.)
  - *Can only do lattice excitations*





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