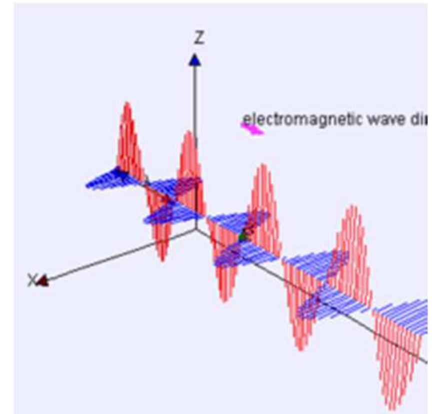
The Probes (perturbations)

1) Electro-magnetic field



$$\vec{E} = \hat{e}E_0 e^{i(\vec{k}.\vec{r}-\omega t)}$$

$$\vec{B} = \frac{1}{\omega}\vec{k} \times \vec{E}$$

$$\boxed{\begin{array}{c} E = \hbar\omega = \dfrac{hc}{\lambda} \\ E(\lambda = 1\text{Å}) = 12.4\,keV \end{array}}$$

2) Particles

$$\psi \sim e^{i\vec{k}.\vec{r}}$$

Particle	electron	positrons	muons	neutrons	proton	Nuclei $^A_Z X$	ions $^A_Z X^{n\pm}$
Mass	m_e=9,1 ×10^{-31} kg	m_p=9,1 ×10^{-31} kg	m_μ=1,88 ×10^{-28} kg	M_N=1,675 ×10^{-27} kg	M_P=1,673 ×10^{-27} kg	Z.M_P+ (A-Z).M_N-E_B/c^2	~Z.M_P+ (A-Z).M_N-E_B/c^2
Charge	-e	+e	-e	0	+e	+Ze	± ne
Spin	1/2	1/2	1/2	1/2	1/2	0 if Z and A are even S > 1/2 for 75% of isotopes	Depends on n ($\mu_e >> \mu_{Nucleus}$)

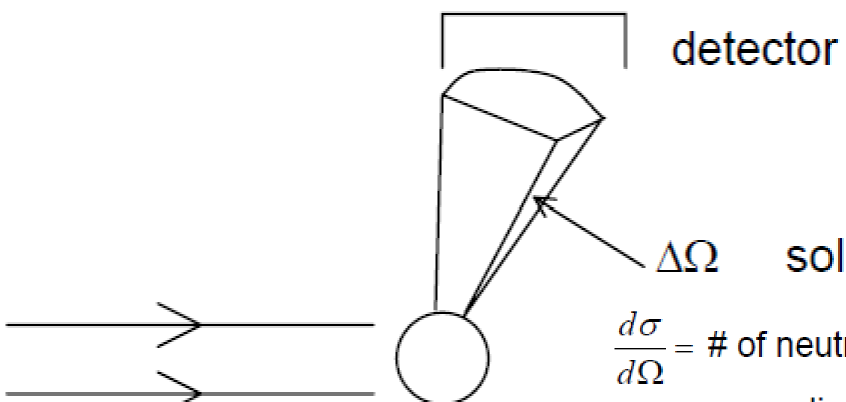
(Internal probe)

	neutron
mass	$m_n = 1.675 \times 10^{-27} kg$
charge	0
spin	$s = ½$
magnetic dipole moment	$\mu_n = \frac{-e\hbar}{2m_n} g s_n$ with $g_n = 3.826$
energy	$E = \frac{\hbar^2 k^2}{2m_n} \qquad k = \frac{2\pi}{\lambda}$ $E[meV] = \frac{81.81}{\lambda^2 [Å]}$
interaction with matter:	
Coulomb interaction	—
strong-force interaction	✓
magnetic dipole-dipole interaction	✓

=> For wave-lengths ~ interatomic distances, $E_{Neutron}$ ~ 10 meV

Interaction of Neutrons with Matter

	elastic scattering	**inelastic scattering**
strong-force interaction ("nuclear scattering")	position of nuclei in solid (lattice structure)	lattice vibrations (phonons)
magnetic interaction	position and orientation of electronic magnetic moments in solids (ferromagnetism, antiferromagnetism)	spin excitations (magnons, spin waves)



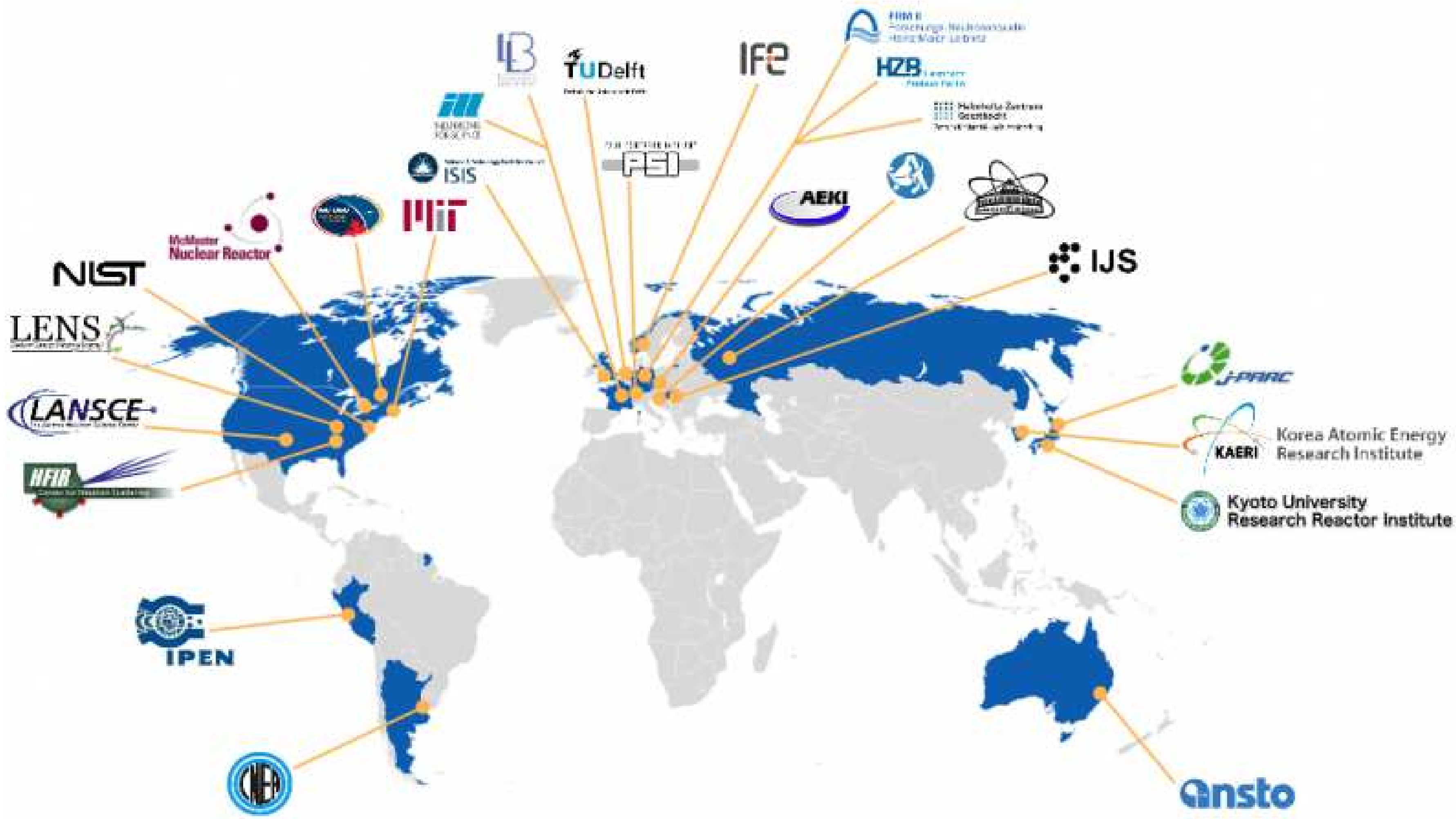
$\Delta\Omega$ solid angle element covered by detector

$\frac{d\sigma}{d\Omega}$ = # of neutrons scattered into solid angle element $d\Omega$ per unit time, normalized to incident flux. Material-specific quantity, experimental conditions (size of detector, incident flux) normalized out.

dimensions: $\left[\frac{d\sigma}{d\Omega}\right] = \frac{1}{[\Delta\Omega]\,[t]\,[\phi]} =$ area

dimensionless

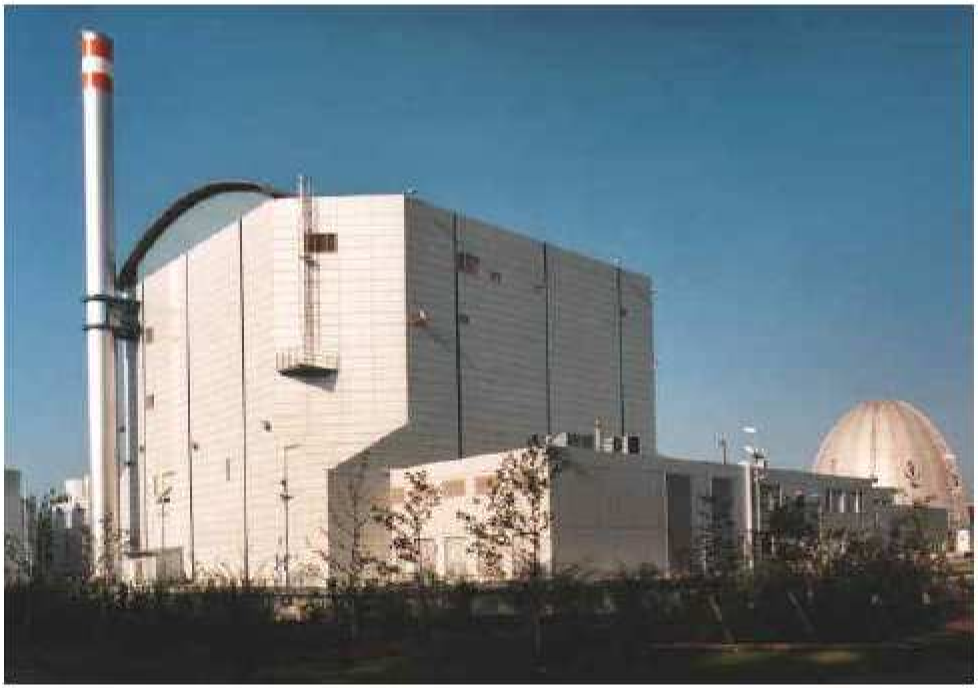
Neutron Sources Worldwide

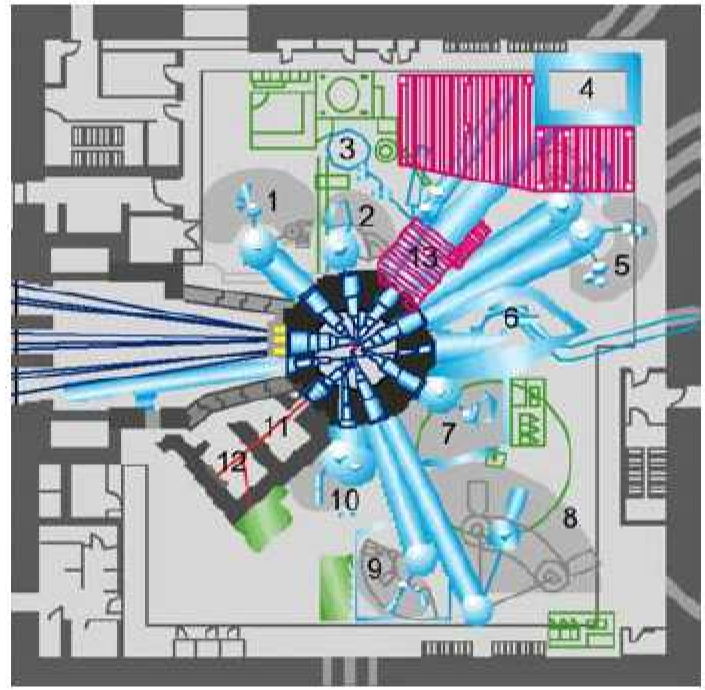


- Research reactors
- Spallation sources

Research Reactors

$$^{235}U + n \rightarrow A + B + 2.3n \quad \text{(A, B: fission fragments)}$$





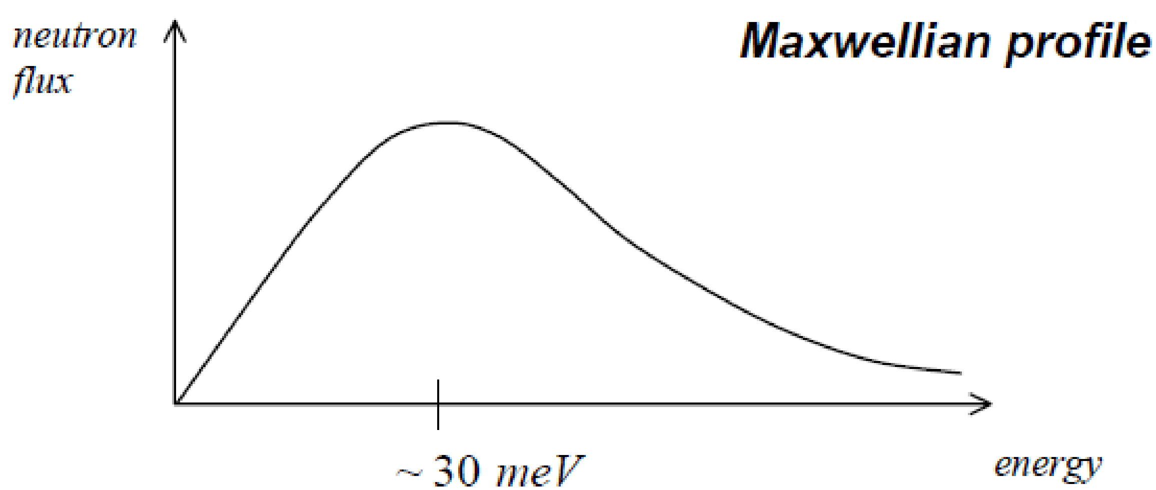
Research reactor FRM-II in Munich, Germany
Outside view of the building (left) and layout of the experimental hall (right). The neutron beam tubes (blue) tap into the flux emitted from the reactor core (center) and guide the neutrons to various neutron scattering instruments. http:///www.frm2.tu-muenchen.de

Research Reactors

Research Reactors:

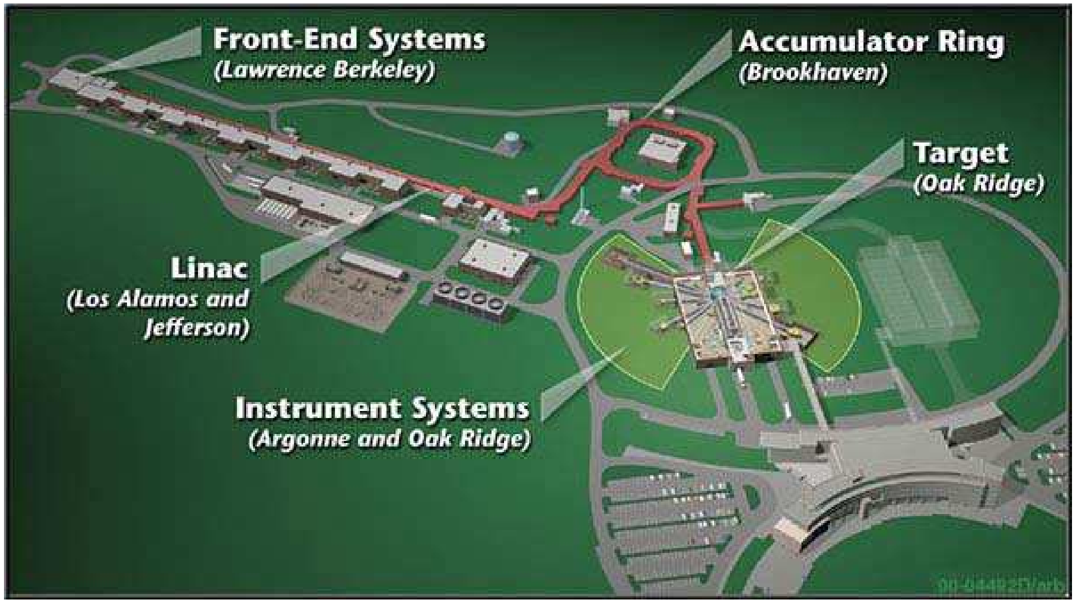
$$^{235}U + n \rightarrow A + B + 2.3n \quad \text{(A, B: fission fragments)}$$

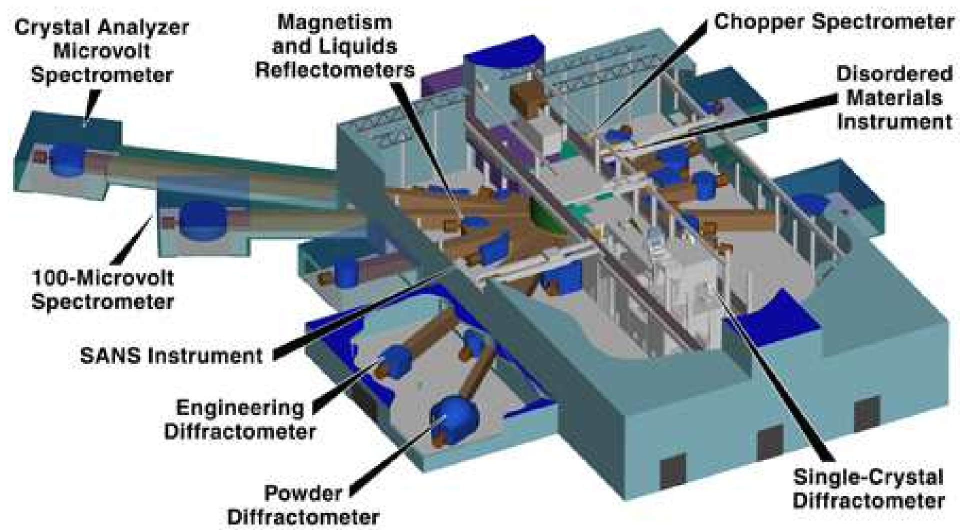
- Optimized for neutron flux => Low power (Research reactors are poor electrical generators)
- Fission is most favorable for thermal neutrons



Spallation Source

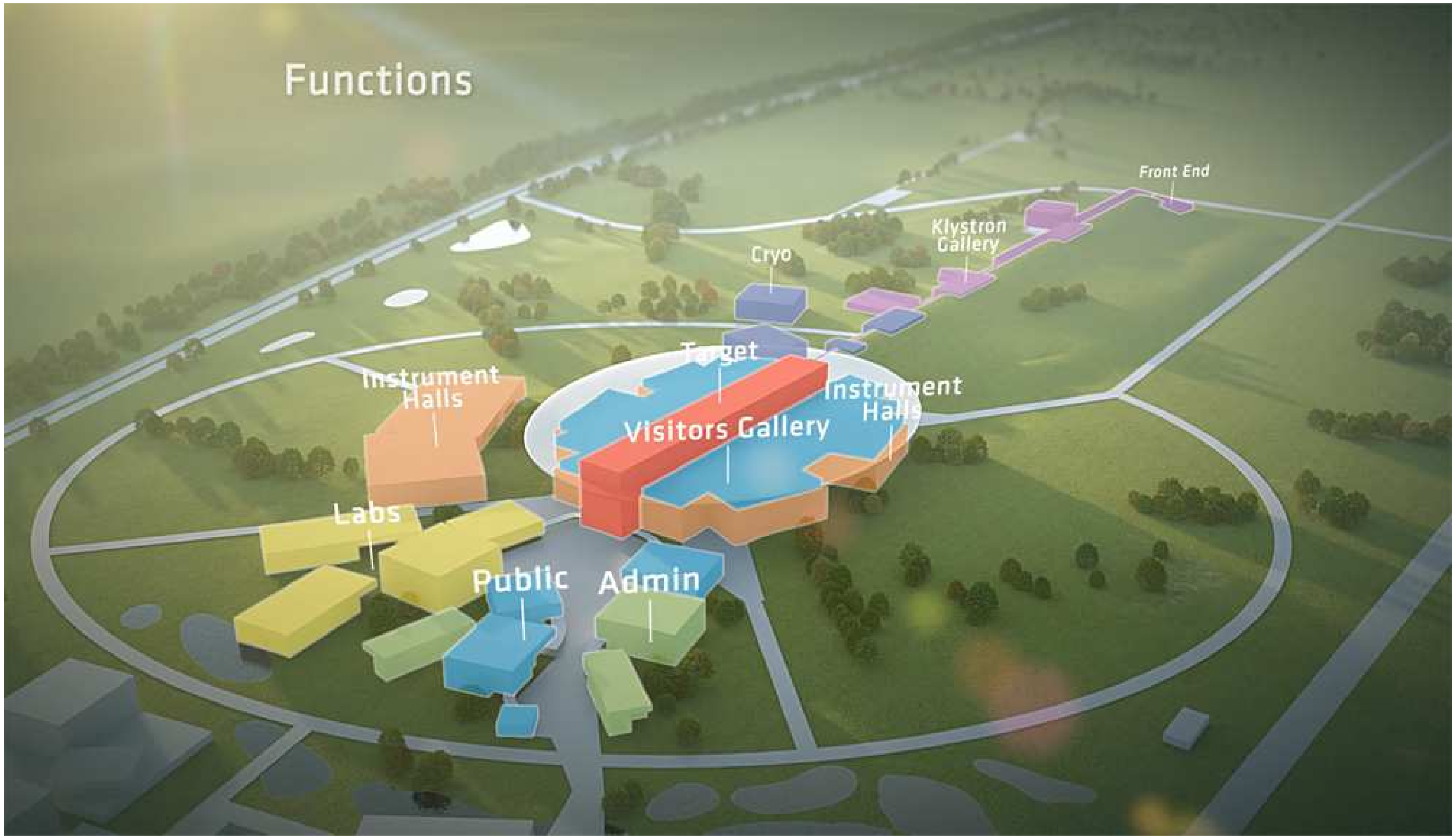
$$p + Hg \rightarrow A + B + xN$$ x = 20-30 !!





Spallation Source

EUROPEAN
SPALLATION
SOURCE



Neutron Detectors

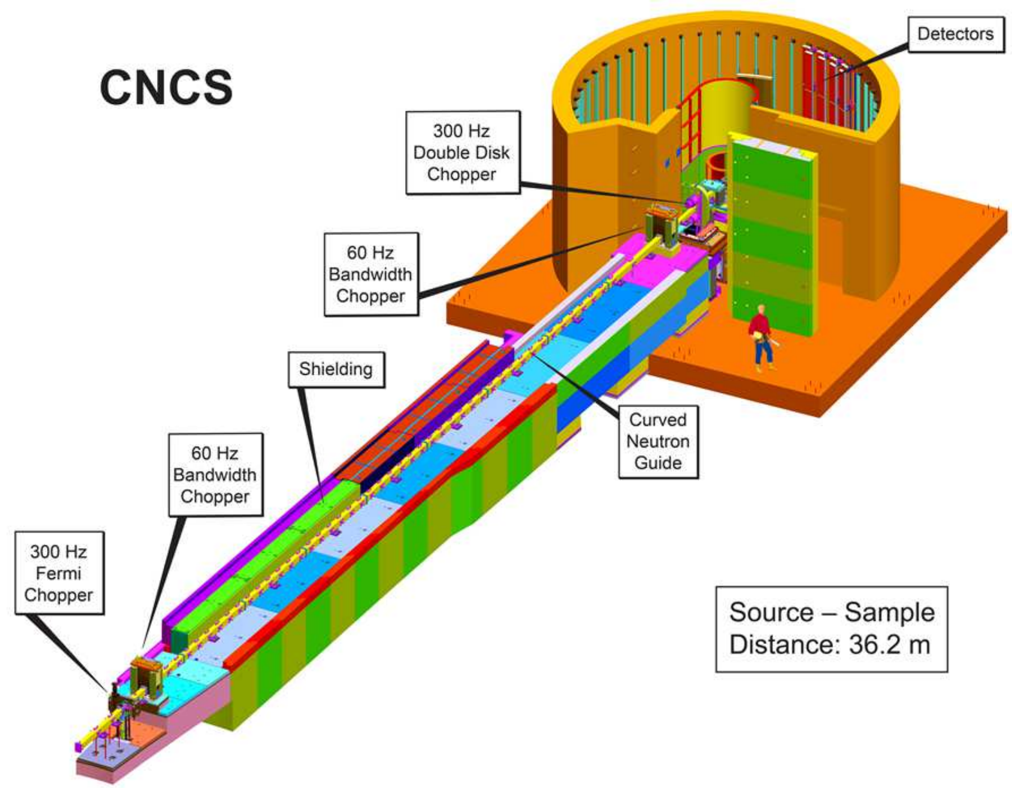
Neutrons have no charge and interact weakly with matter: hard to detect directly

Idea: convert them into charge particles

$$n + {}^{3}He \rightarrow {}^{3}H + p$$

The protons are collected by a high electric field and converted into electric current.

Another type c has a high
neutron captu
$n + {}^{10}B \rightarrow {}^{7}Li +$
The energetic les, which are
again collecte

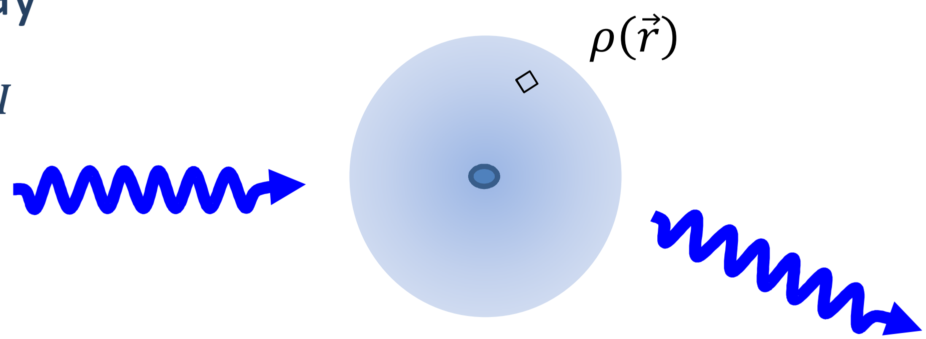


Neutron vs x-ray Scattering

Reminder

Incident x-ray

$\hbar\omega_I, \vec{k}_I, \hat{\varepsilon}_I$



$$\frac{d\sigma}{d\Omega}(\vec{Q}) = r_0{}^2(\hat{\varepsilon}_F{}^*.\hat{\varepsilon}_I)^2\left|F(\vec{Q})\right|^2 \quad \text{with } F(\vec{Q}) = \int \rho(\vec{r})e^{i\vec{Q}\vec{r}}d\vec{r}$$

How did we get there ?

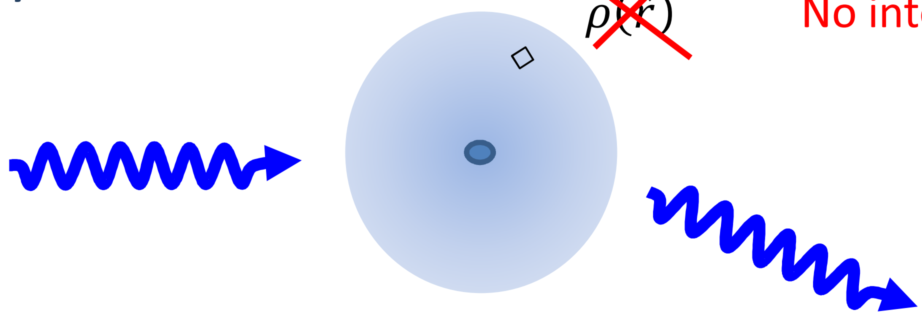
Thomson scattering from ◇ integrated over space

$$W_{I\rightarrow F} = \frac{2\pi}{\hbar}\left|\left\langle F\left|\frac{e^2A^2}{2m}\right|I\right\rangle\right|^2 \rho(E_F)$$

Neutron vs x-ray Scattering

Incident ~~x-ray~~ neutron

$E_I, \vec{k}_I$



$\cancel{\rho(\vec{r})}$

No interaction with electronic cloud

$$\frac{d\sigma}{d\Omega}(\vec{Q}) = r_0{}^2 \cancel{(\hat{\varepsilon}_F{}^* . \hat{\varepsilon}_I)^2} \left|F(\vec{Q})\right|^2 \quad \text{with } F(\vec{Q}) = \int \rho(\vec{r}) e^{i\vec{Q}\vec{r}} d\vec{r}$$

How did we get there ?

~~Thomson~~ scattering from ◇ integrated over space

$$W_{I \to F} = \frac{2\pi}{\hbar} \left| \left\langle F \left| \cancel{\frac{e^2 A^2}{2m}} \right| I \right\rangle \right|^2 \rho(E_F)$$

Interaction of ~~electrons with electro-magnetic field~~

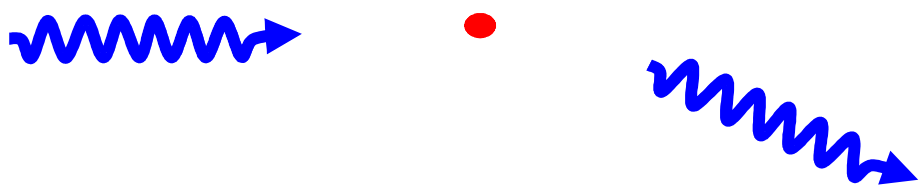
Neutron vs x-ray Scattering

$$W_{I \to F} = \frac{2\pi}{\hbar} \left| \left\langle F \left| \frac{2\pi\hbar^2}{m_n} b \, \delta(\vec{r} - \vec{R}) \right| I \right\rangle \right|^2 \rho(E_F)$$

Incident ~~x-ray~~ neutron

$E_I, \vec{k}_I$

Interaction of neutrons with nucleus: strong-force

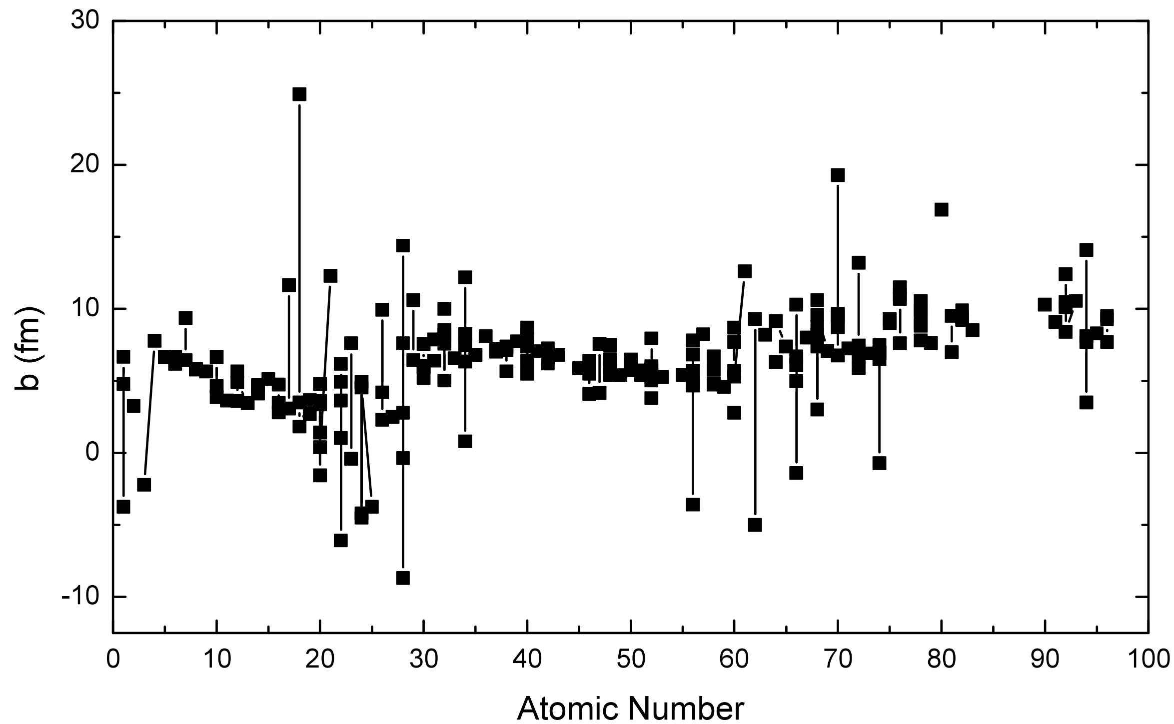


$$\frac{d\sigma}{d\Omega}(\vec{Q}) = ?$$ See exercises

Neutron Scattering length

b: scattering length

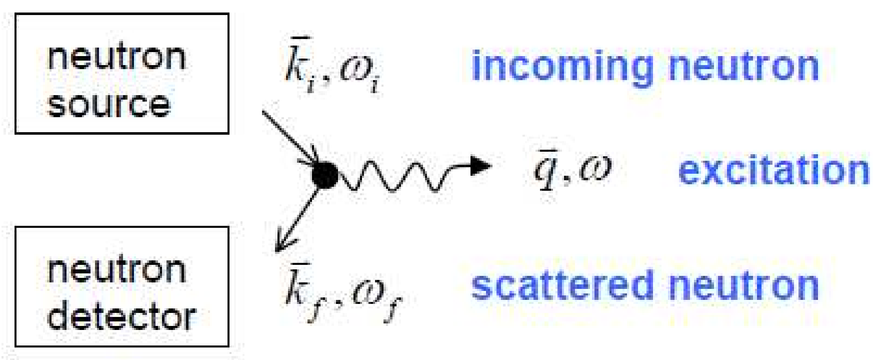
$$V(\vec{r}) = \frac{2\pi\hbar^2}{m_n} b\, \delta(\vec{r} - \vec{R})$$



http://www.ncnr.nist.gov/resources/n-lengths/

- 'Random ' variation from nucleus to nucleus but also among isotopes !

Neutron Scattering Experiment



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

$$\omega = \omega_f - \omega_i = \frac{\hbar}{2m_n}\left(k_f^{\,2} - k_i^{\,2}\right)$$

$\omega = 0$ elastic scattering

$\omega \neq 0$ inelastic scattering

Conceptually very similar to photons/x-rays !

=> Calculation of the scattering cross-section in the exercise class

BUT possibility of magnetic scattering (resolution of magnetic structures)

Neutron vs x-ray Scattering

$$\left.\begin{aligned}|k_i\rangle &= \frac{1}{\sqrt{L^3}} e^{i\vec{k}_i\cdot\vec{r}} \\ |k_f\rangle &= \frac{1}{\sqrt{L^3}} e^{i\vec{k}_f\cdot\vec{r}}\end{aligned}\right\}$$ plane waves, normalized to sample size L

$$\rho_f(E) = \underbrace{\left(\frac{L}{2\pi}\right)^3}_{\text{density of states in } k\text{-space}} \frac{d\vec{k}_f}{dE}$$

for single nucleus: $\frac{d\sigma}{d\Omega} = |b|^2$

In a crystal: If all nuclei are identical:

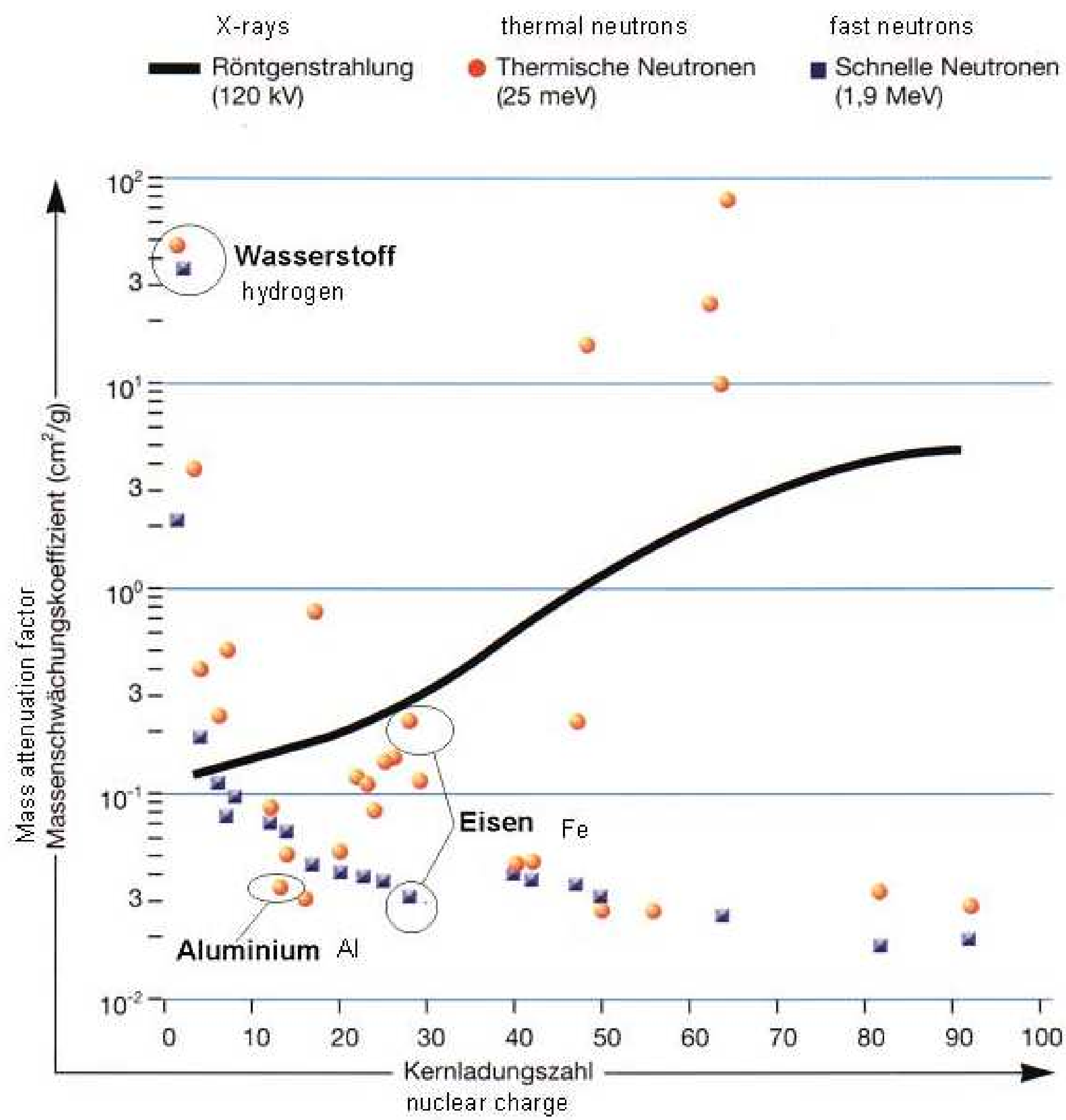
$$\frac{d\sigma}{d\Omega} = b^2 \frac{N(2\pi)^3}{v_o} \sum_{\vec{K}} \delta(\vec{Q} - \vec{K})$$

for unit cell with several atoms, basis vector $\vec{d}$

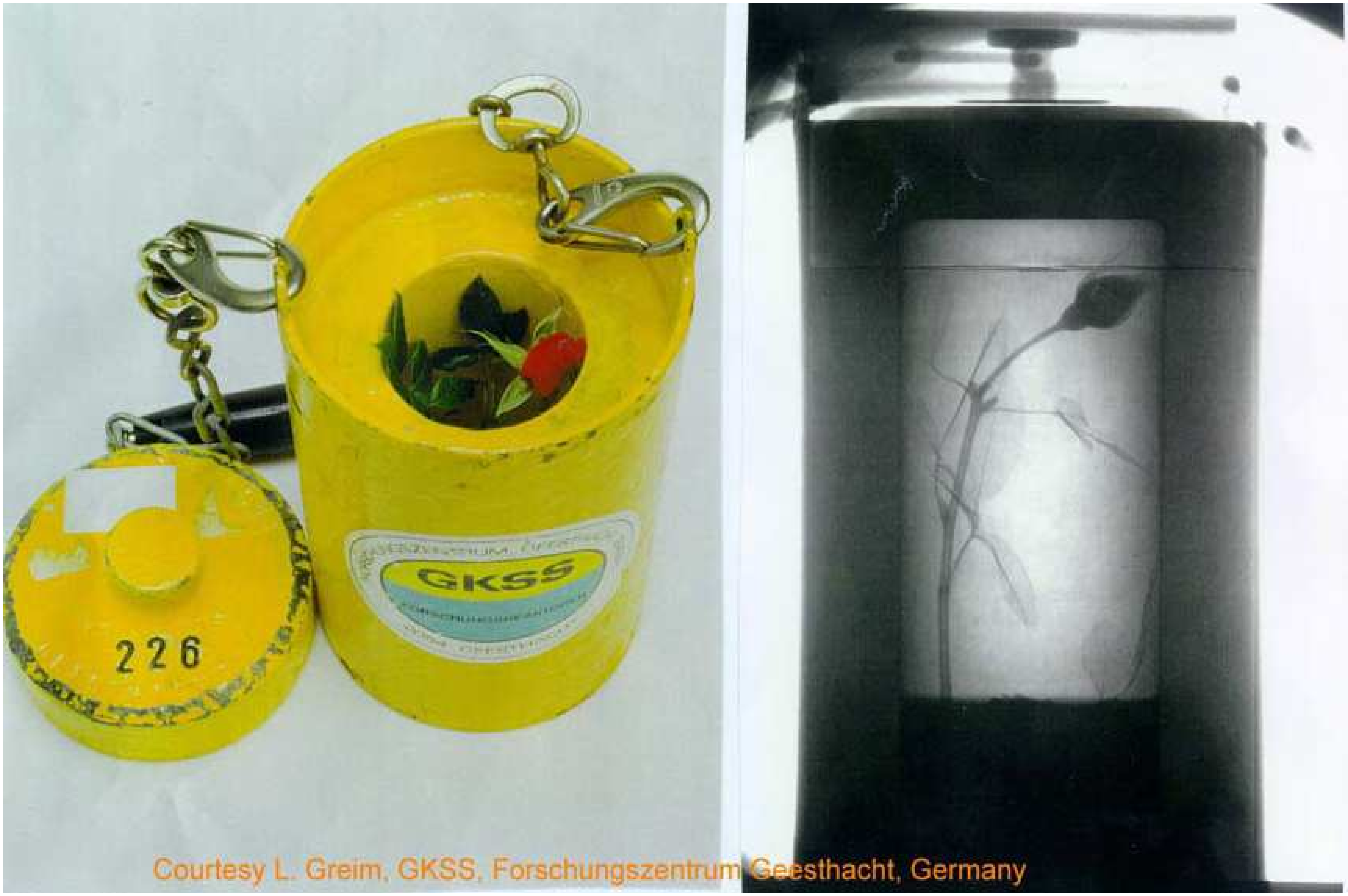
$$\frac{d\sigma}{d\Omega} = N \frac{(2\pi)^3}{v_0} \sum_{\vec{K}} \delta(\vec{Q} - \vec{K}) \left|F_N(\vec{K})\right|^2$$

$$F_N(\vec{K}) = \sum_{\vec{d}} e^{i\vec{Q}\cdot\vec{d}} b_{\vec{d}}$$ "nuclear structure factor"

Neutron Absorption

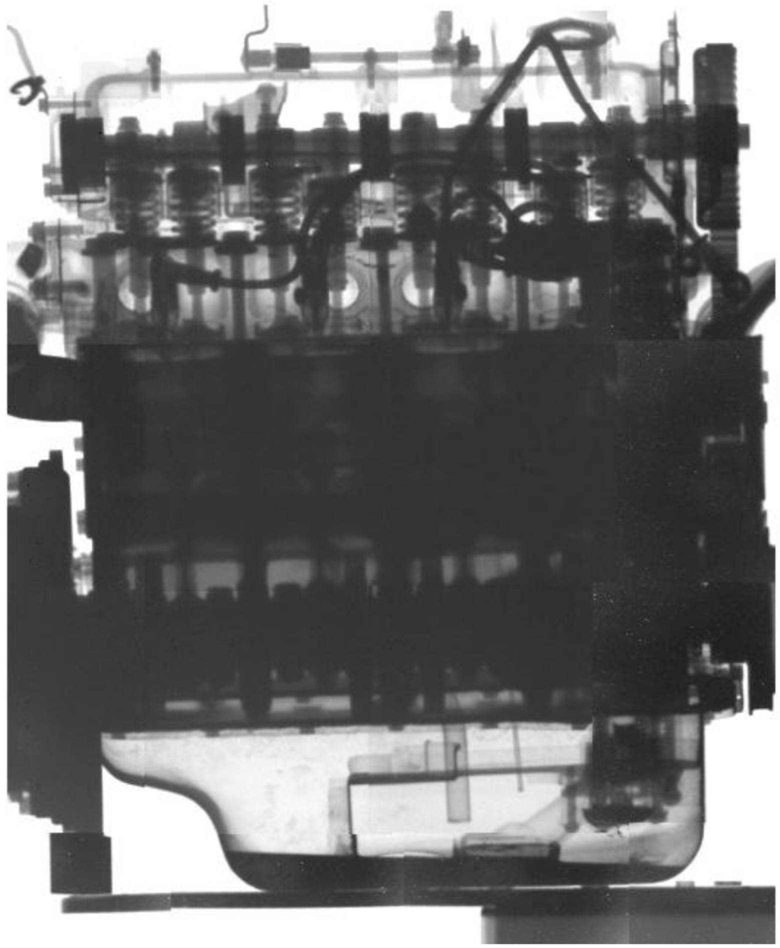


Neutron Absorption



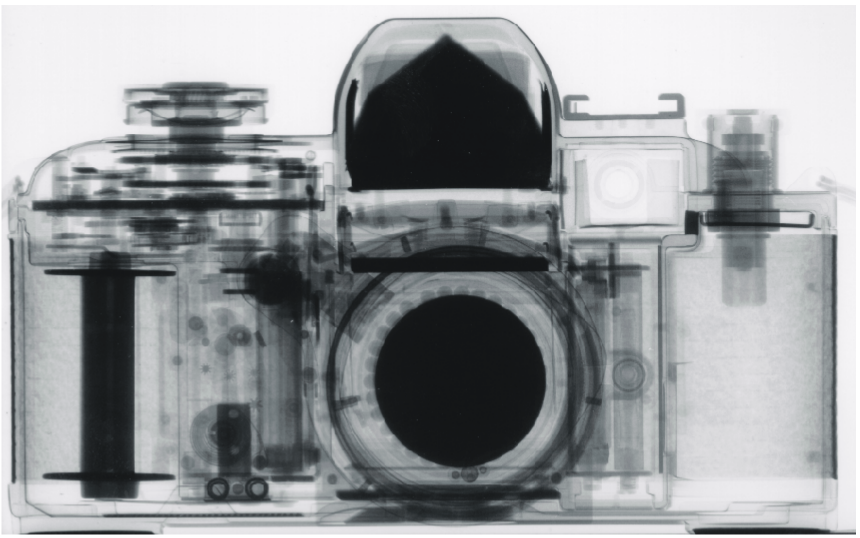
Courtesy L. Greim, GKSS, Forschungszentrum Geesthacht, Germany

Neutron Absorption

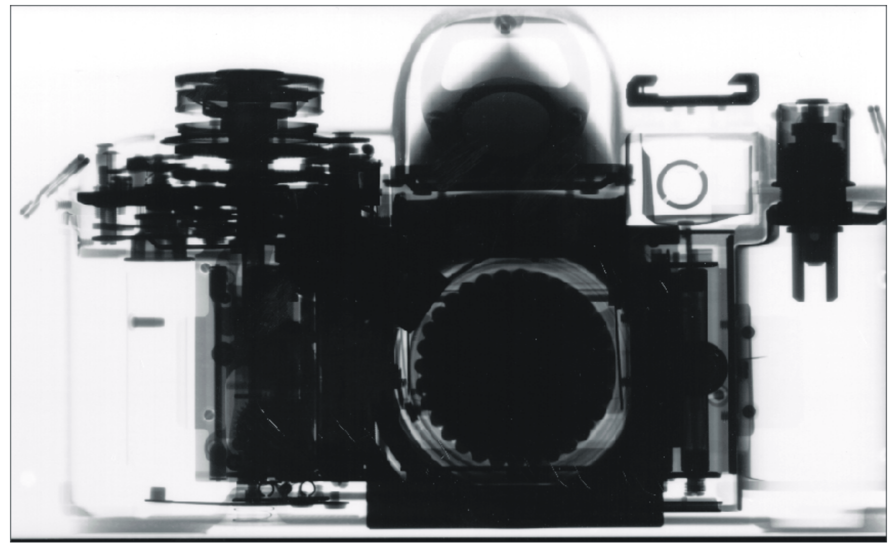


Neutron vs x-ray Radiography

Neutrons

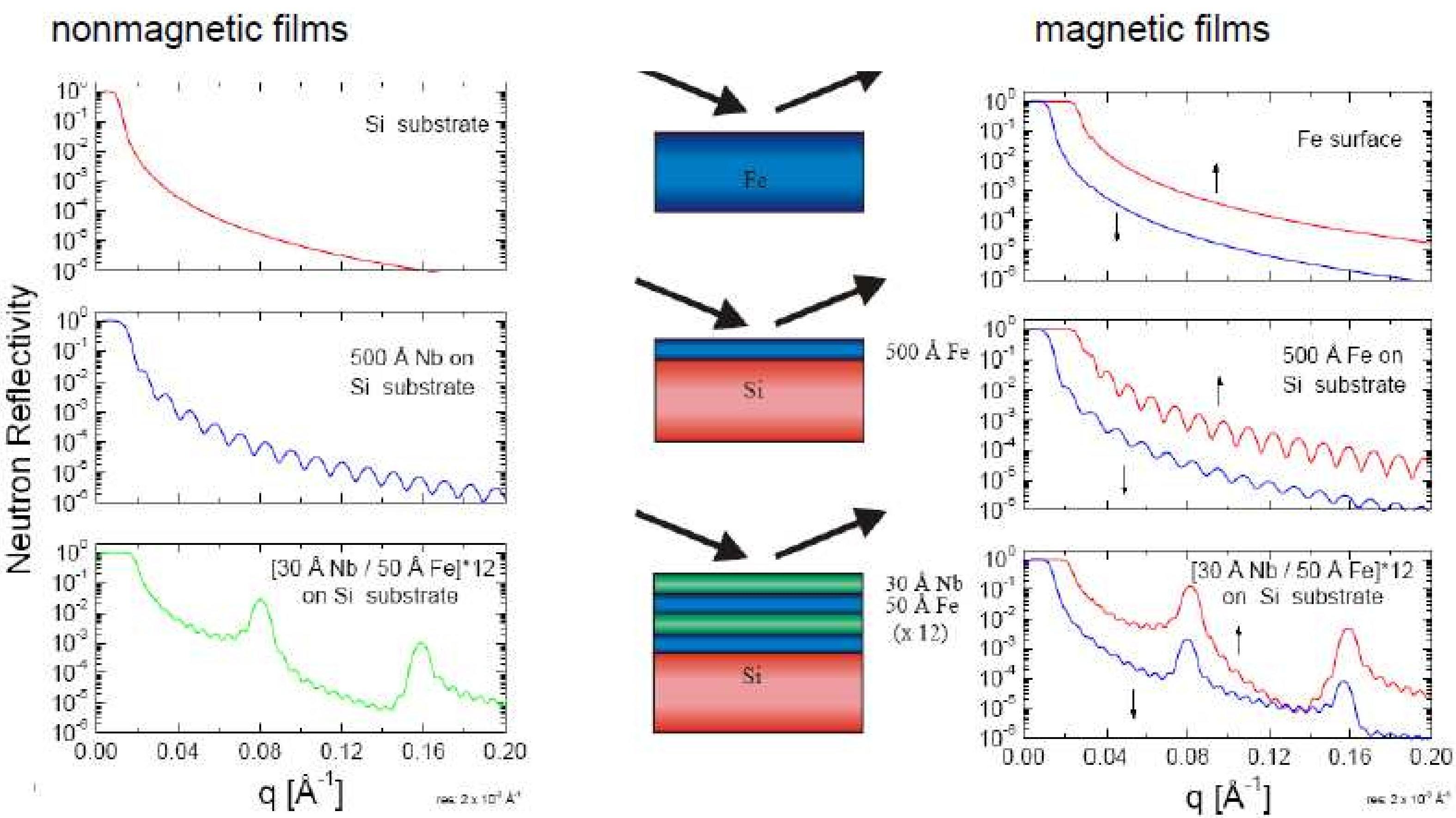


X-rays



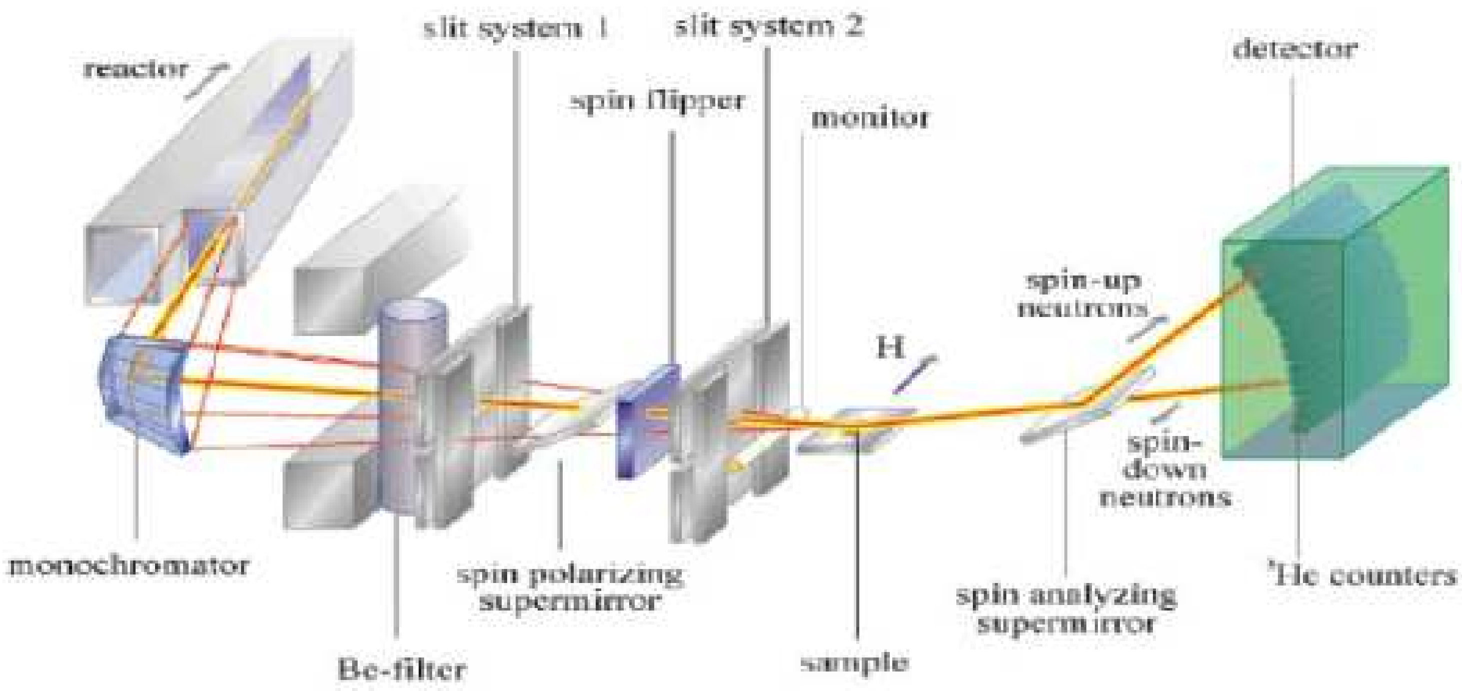
http://mnrc.ucdavis.edu/radiography.html

Ferromagnetic mirrors



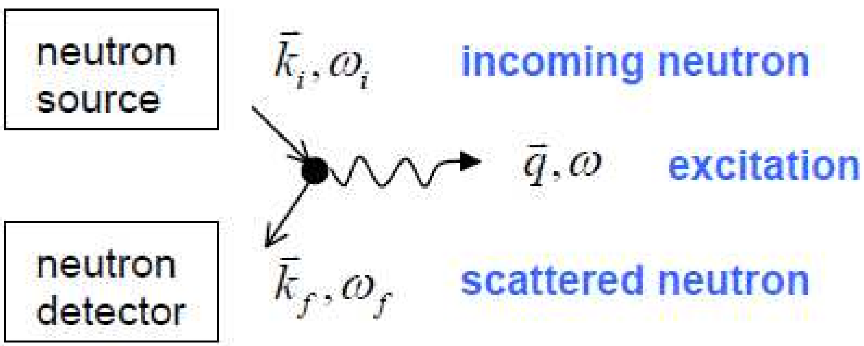
Neutron reflectivity from nonmagnetic and magnetic films
http://www.orau.org/council/02presentations/klose.pdf

Ferromagnetic mirrors



Polarized-beam reflectometer
http://www.orau.org/council/02presentations/klose.pdf

Inelastic Neutron Scattering



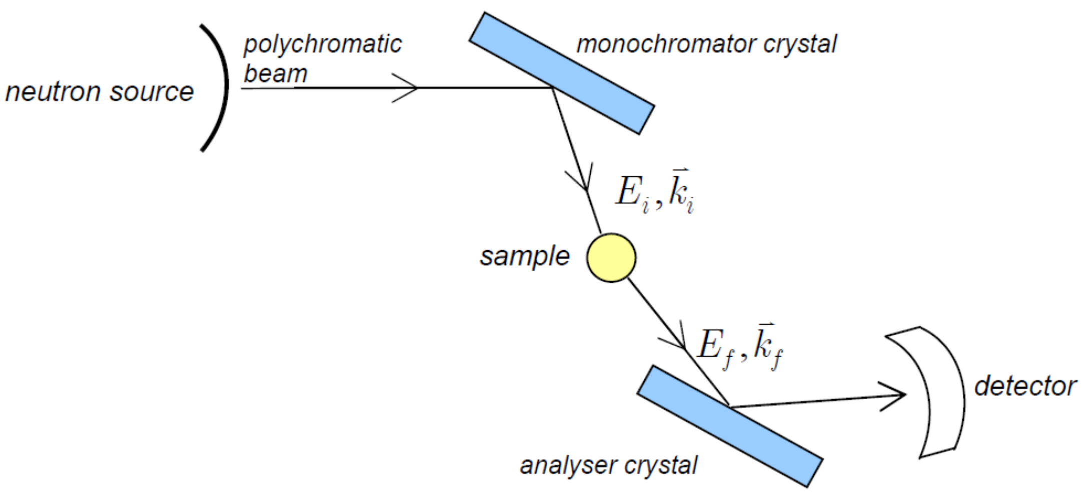
$$\vec{Q} = \vec{k}_f - \vec{k}_i$$

$$\omega = \omega_f - \omega_i = \frac{\hbar}{2m_n}\left(k_f^{\,2} - k_i^{\,2}\right)$$

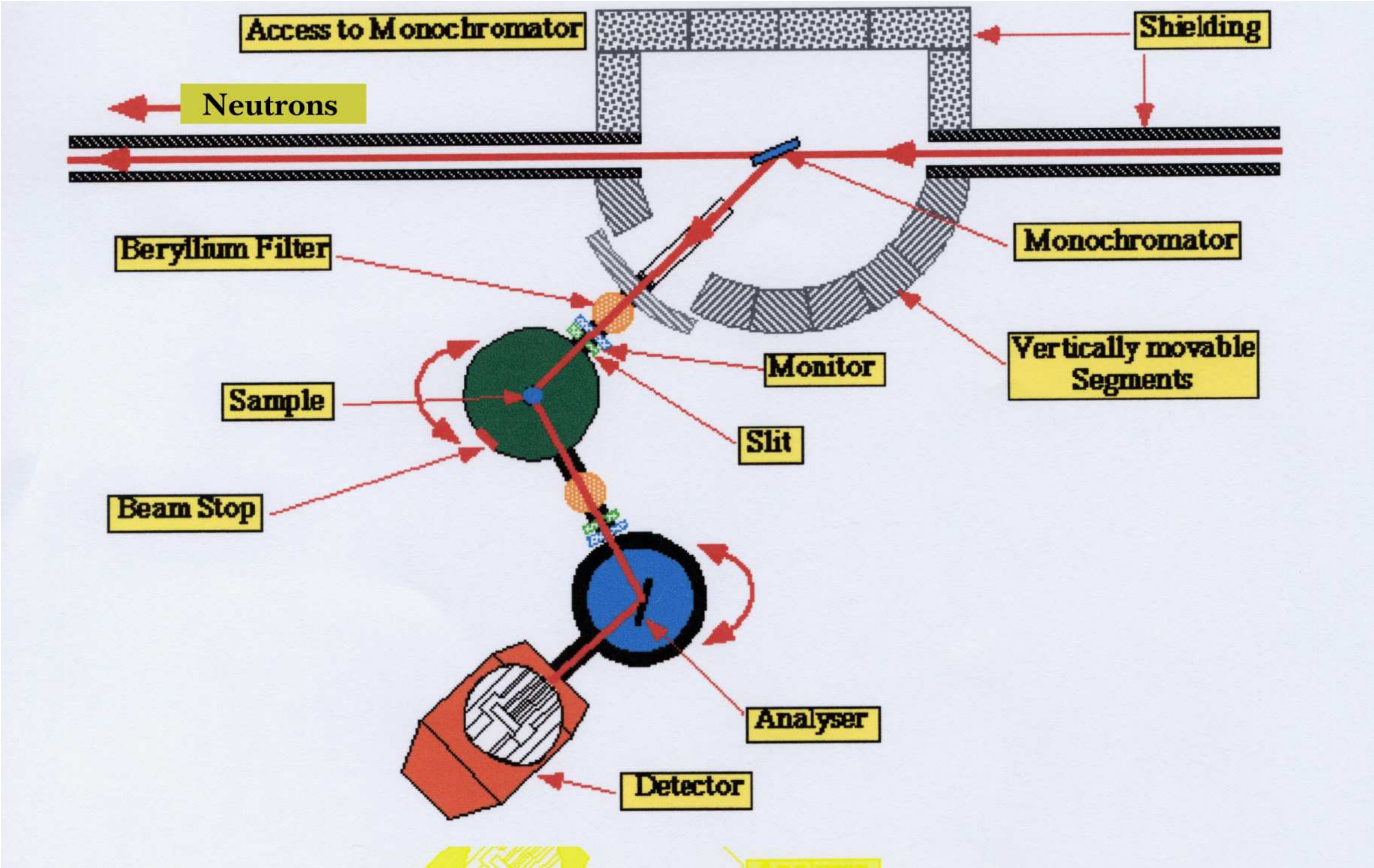
$\omega = 0$ elastic scattering

$\omega \neq 0$ inelastic scattering

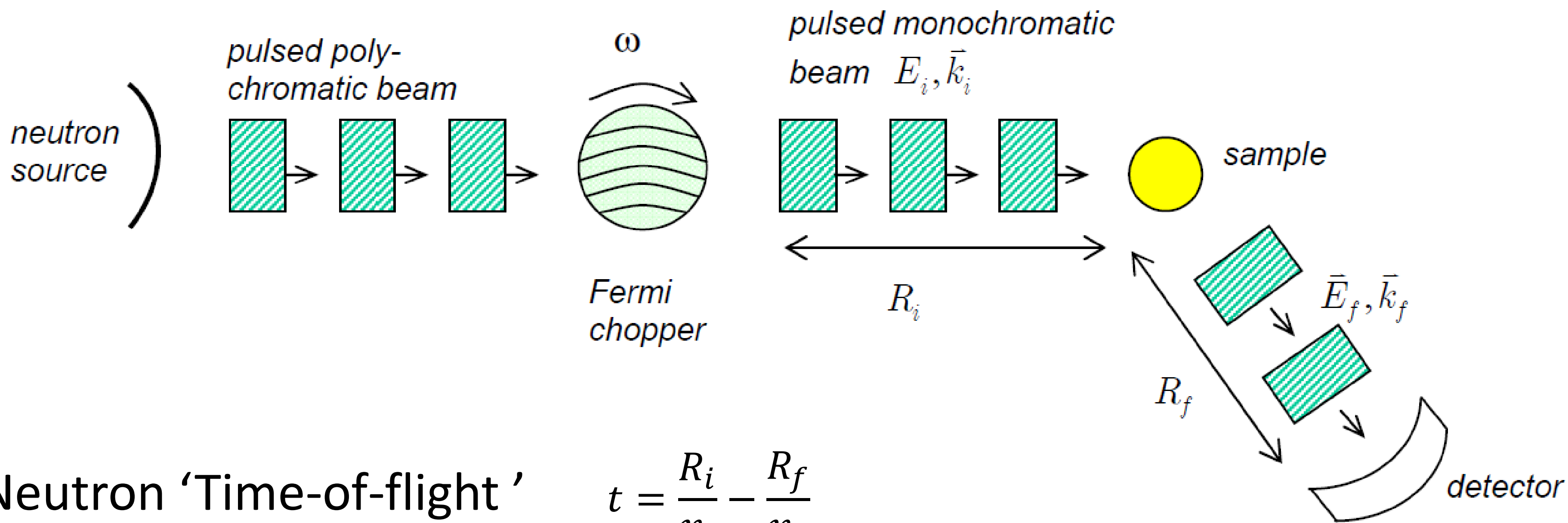
Triple Axis Spectrometer



Triple Axis Spectrometer



Time-of-Flight Spectrometer



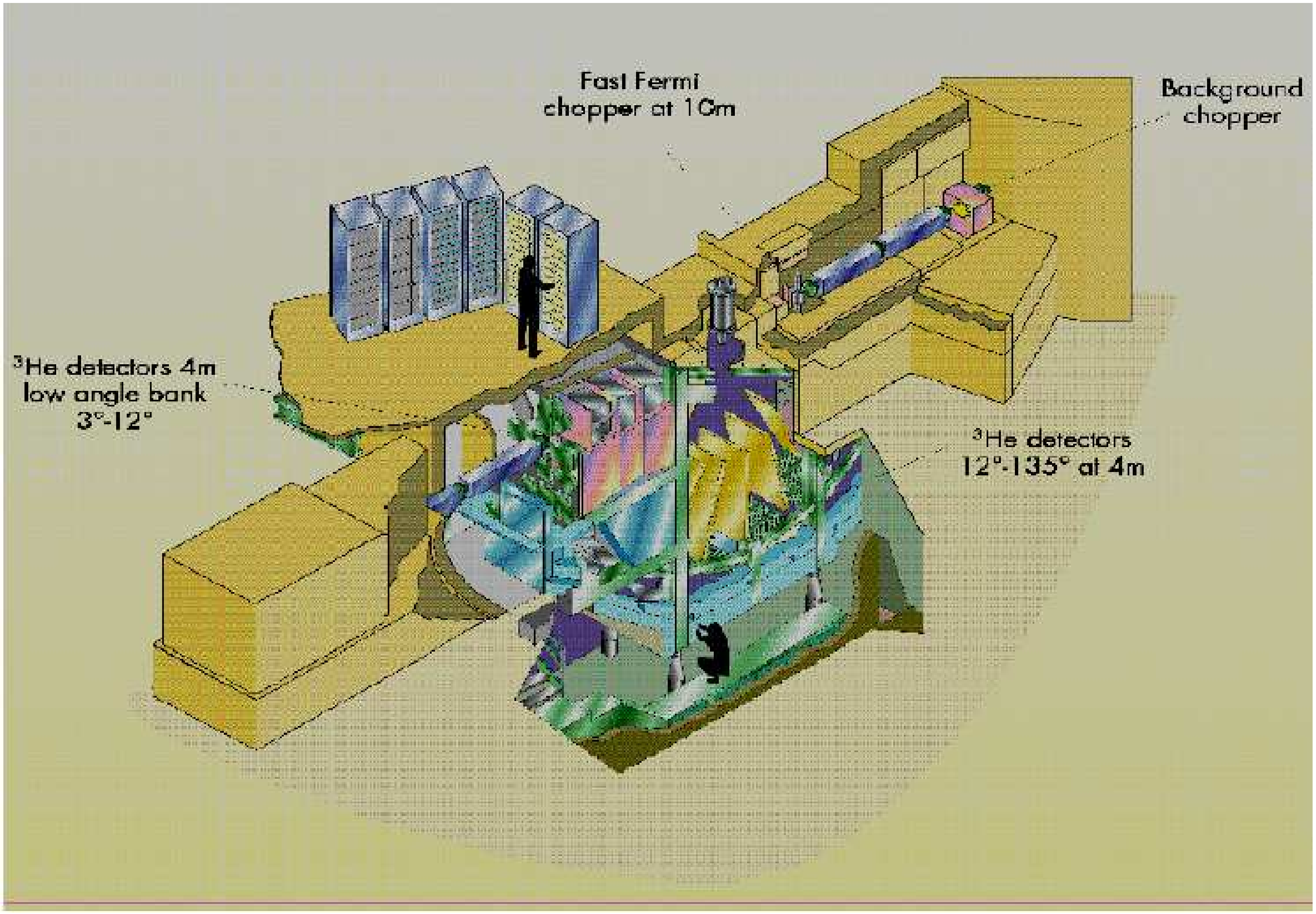
Neutron 'Time-of-flight '

$$t = \frac{R_i}{v_i} - \frac{R_f}{v_f}$$

$$v_f = \frac{R_f}{t - {R_i}/{v_i}}$$

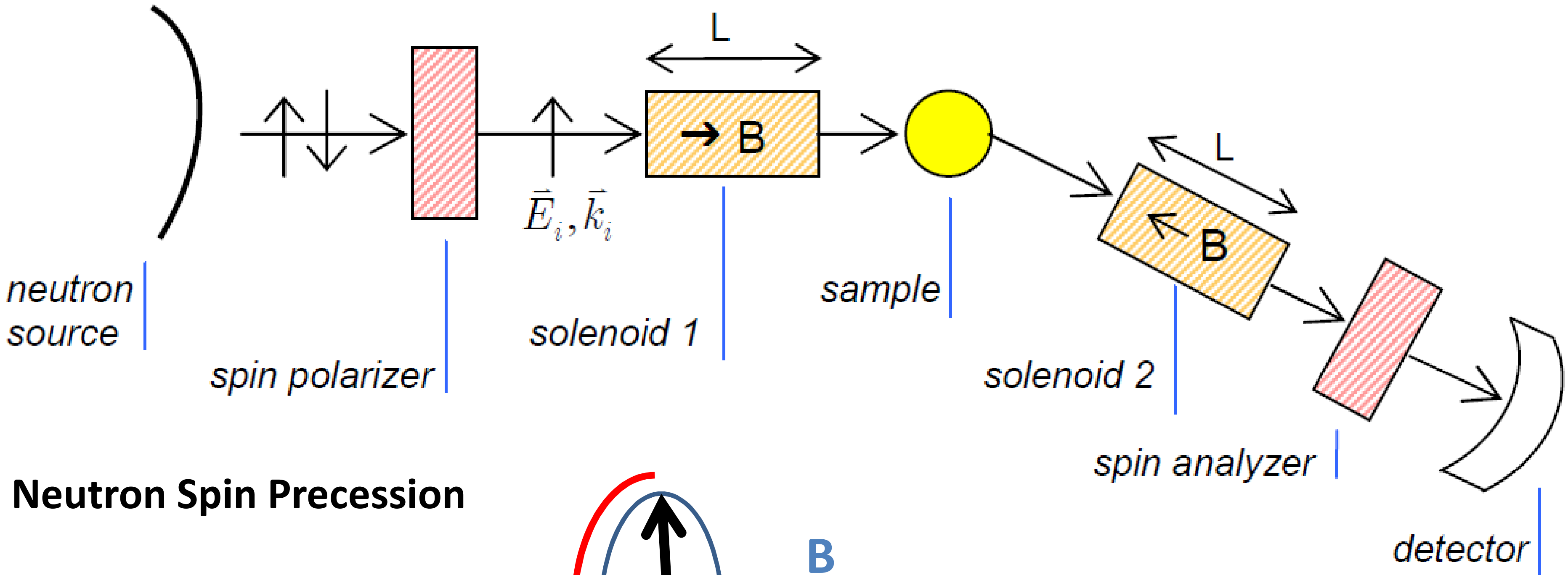
$$E_f = \frac{1}{2} m_N {v_f}^2 = \frac{1}{2} m_N \left(\frac{R_f}{t - {R_i}/{v_i}} \right)^2$$

Time-of-Flight Spectrometer



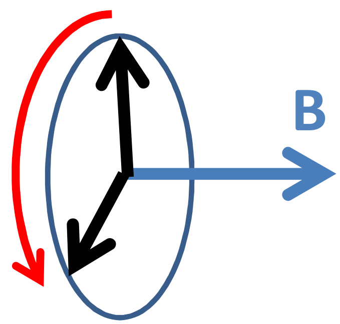
MARI Spectrometer @ISIS

Spin-Echo Spectrometer



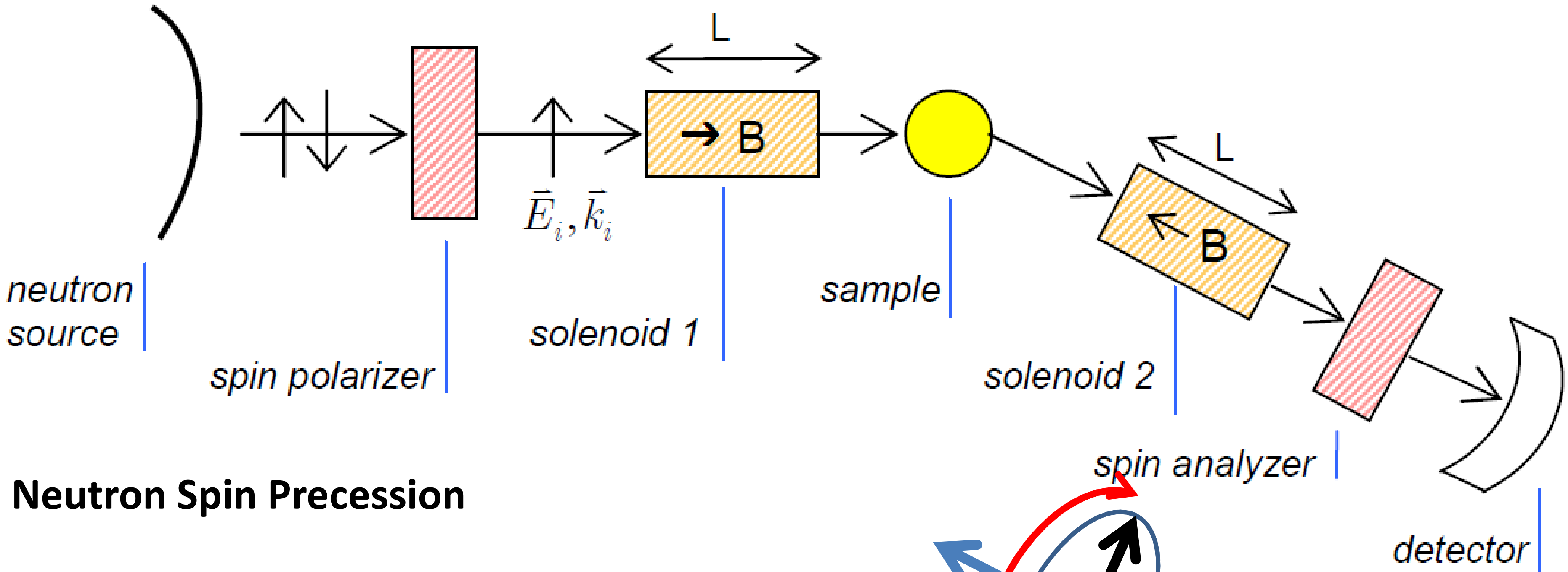
Neutron Spin Precession

$$\phi_i = \omega_L t = \omega_L \frac{L}{v_i}$$



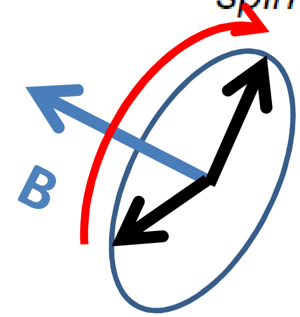
Larmor precession frequency $\omega_L = \frac{\gamma \mu_N B}{\hbar}$

Spin-Echo Spectrometer



Neutron Spin Precession

$$\phi_f = -\omega_L t$$
$$= -\omega_L \frac{L}{v_f}$$



Back to initial polarization if $v_i = v_f$ (elastic scattering)

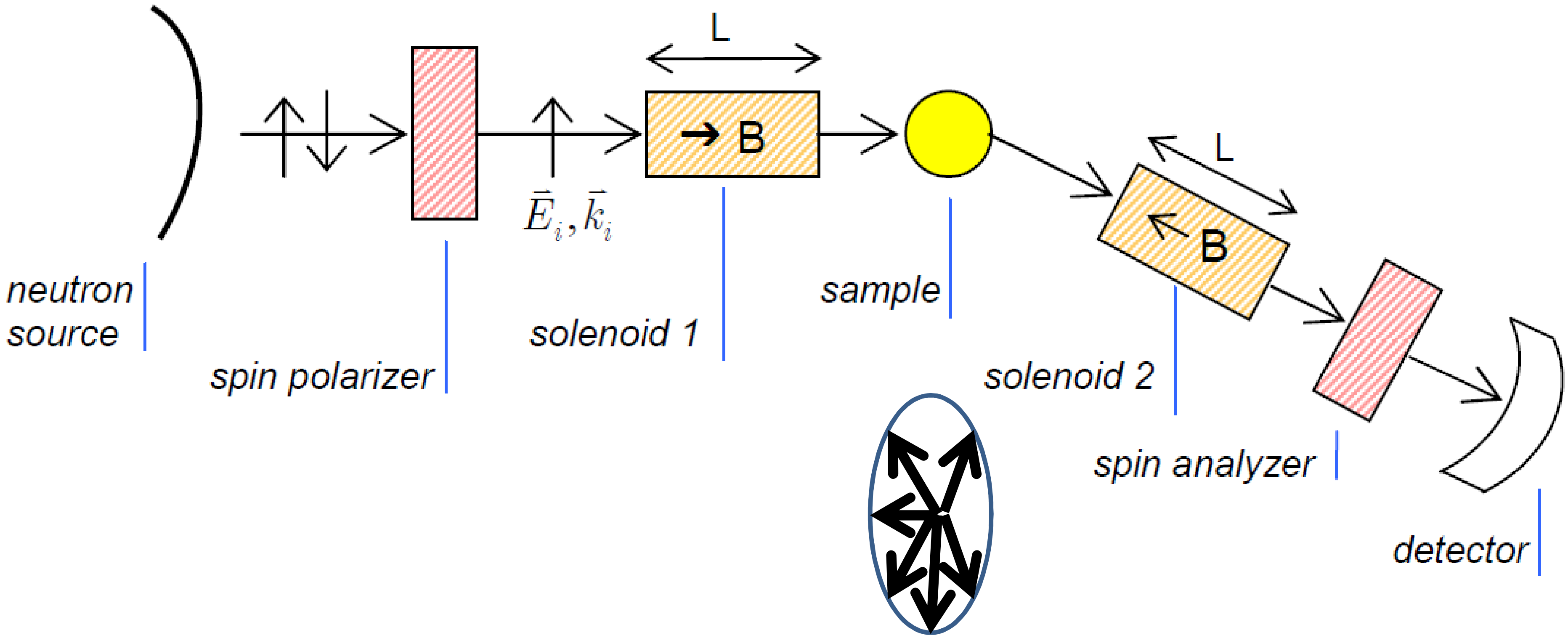
But shift $\Delta\phi$ if $v_f = v_i + \Delta v \neq v_i$

$$\Delta\phi = \phi_i - \phi_f = \omega_L L\left(\frac{1}{v_i} - \frac{1}{v_i + \Delta v}\right) \sim \frac{\omega_L L}{{v_i}^2}\Delta v$$

$$\hbar\omega = \frac{m_N}{2}\left({v_f}^2 - {v_i}^2\right) = m_N \Delta v$$

$$\Delta\phi \sim \frac{\omega_L L}{{v_i}^3}\frac{\hbar\omega}{m_N} = \omega_L \tau_{SE}$$

Spin-Echo Spectrometer



NB: If the beam is not perfectly monochromatic (spread of v_i),
it is depolarized at the sample position BUT recombination works the same !

Consequence: monochromaticity of the incident beam does not limit the experimental resolution that can be enhanced by order of magnitudes here !

Spin-Echo Spectrometer

NSE at NIST
http://www.ncnr.nist.gov/instruments/nse/NSE_70deg_20010226.png

Neutron scattering from quantum condensed matter

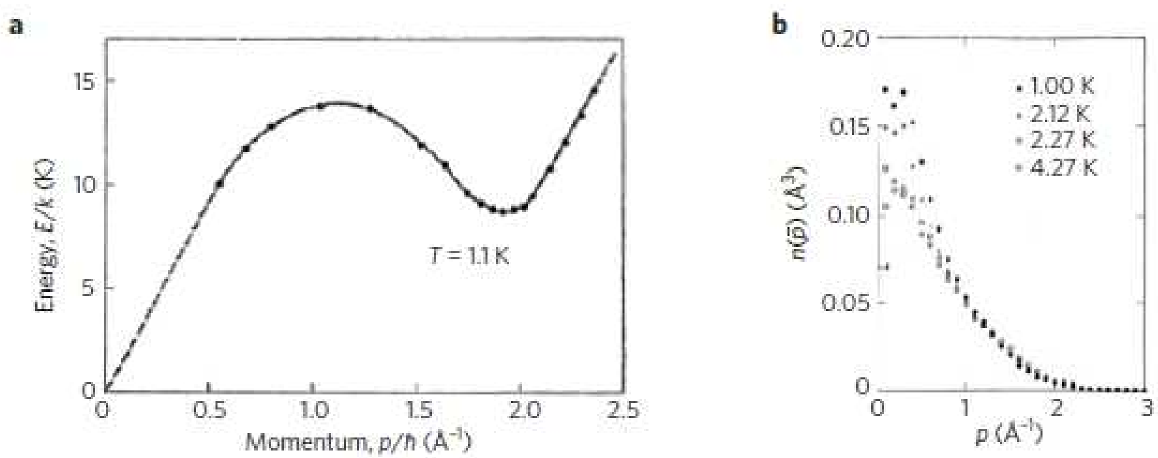
Steven T. Bramwell and Bernhard Keimer

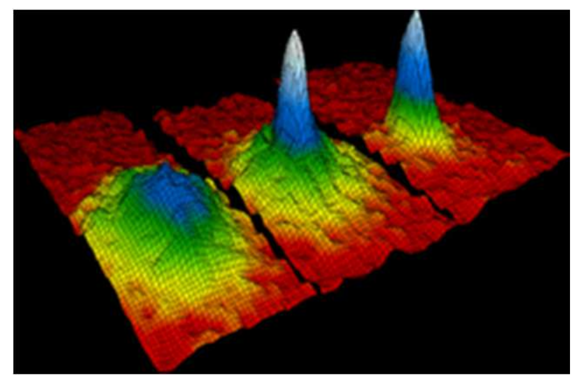
Collective quantum phenomena such as magnetism, superfluidity and superconductivity have been pre-eminent themes of condensed-matter physics in the past century. Neutron scattering has provided unique insights into the microscopic origin of these phenomena.

NATURE MATERIALS | VOL 13 | AUGUST 2014 | www.nature.com/naturematerials 763

Ex: Superfluid He

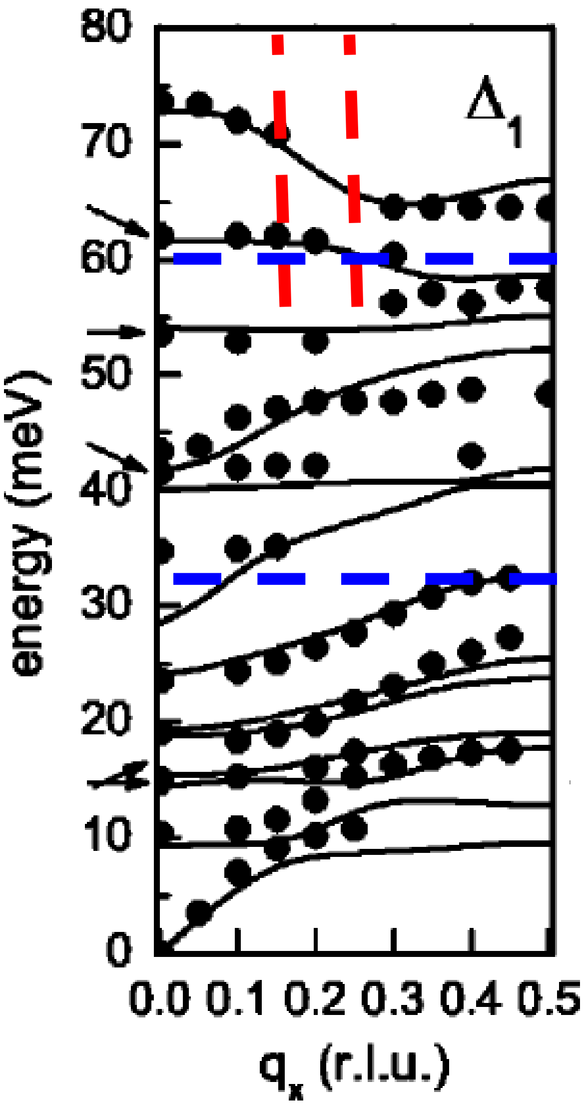
Analogy with BEC



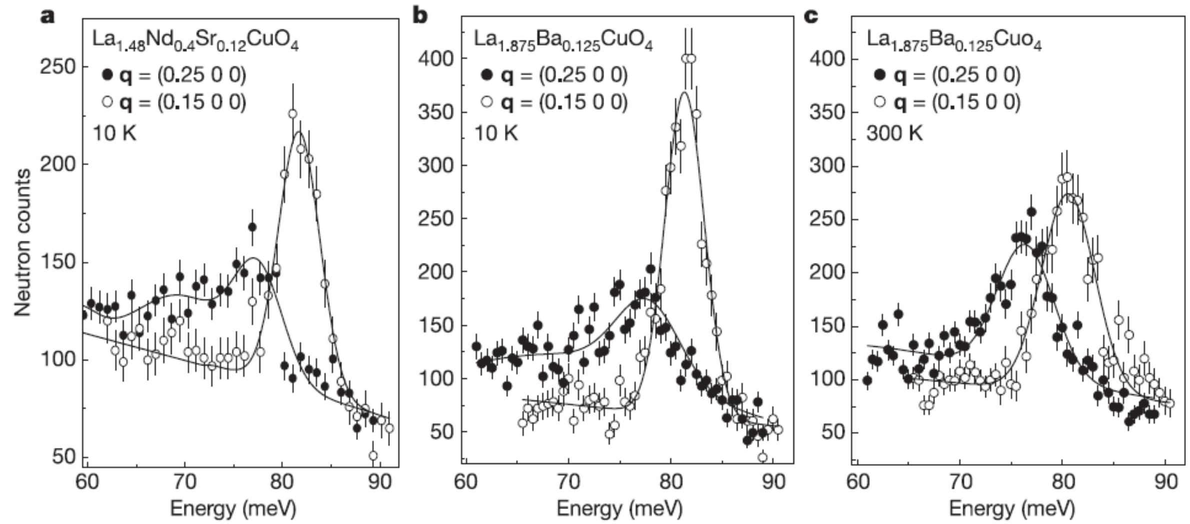


Triple Axis Spectrometer

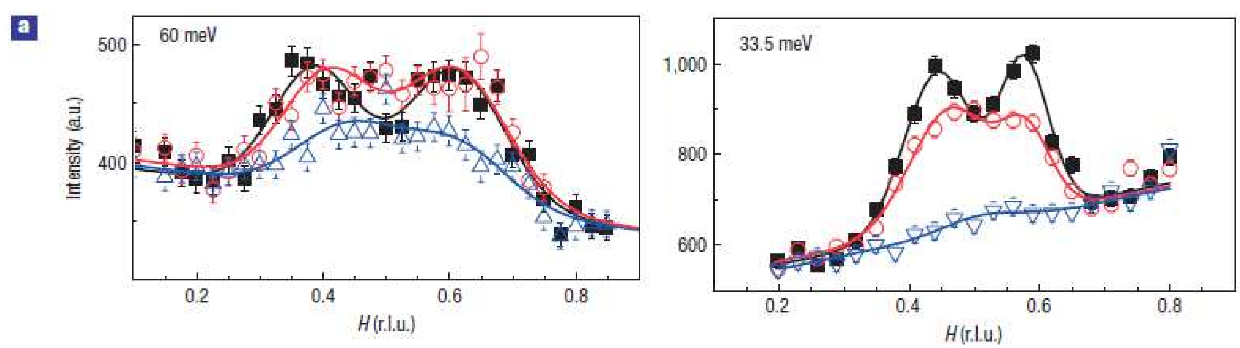
Dispersion Measurement



Constant-q scans

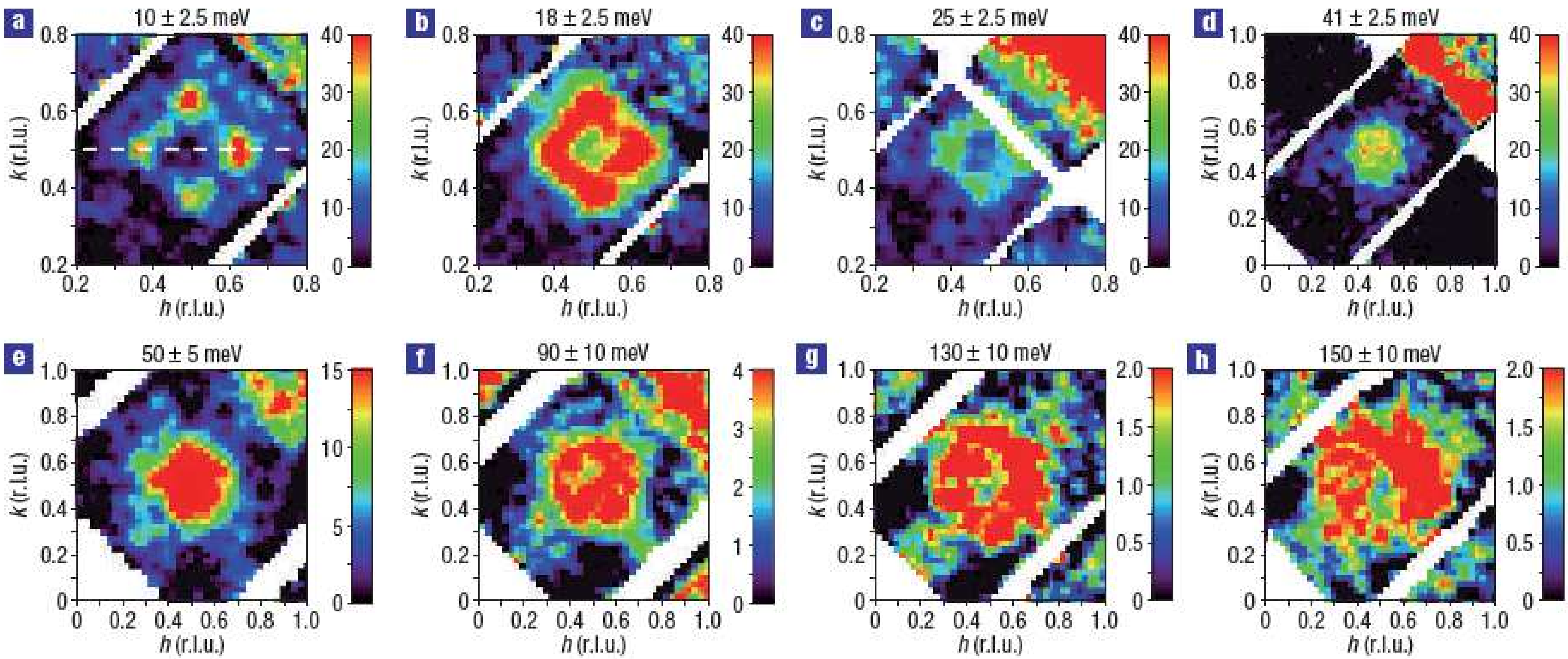


Constant-E scans (nb: here magnons)



Pintschovius et al. PRB 2004
Reznik et al. Nature 2006
Hinkov et al. Nature Physics 2007

Time-of-Flight Spectrometer



Reciprocal space maps at constant energy transfer

Vignolle et al. Nature Physics **3** 163 (2007)