The neutron: an introduction

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The neutron: discovery & properties

In 1932 the 'neutron' was waiting to be discovered in many Laboratories

The reaction that led Chadwick at the Cavendish (Cambridge) to the discovery was

$$^{9}Be + \alpha = {}^{12}C + n$$

The discovery was made based on the conservation of mass.

$m_n = 1.008665$ atomic units

$\mu_n = -1.913\ \mu_N$ (nuclear magnetons)

Charge $q_n = (1.5 \pm 2.2) \times 10^{-22}$ proton charge; i.e. ~ zero

Electric dipole moment $< 6 \times 10^{-25}$ e-cm, i.e. zero

Properties of the neutron

The neutron is unstable and decays with half-life of **925(10) secs**

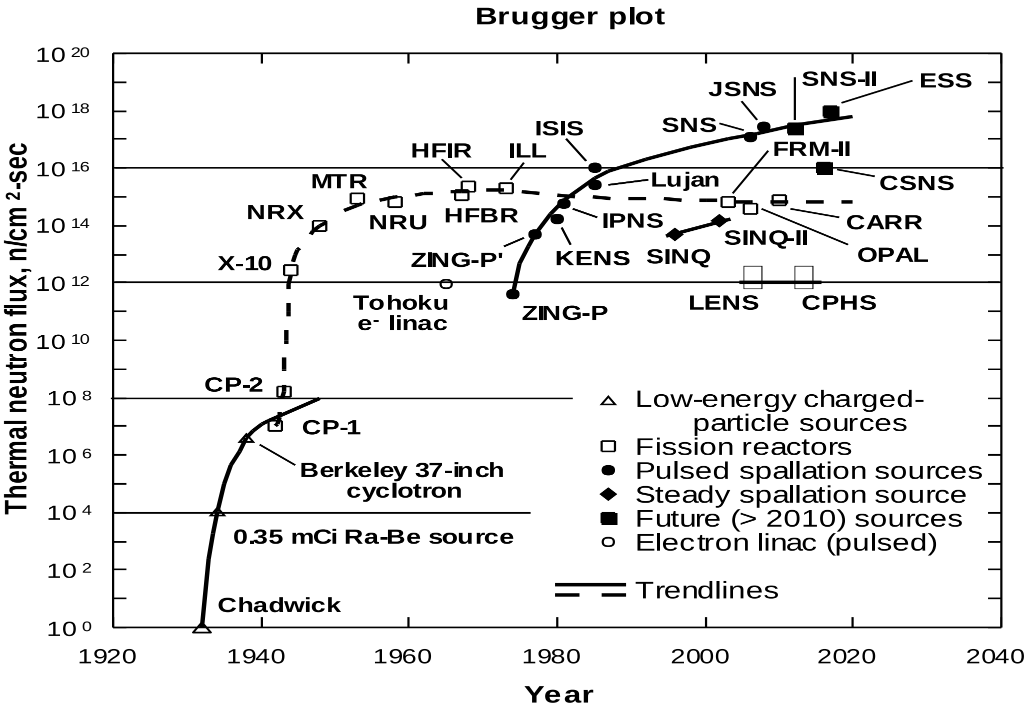
$$n \rightarrow p \text{ (proton)} + e \text{ (electron)} + \nu \text{ (antineutrino)}$$

The neutron consists of a proton + π meson. It is the disassociation into the proton and π meson that is responsible for the magnetic moment. At a more fundamental level it involves *"3 quarks held together by a vector (spin 1) bosons called gluons with a small admixture of quark–antiquark pairs"*

The up-quark has charge of +2*e*/3 and the down-quark one of - *e*/3. Thus the neutron, consisting of two down-quarks and one up-quark, is electrically neutral, whereas the proton, consisting of two up-quarks and one down-quark, has a charge of +*e*.

The diffraction of neutrons was already demonstrated in 1936, using neutrons from Be sources. Much of the theory of scattering was worked out by Halpern & Johnson in 1939.

Advances in the effective thermal flux for neutron experiments



What changed neutron scattering was new technology - the fission reactor

Production of neutrons

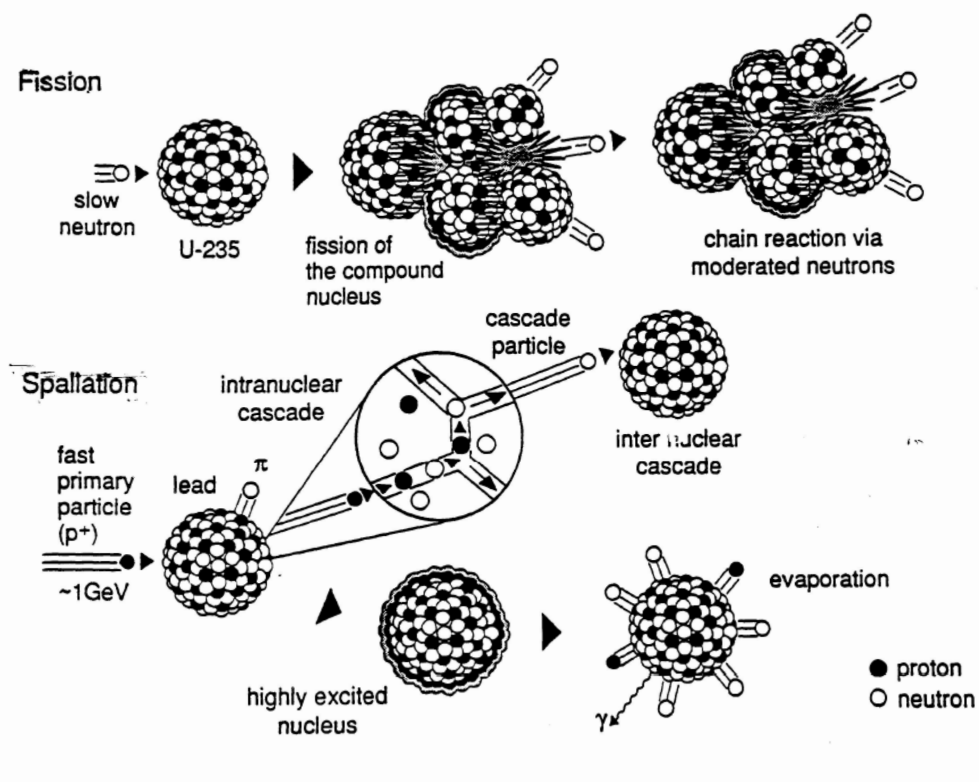


Figure 2: Schematic representation of fission and spallation

Note the high cost in heat production with fission (200 MeV/n); the smaller (~25) for spallation and even smaller (~3) for fusion.

Reaction		Yield n per particle or per event	Deposited Heat MeV/n
T(d,n)	(0.2 MeV)	8×10^{-5} n/d	2500
W(e,n)	35 MeV)	1.7×10^{-2} n/e	2000
^{9}Be(d,n)	(15 MeV)	1.2×10^{-2} n/d	1200
Fission	(^{235}U(n,f))	~ 1 n/fission*	200
(T,d) fusion		~ 1 n/fusion	3
Pb spallation	(1 GeV)	20 n/p**	23
^{238}U spallation	(1 GeV)	40 n/p**	50

* The yield per fission event is 2.4 but ~ 1.4 neutrons are required to maintain the reaction and compensate for parasitic losses.

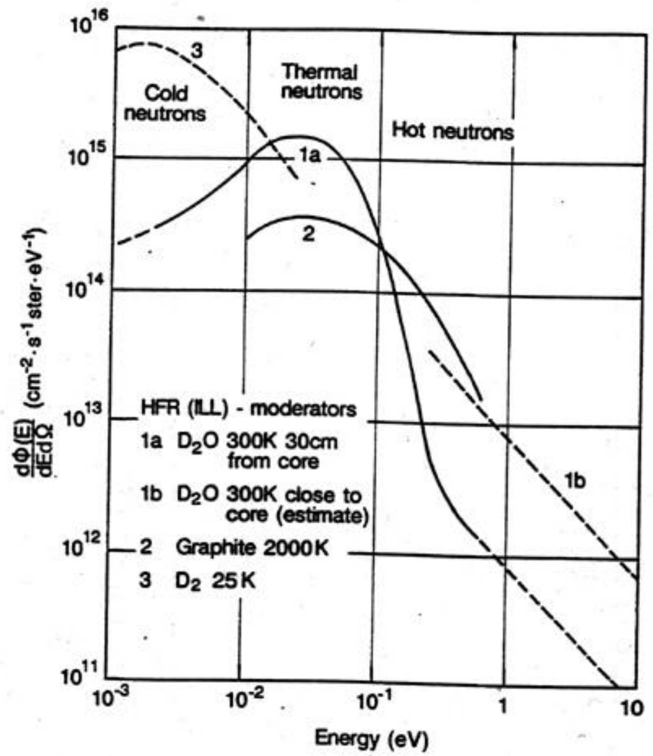
** For 60 cm long targets, 20 cm Ø for Pb and 10 cm Ø for ^{238}U

Table 2: Neutron yields and deposited heat for some neutron producing reactions [1]

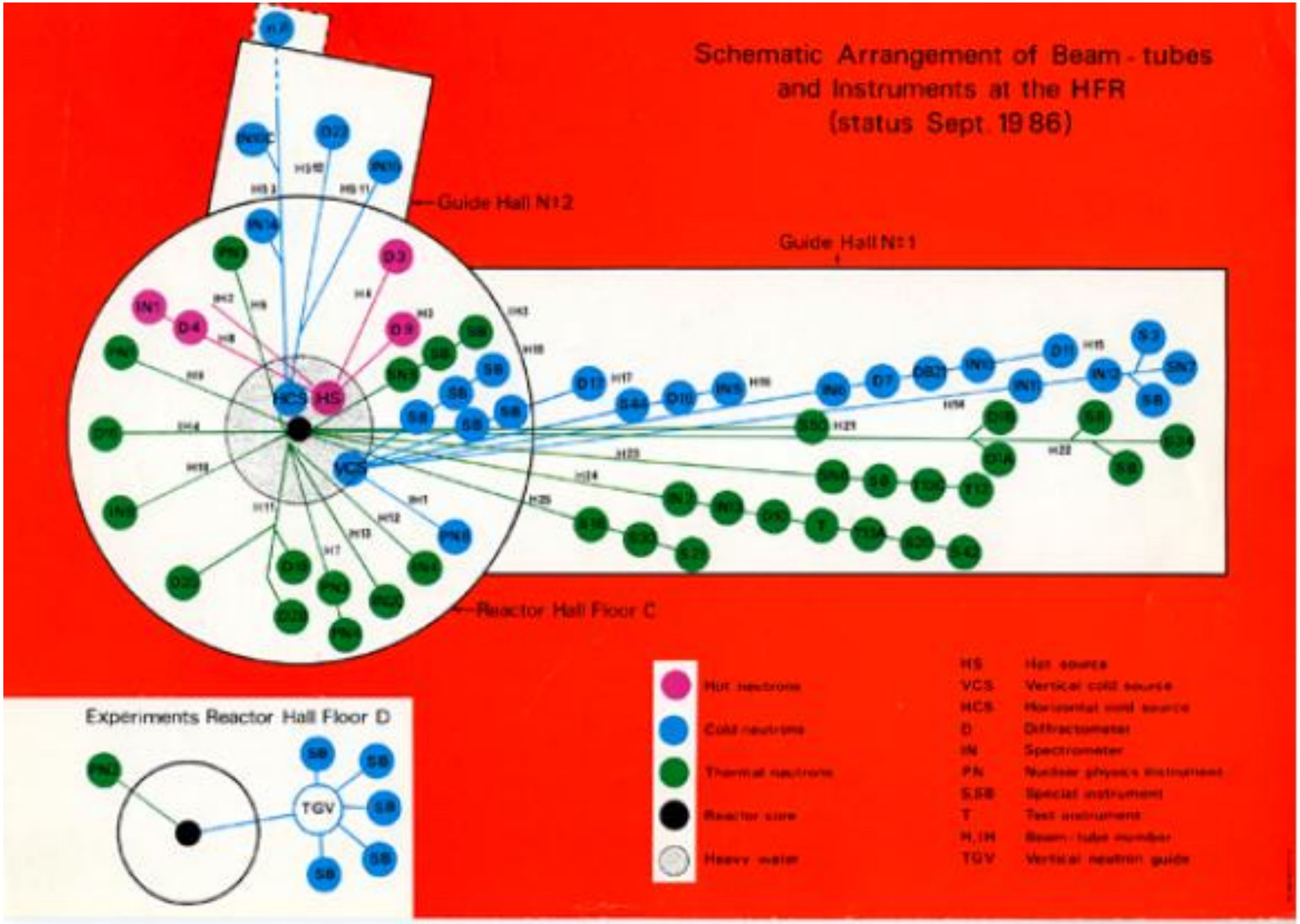
Moderation and tailoring the spectral distribution

When the neutrons emerge from the reactor they have a thermal spectrum, but often we want more "hot" (higher energy, shorter wavelength) or "cold" (lower energy or longer wavelength) neutrons.

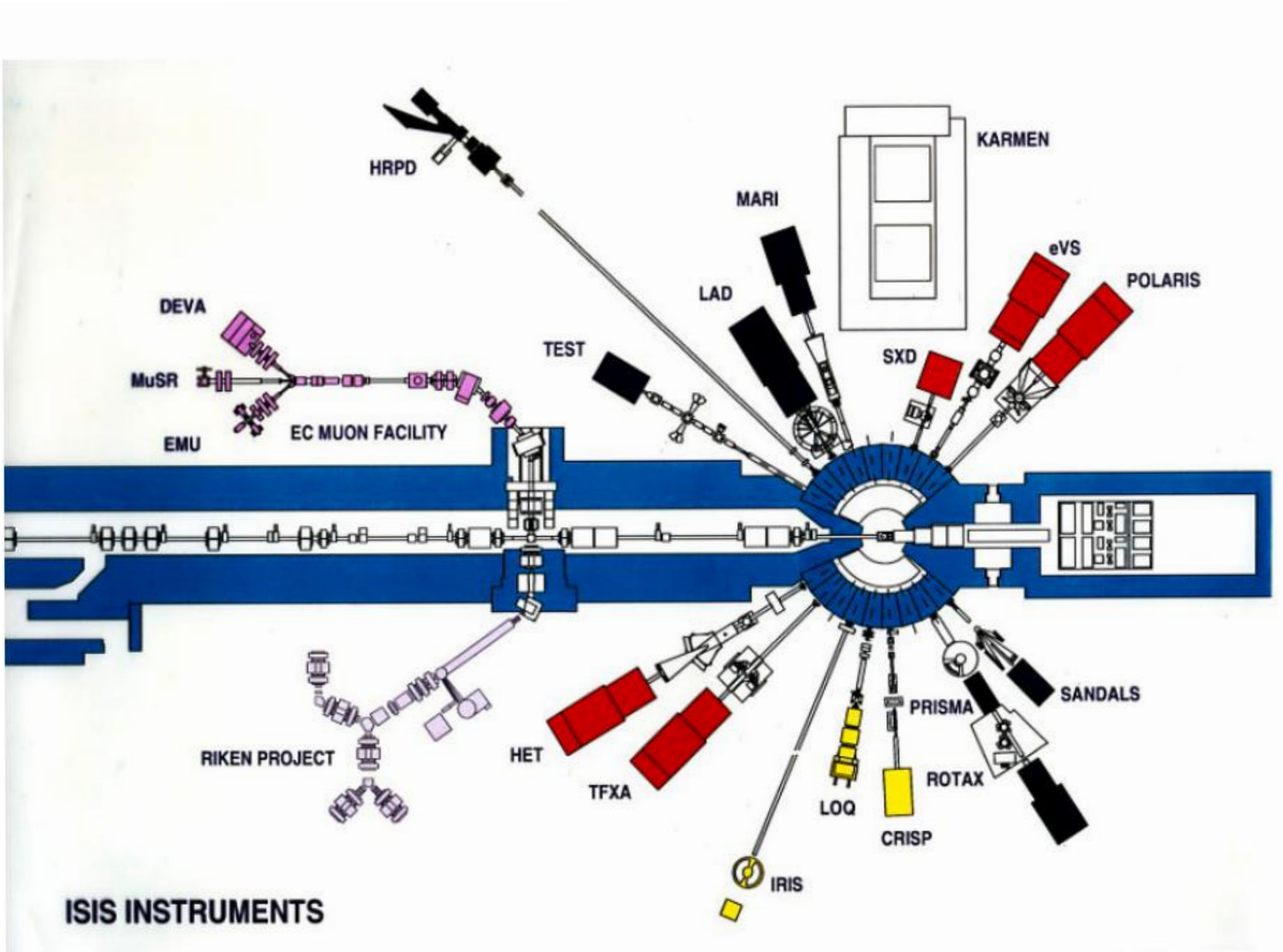
To obtain such distributions we pass the neutrons into "moderators". These change the spectral distribution as the neutron "gas" comes into equilibrium with the moderators.



Beam tube arrangements at the ILL, Grenoble



Instrument outline at the ISIS pulsed source



Detection of neutrons

Since neutrons have zero charge they cannot be detected directly, instead a charge particle needs to be produced and then detected.

<u>Counters</u>:

BF_3 $\quad$ $^{10}B_5 + {}^1n_0 \rightarrow {}^7Li_3 + {}^4He_2 + 2.7\ \mathrm{MeV}$

^3He $\quad$ $^3He_2 + {}^1n_0 \rightarrow {}^3H_1 + {}^1H_1$

<u>Film/scintillators</u>:

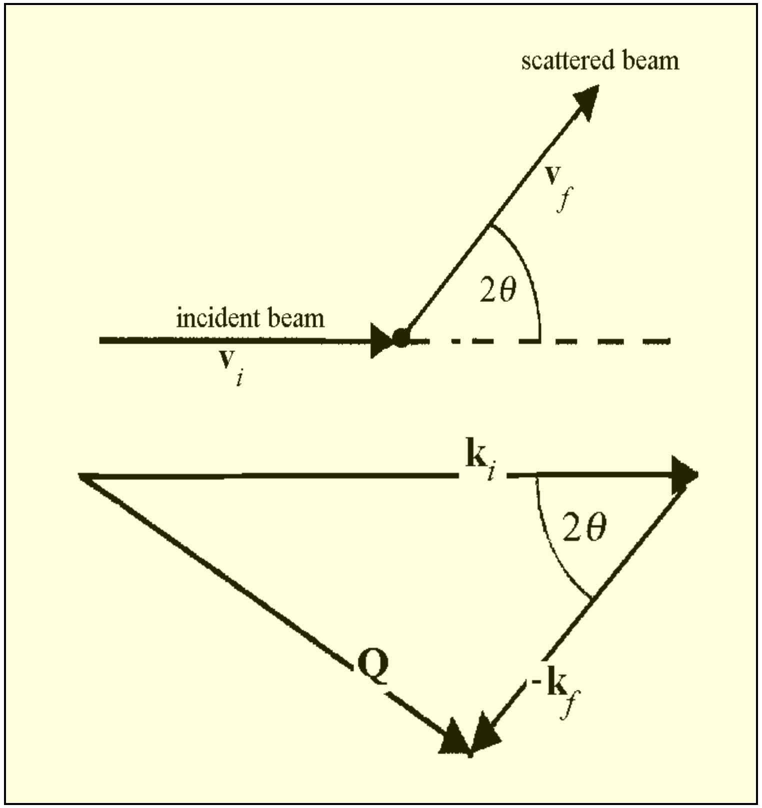
$$^6Li_3 + {}^1n_0 \rightarrow {}^3H_1 + {}^4He_2$$

Most detectors need bulky shielding as they are sensitive also to γ rays

Scattering process

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

$$\hbar\omega = E_i - E_f = \frac{\hbar^2}{2m_n}\left(k_i^2 - k_f^2\right)$$



$$|\mathbf{Q}|^2 = |\boldsymbol{k}_i|^2 + |\boldsymbol{k}_f|^2 - 2\,|\boldsymbol{k}_i||\boldsymbol{k}_f|\cos(2\theta)$$

In **elastic** scattering; $|\boldsymbol{k}_i| = |\boldsymbol{k}_f|$
so the above reduces to

$$|\mathbf{Q}| = 2|\boldsymbol{k}|\sin\theta$$

Since $|\boldsymbol{k}| = 2\pi/\lambda$; where $\lambda = h/(m_n v)$ {de Broglie}
Then $|\mathbf{Q}| = Q = (4\pi/\lambda)\sin\theta$

Neutron interactions

There are two we shall be concerned with: with the **nucleus** and with the **electron spins**. Others are very small and can be neglected, except in special cases.

Neutron-nuclei interaction. Since the nucleus is much smaller than the neutron wavelength, this is so-called "s" wave scattering and there will be *no momentum dependence*.

The potential will depend on the isotope and nuclear spin. However an average value exists, which is weighted over isotopes and nuclear spins and this value is tabulated. It is called $b_{coherent}$, or b_{coh}, or just b. $\sigma_{coh} = 4\pi(b_{coh})^2$

Incoherent cross section due to the fluctuations around the mean value is given by $\sigma_{inc} = 4\pi \; \{\langle b^2\rangle - \langle b\rangle^2\} = 4\pi \; (b_{inc})^2$

Nuclear interaction

Nuclear positions in unit cell – **same as crystal structure as strong Coulomb interaction assures that nucleus is at center of electron cloud (Ze)**

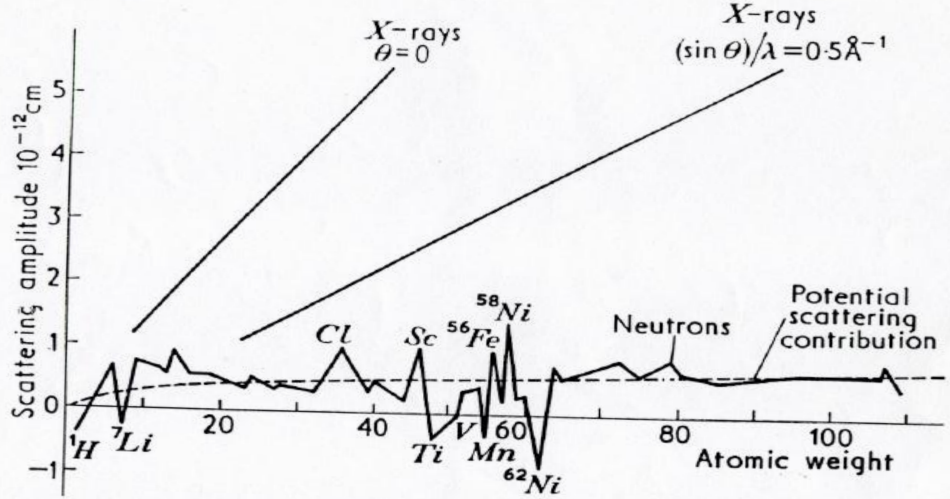
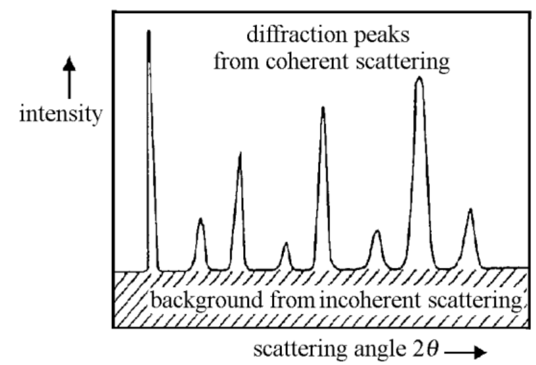


FIG. 14. Irregular variation of neutron scattering amplitude with atomic weight due to superposition of 'resonance scattering' on the slowly increasing 'potential scattering': for comparison the regular increase for X-rays is shown. (From *Research*, London, 7, 257, 1954.)



In a few cases, e.g. H and V, $(b_{inc})^2 >> (b_{coh})^2$
***not* true for D**

Variation of b_{coh} as f(Z); note –*ve* values and also small variation overall. Light/heavy atom distinction

Neutron–nuclear interaction

Averaging must be done over all isotopes, weighted by their abundance.

The spin of the nucleus is I and a compound nucleus may be formed with spin $I \pm 1/2$

This leads to

$$\sigma_{coh} = 4\pi\, b_{coh}^2 = 4\,\pi\,(w_+ b_+ + w_- b_-)^2$$

$$\boldsymbol{\sigma_{tot} = 4\,\pi\,(w_+ b_+^2 + w_- b_-^2)}$$

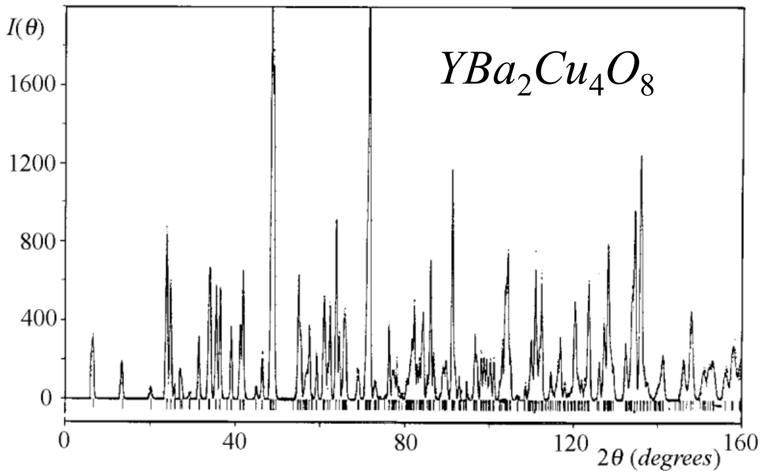
where $w_+ = (I+1)/(2I+1)$; $w_- = I/(2I+1)$; and $w_+ + w_- = 1$

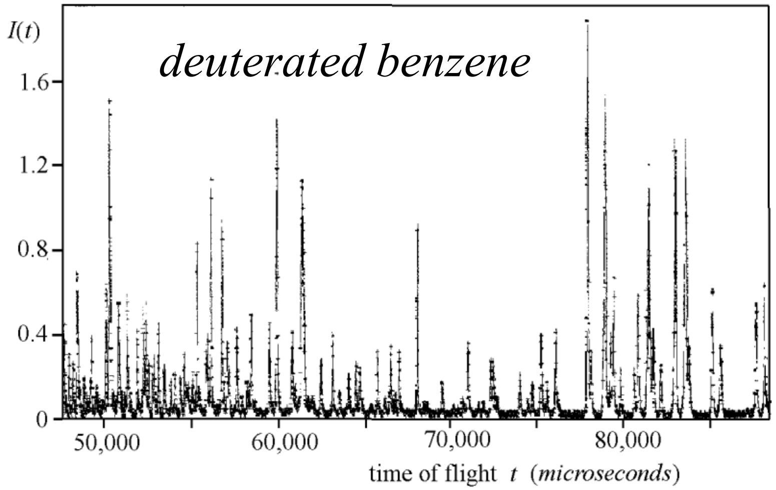
$$\boldsymbol{\sigma_{tot} = \sigma_{coh} + \sigma_{inc}}$$

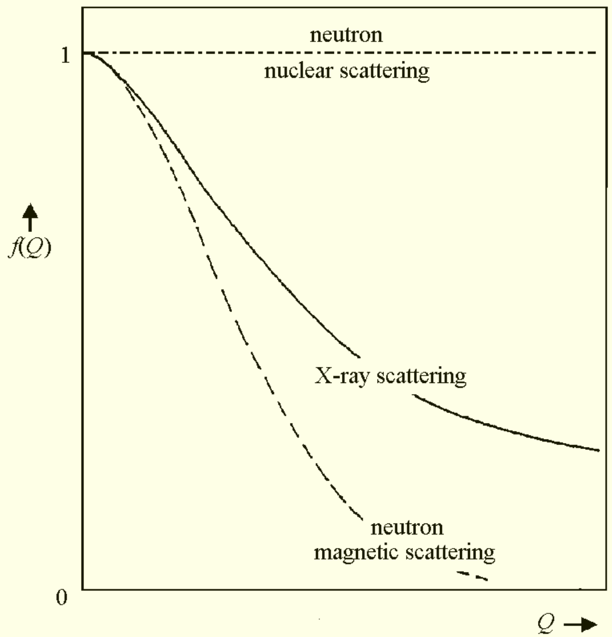
Unless polarised neutrons and low temperatures are used, the quantities σ_{coh} and σ_{inc} are constant for a given isotope dependence.

Nuclear scattering

The coherent part of the cross section







Data out to high Q as scattering is from nucleus, which is much smaller that radiation wavelength

Neutrons give better *T*-factors

Diffraction – neutron elastic scattering

For diffraction we are interested in the relationship between different particles, j and j' in the material. This is called the correlation function $S(\vec{Q},\omega)$ where $\vec{Q}$ is the momentum transfer and $\hbar\omega$ is the energy transfer. For diffraction there is no energy transfer.

$$S(\vec{Q},0) \propto \sum_{jj'} \left\langle \exp[-i\vec{Q}\bullet\vec{R}_j(0)] \right\rangle \left\langle \exp[+i\vec{Q}\bullet\vec{R}_{j'}(0)] \right\rangle$$

This leads to the familiar structure factor and the intensity given by

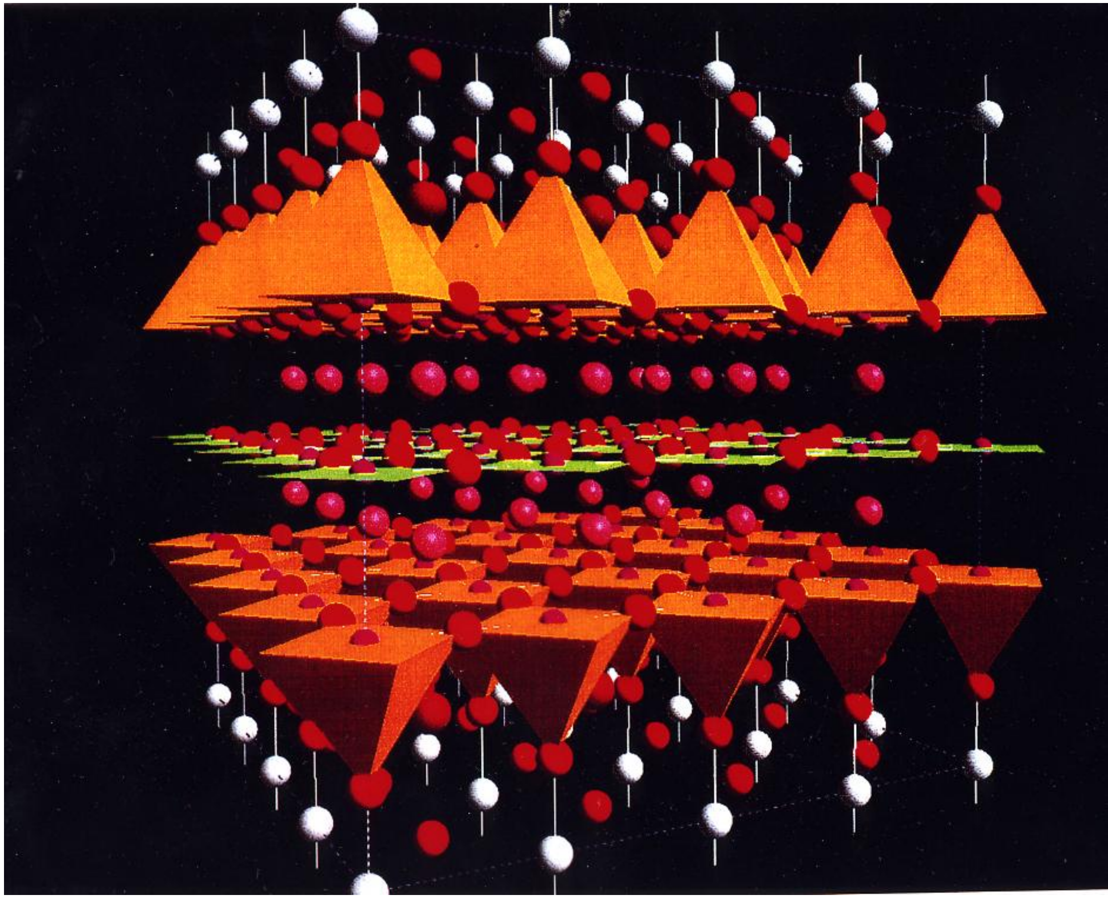
$$I \propto \left(\frac{d^2\sigma}{d\Omega\, d\omega} \right) \propto \frac{k_f}{k_i} S(\vec{Q},0)$$

Structural information at the atomic level from neutrons

This is the atomic structure of the famous superconductor $YBa_2Cu_3O_{6.5}$ (T_c ~ 93 K)

When it was discovered in 1987 the question was the relation of the Cu and oxygen. X-rays could not detect O in the presence of the heavier atoms and got the structure wrong.

It was solved with neutrons at ILL and ANL at the same time from powder diffraction.



The incoherent cross section

The coherent cross section dominates for most atoms and allows us to determine the position of one atom with respect to the others.

The incoherent cross section $4\pi\,(b_{inc})^2$ is given by

$$b_{inc}^{\;2} = \left[\overline{b^2} - \left(\overline{b}\right)^2\right]$$

The incoherent cross section tells us the correlations in space and time between a particle with itself, e.g. diffusion

The two most famous elements with large incoherent cross sections are H and V.

	H	**D**	
σ_{coh}	2	5.4	barns
σ_{inc}	***79***	2.1	barns

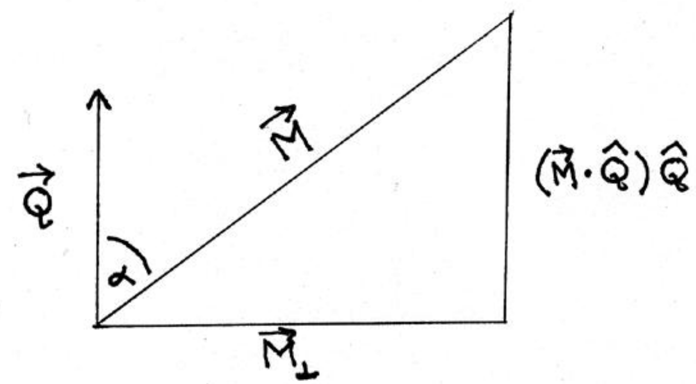
Neutron–electron interaction

The interaction is between the spin of the neutron and those of the unpaired spins in the solid. Since it is these same unpaired electron spins in the solid that give it its magnetic properties, the interaction is often called the ***magnetic interaction***.

Since the spins of a system have a direction, i.e. are vectorial in nature, this interaction is also vectorial.

$$\vec{M}_{\perp} = \hat{Q}\, x\, (\vec{M}\, x\, \hat{Q}) = \vec{M} - (\vec{M} \bullet \hat{Q})\hat{Q}$$

$$\left| M_{\perp} \right| = \left| \vec{M} \right| \sin^{2} \alpha$$



Neutron–electron interaction

Scattering is from electron spins and the orbital moment that they induce around the nucleus. These cannot be separated in neutron scattering so the total scattered intensity is proportional to the magnetic moment in the solid.

The fact that the scattering is from the electrons, which are located *outside* the nucleus and thus have spatial extent similar to the neutron's wavelength means that the scattering is not *s* wave and there is a "form factor", f(Q)

The magnetic scattering is generally weaker than the nuclear scattering, but for some elements can be larger.

Detection of antiferromagnetism in MnO

New peaks arise because the periodicity of the antiferromagnetic cell is larger than that of the lattice. In a cubic system with a powder sample the orientation of the moments cannot be determined, because of domain effects. In MnO we now know the spins lie almost along the <111> axes.

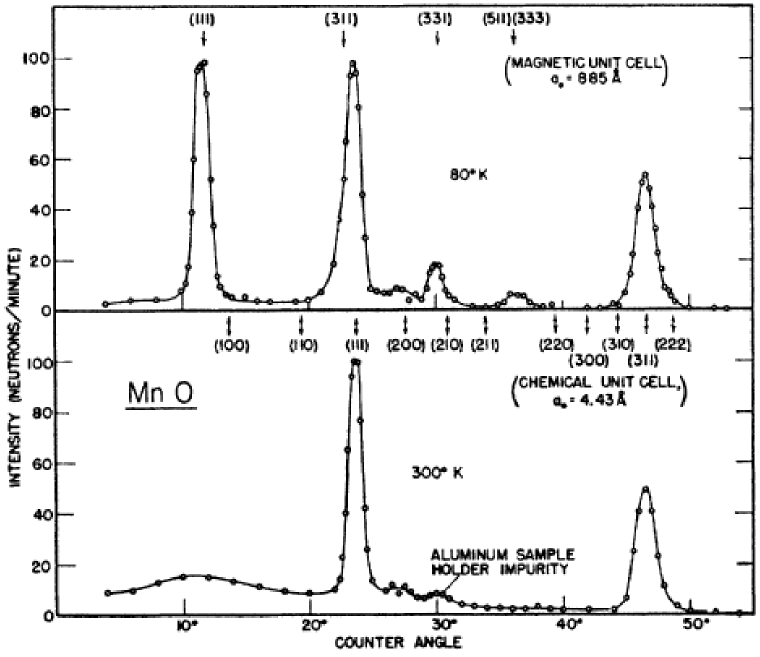
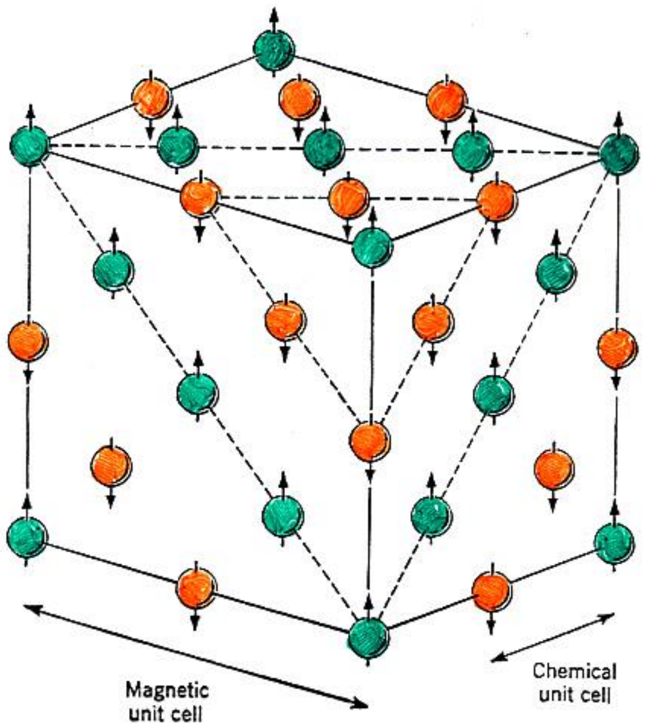


FIG. 1. Neutron diffraction patterns for MnO at room temperature and at 80°K.



C. G. Shull and J. S. Smart, Phys. Rev 76, 1256 (1949)

Advantages of neutrons

(1) Variation of b_{coh} – allows sensitivity to light atoms in the presence of heavy ones.

(2) Large difference between b_{coh} for H and D

(3) Presence of large b_{inc} for H. This allows examination of diffusion processes for H

(4) Neutrons have low energy; thus inelastic thermal processes can be examined.
1.8 Å neutron E = 25.2 meV = 293 K
1.8 Å photon E = 6.89 keV = 80 x 10^6 K

Advantages of Neutrons – continued

(5) Neutrons have a magnetic moment and hence interact strongly with magnetic materials

(6) Because they are neutral they penetrate easily; normally little absoprtion

(7) Weak interaction so the first Born approximation may be used; quantitative interpretation.

Disadvantages of neutron scattering

There are not enough of them! The fluxes are too low and the experiments take too long! The samples needed are too big!

For powder diffraction at least 100 mg;
For single crystal elastic a few mg
For single crystal inelastic 100 - 1000 mg.

Limitations of flux with neutrons

Even with new sources the neutron fluxes are severely limited. We have little more flux than x-ray tubes from the 1940s, whereas synchrotrons have extended fluxes 10 orders of magnitude!

The message here is: **don't try to use neutrons if you can solve it with x-rays**

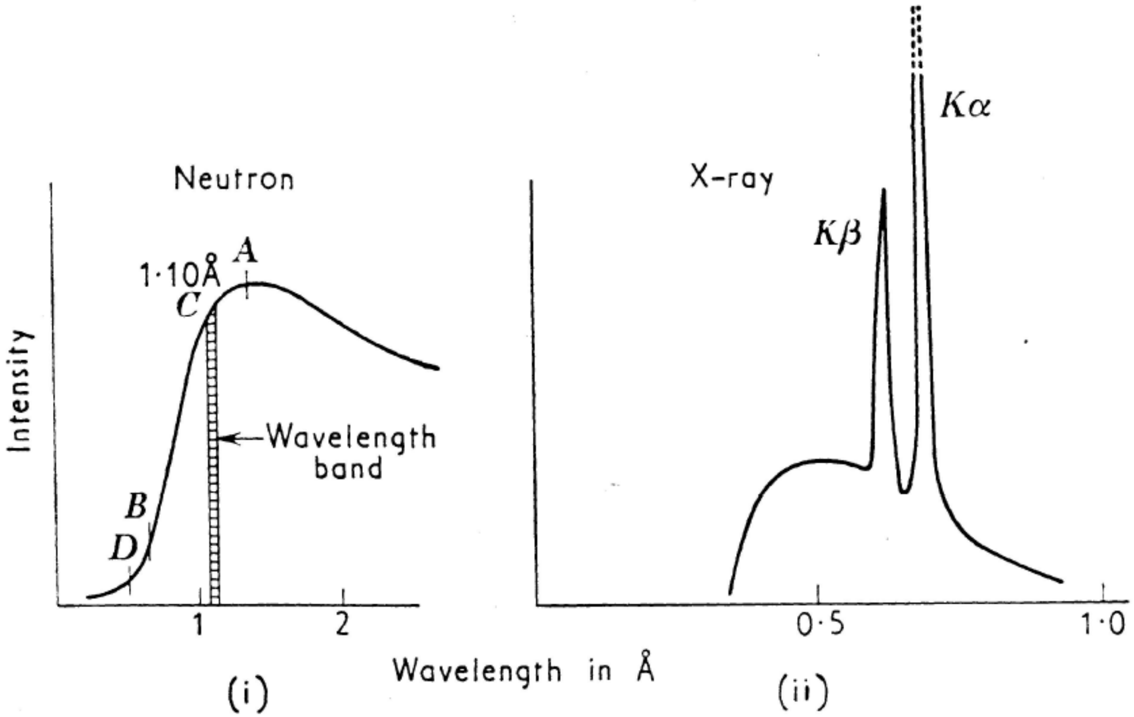
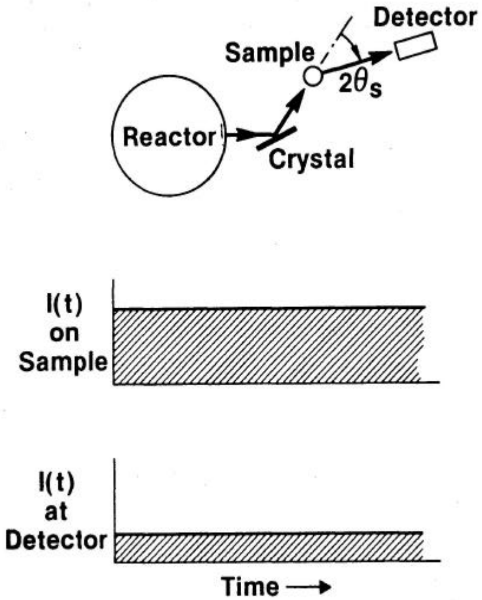


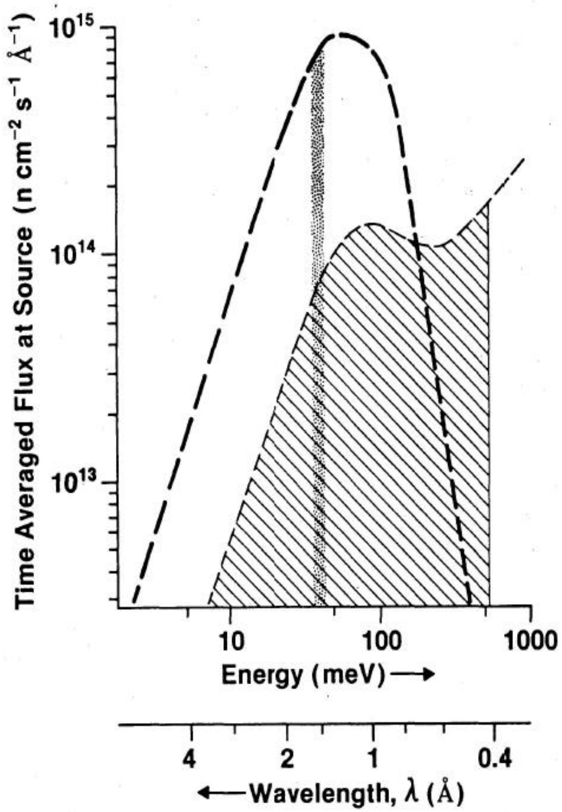
Fig. 2. The intensity versus wavelength distribution (i) for the neutron beam emerging from a reactor, indicating the band of wavelength selected by a monochromator, is contrasted with the distribution (ii) from an X-ray tube which gives intense lines of 'characteristic' radiation.

A simple comparison between diffraction from a powder sample at a reactor and pulsed source

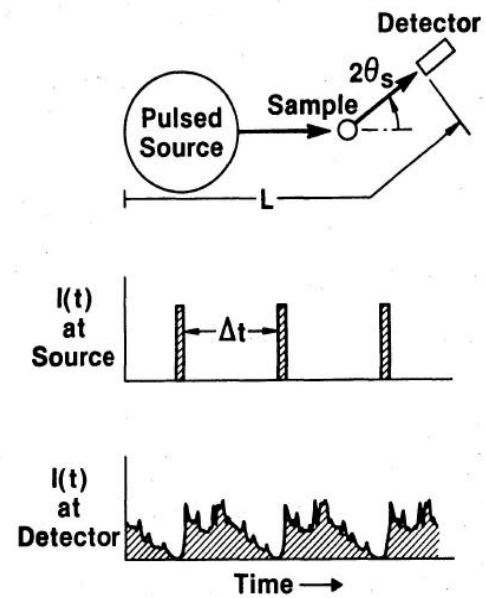
Variable θ
Fixed λ



Incident spectra



Variable λ
Fixed θ



$\sin \theta = \lambda/2d$

$\lambda = 2d \sin \theta$

Quantities to memorise for neutrons

E(meV) = 81.8/λ^2 where λ is in Å
1 meV = 11.6 K
E(5 meV) has λ = 4.05 Å

Thermal neutrons **25.3 meV = 293 K with λ =1.8Å**
v = 2200 m/s
E=6.11 Thz (1 THz ~ 4 meV)

$$\boldsymbol{Q} = \boldsymbol{k_i} - \boldsymbol{k_f}$$

$$\hbar\omega = E_i - E_f = \frac{\hbar^2}{2m_n}\left(k_i^2 - k_f^2\right)$$

$$|\mathbf{Q}|^2 = |\boldsymbol{k_i}|^2 + |\boldsymbol{k_f}|^2 - 2\,|\boldsymbol{k_i}||\boldsymbol{k_f}|\cos(2\theta)$$