neutrons: what for? and how?

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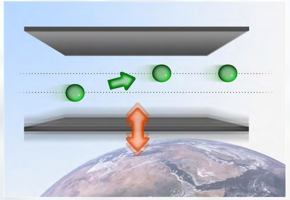
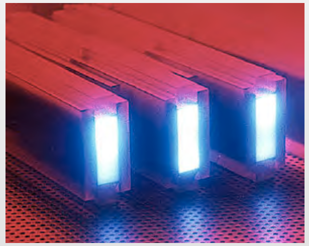
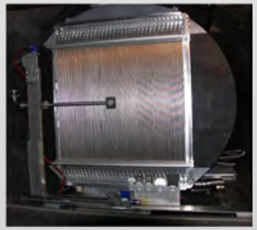
ESS AB, Lund Sweden

experiments with neutron beams



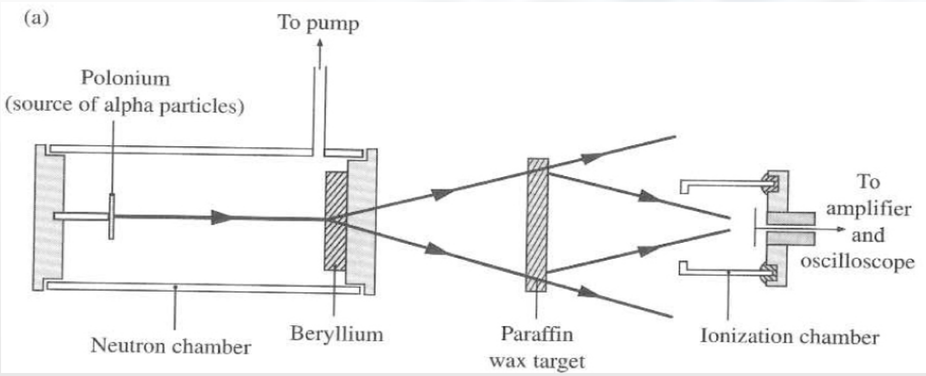
- neutron properties
- neutron scattering applications
- neutron sources
- instruments and applications





the discovery of the neutron

James Chadwick 1932



Cavendish Laboratory, Cambridge

neutrons: no charge, mass close to proton – 1.675 10^{-23} kg

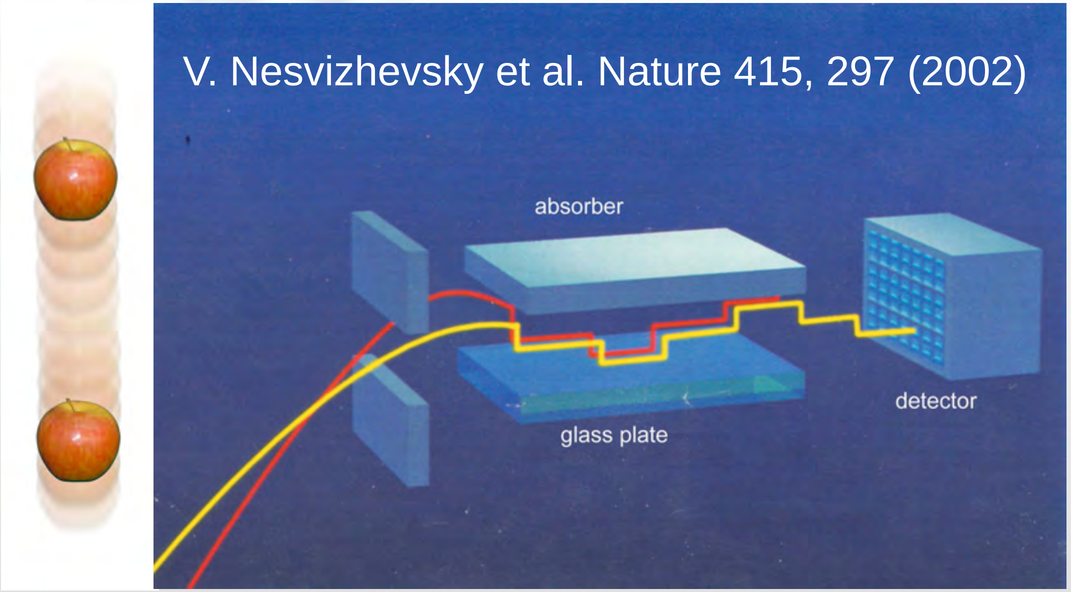
spin 1/2 - magnetic moment 1.93 μ_N

free neutrons are unstable β-decay proton, electron, anti-neutrino

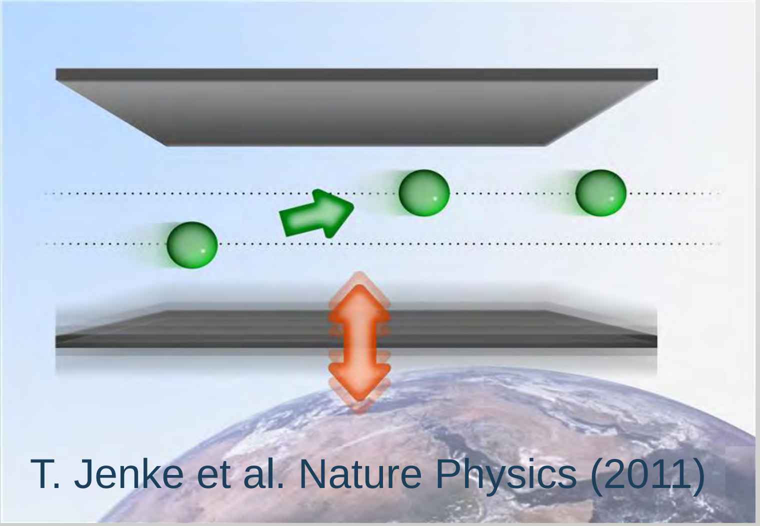
life-time 886±1 sec

neutron : an object to be studied
fundamental interactions

confirmation of quantum effects in
presence of gravity field



V. Nesvizhevsky et al. Nature 415, 297 (2002)


T. Jenke et al. Nature Physics (2011)

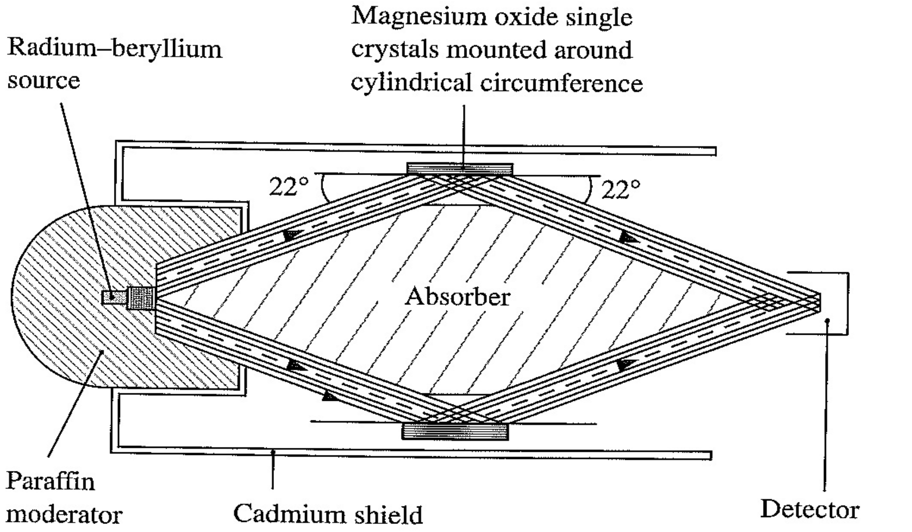
new developments

resonance spectrometry

neutron properties

wave-particle duality

diffraction of thermalised neutrons



D.P Mitchell and N. Powers (1936)

kinetic energy

$$E(\text{meV}) = 2.072\left[k(\overset{0}{\text{A}}^{-1})\right]^2 \approx \left[\frac{9}{\lambda(\overset{0}{\text{A}})}\right]^2$$

$$v\,(\text{m/s}) = \frac{3{,}956}{\lambda(\overset{0}{\text{A}})}$$

$$1(\overset{0}{\text{A}}) \approx 82\,\text{meV}$$

$$1\,\text{meV} \approx 8\,\text{cm}^{-1} \approx 0.25\,\text{THz} \approx 11.6\,\text{K}$$

$$T = \frac{L}{v} = 252.77\,\mu\text{sec}\cdot\lambda\left[\overset{o}{\text{A}}\right]\cdot L[\text{m}]$$

fortunately large value!

monochromatisation: diffraction or velocity selection

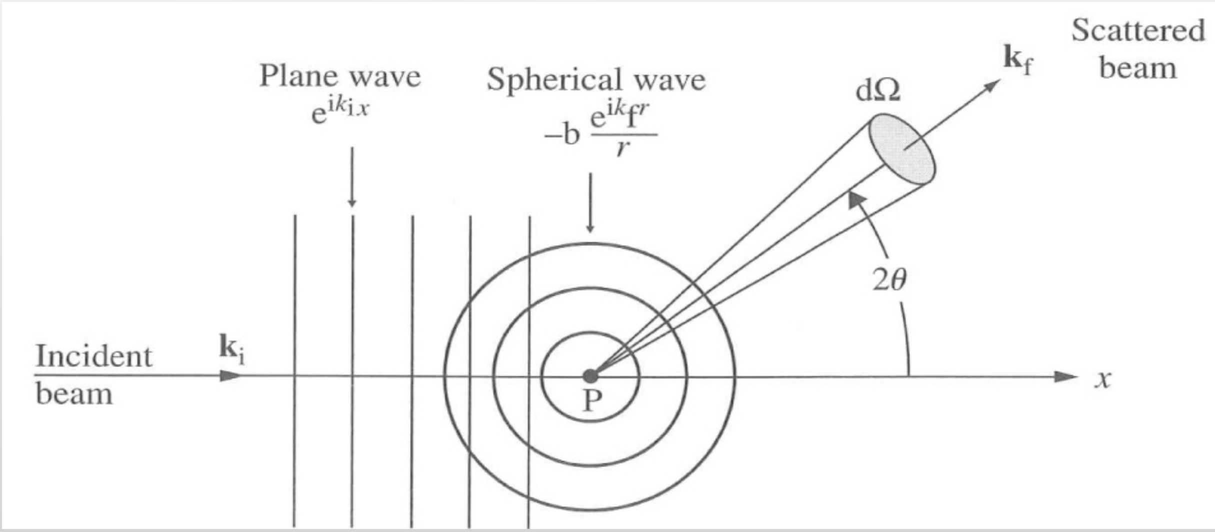
neutron dh = 1 m ≅ 0.1 μeV in gravity on Earth

neutron properties

what do neutrons ‘feel’ or ‘interact’ with?

like a billiards ball and a small compass

single nucleus process



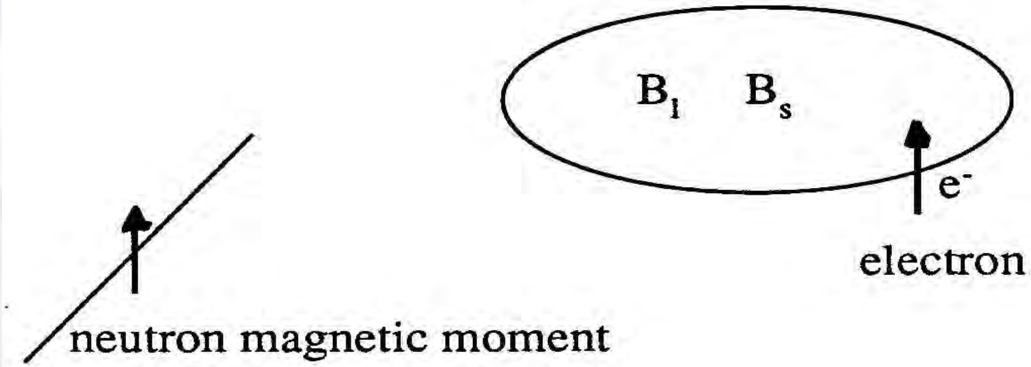
neutron-nuclei interaction

Fermi length $b \approx 10^{-12}$ cm

neutron properties

magnetism

magnetisation densities



magnetic interaction

spin 1/2 total magnetic moment

$M \approx \langle L \rangle + 2\langle S \rangle$

order of magnitude $g_n r_0 M/2 \approx 0.5\ 10^{-12}$ cm

similar to x-ray Thomson scattering

$Zr_0 \approx 10^{-12}$ cm

neutron-nuclei interactions

Fermi length $b \approx 10^{-12}$ cm

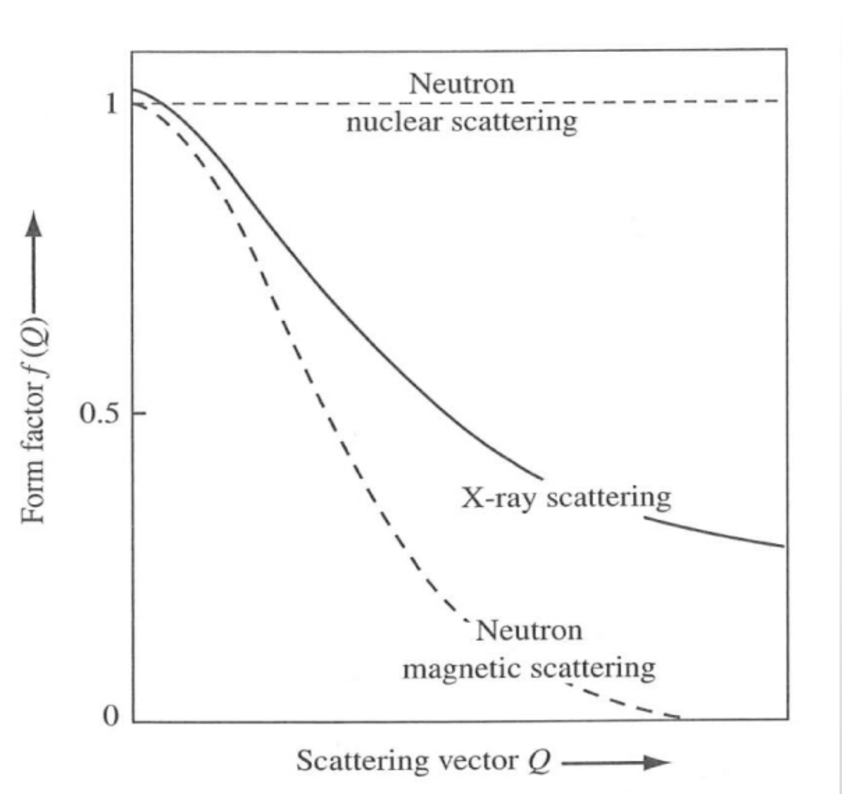
neutron properties

scattering form factors

brief summary

neutron-nuclei interactions

- isotopic sensitivity
- crystal structures
- atomic motions



neutron-magnetic moments interactions

- magnetic structures
- spin dynamics magnetic interactions
- “magnetic” electron densities

coherent and incoherent scattering

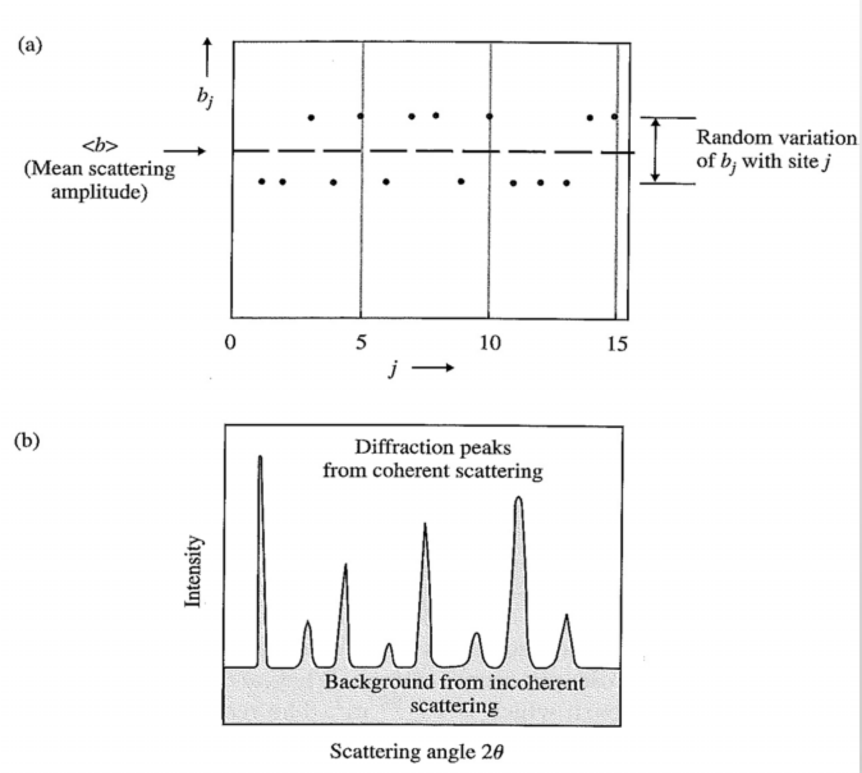
$$\frac{d\sigma}{d\Omega} = \left| \sum_j b_j \exp(i\mathbf{Q}\cdot \mathbf{r}_j) \right|^2$$

different sites, no correlation $\langle b_j b_{j'} \rangle = \langle b_j \rangle \langle b_{j'} \rangle = \langle b \rangle^2$

same site $\langle b_j b_{j'} \rangle = \langle b_j^2 \rangle = \langle b^2 \rangle$

$$\frac{d\sigma}{d\Omega} = \sum_{j,j'} \langle b \rangle^2 \exp[i\mathbf{Q}\cdot(\mathbf{r}_j - \mathbf{r}_{j'})] + \sum_j (\langle b^2 \rangle - \langle b \rangle^2)$$

$$\sigma_{coh} = 4\pi \langle b \rangle^2 = 4\pi b_{coh}^2 \quad \sigma_{incoh} = 4\pi \left(\langle b^2 \rangle - \langle b \rangle^2 \right)$$



isotopic dependence

nuclear spin dependence, I

$$\sigma_{coh} = 4\pi \left(\omega_+ b_+ + \omega_- b_- \right)^2$$

$$\sigma_{incoh} = 4\pi \omega_+ \omega_- \left(b_+ - b_- \right)^2 \quad \omega_+ = \frac{I+1}{2I+1} \quad \omega_- = \frac{I}{2I+1}$$

neutron properties

what do we observe/measure with neutrons ?

isotope labelling (deuteration …..)

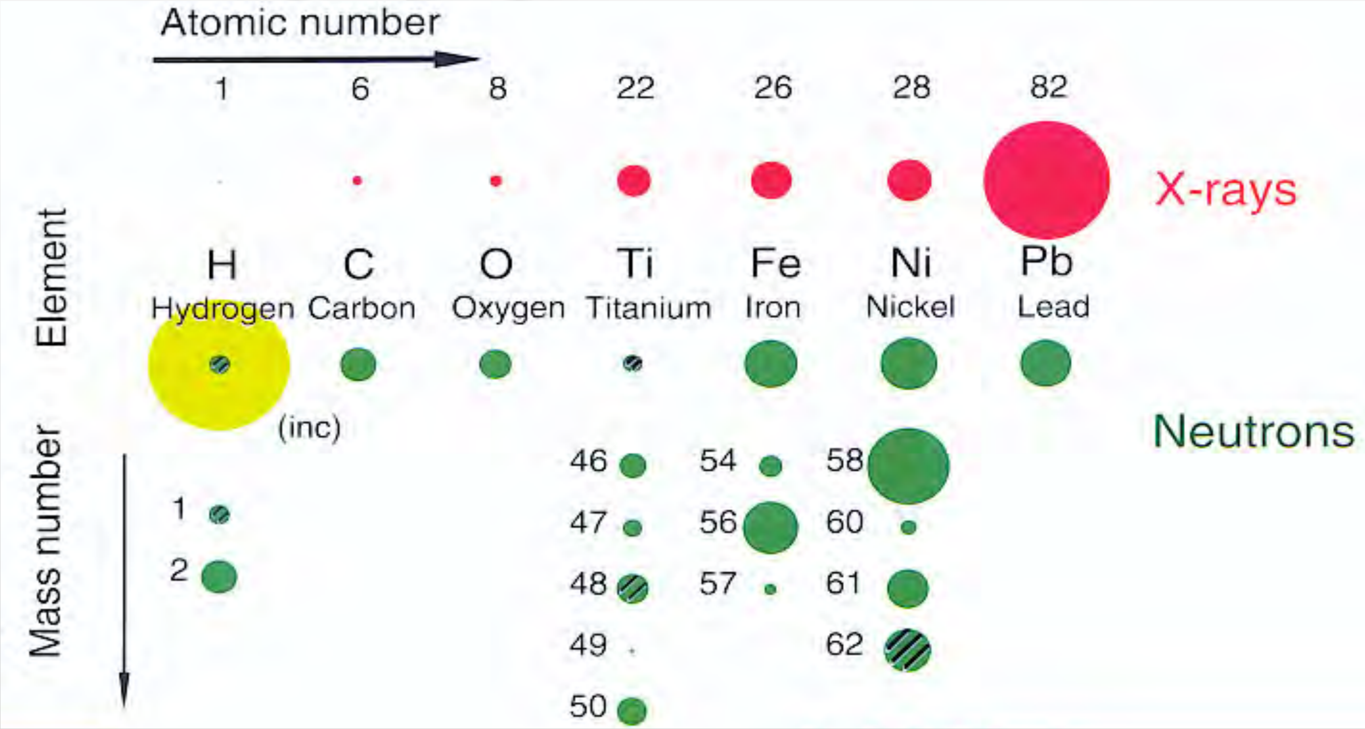
neutron-nuclei interactions
Fermi length b ≈ 10^{-12} cm

some b's are < 0

… phase shift …

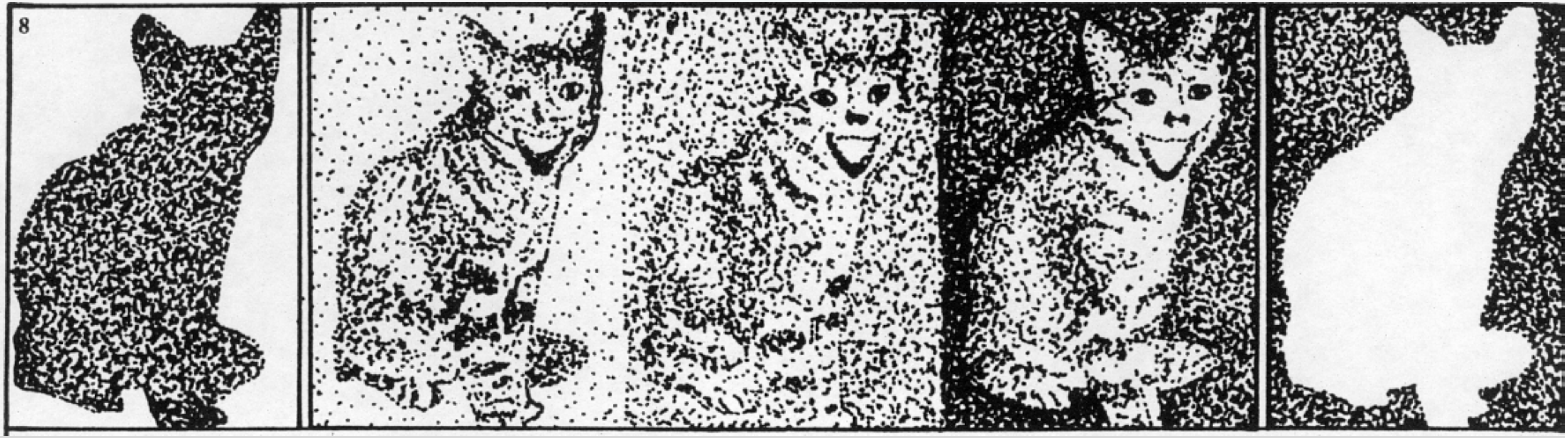
isotopic sensitivity

incoherent scattering



contrast variation

objects in solution different average cross-sections

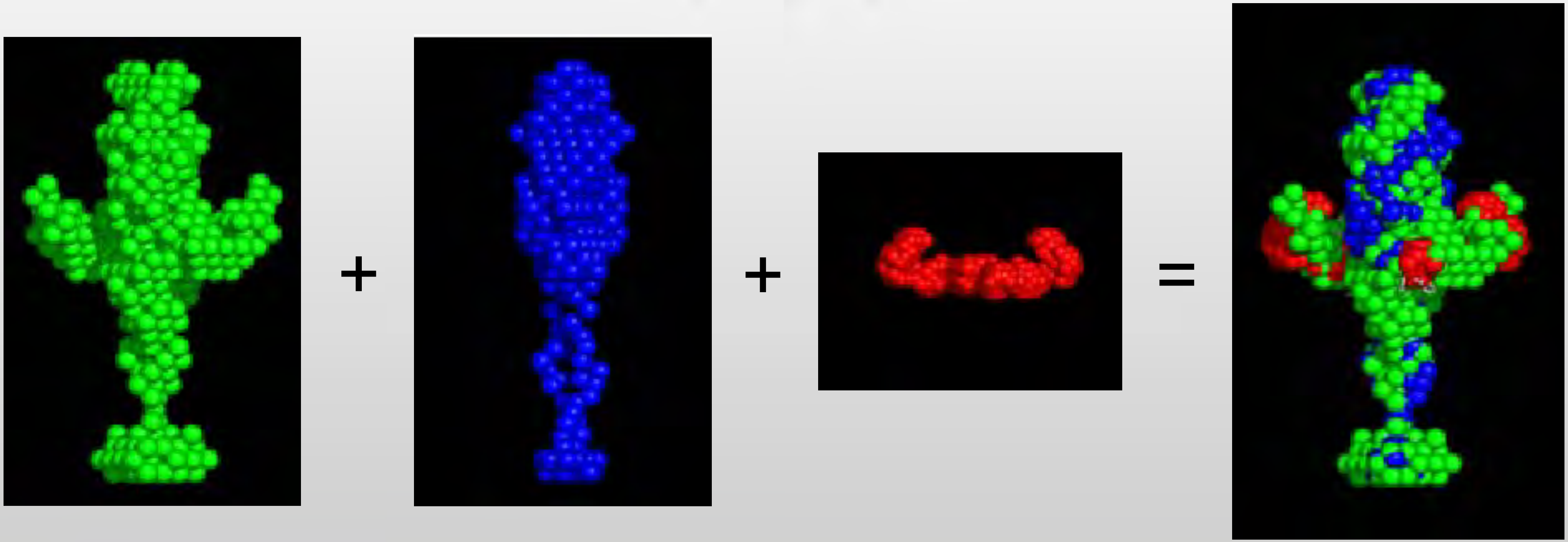


100 % H_2O ▸ 100 % D_2O

- null or full contrast : external shapes
- intermediate contrast : details

neutron properties

sensitivity and selectivity
isotopic substitution/contrast variation

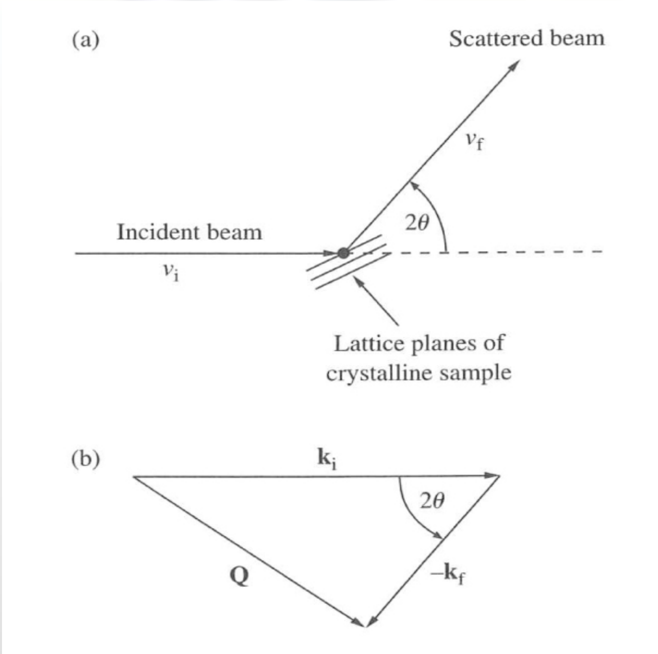


neutron properties

scattering geometry

velocities

momentum space



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

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

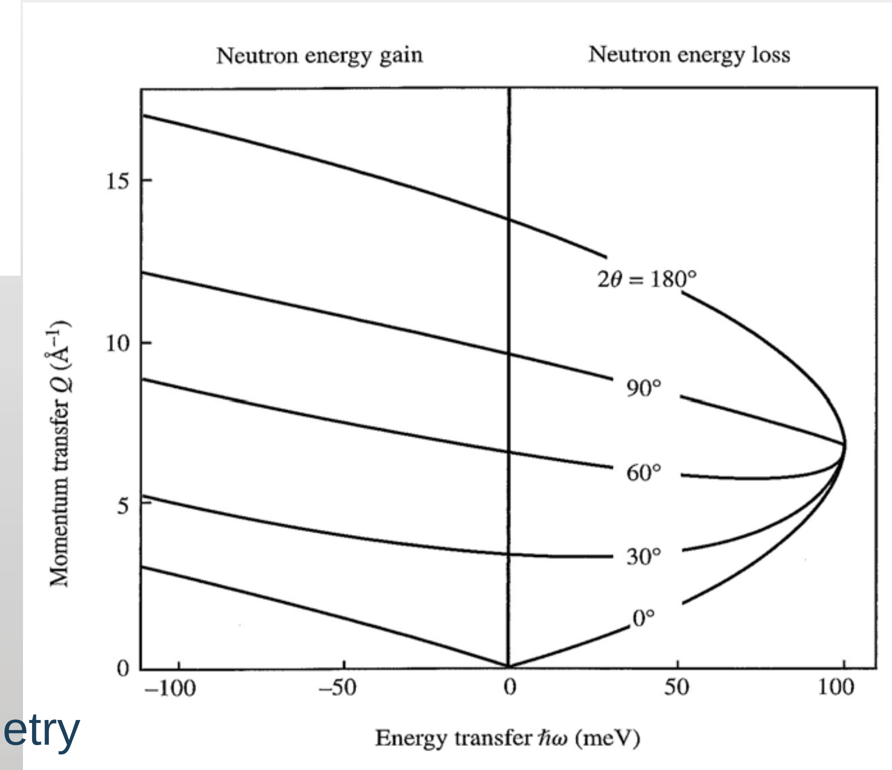
$$Q^2 = k_i^2 + k_f^2 - 2k_i k_f \cos(2\theta)$$

$$\frac{\hbar^2 Q^2}{2m_n} = E_i + E_f - 2\sqrt{E_i(E_i - \hbar\omega)}\cos(2\theta)$$

kinematics

fixed E_i

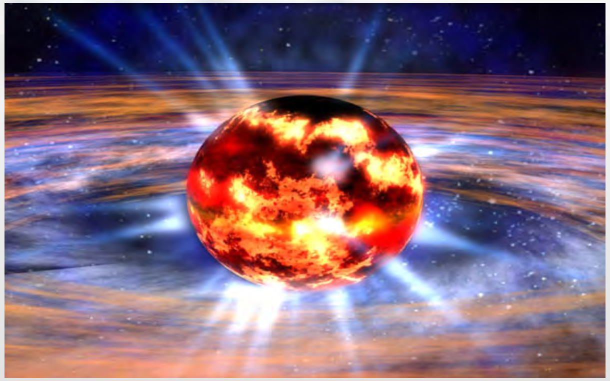
direct geometry



how to produce neutrons?

free neutrons are created through 'escape' from nuclei

neutron stars



neutrons from fission process

neutrons from spallation process

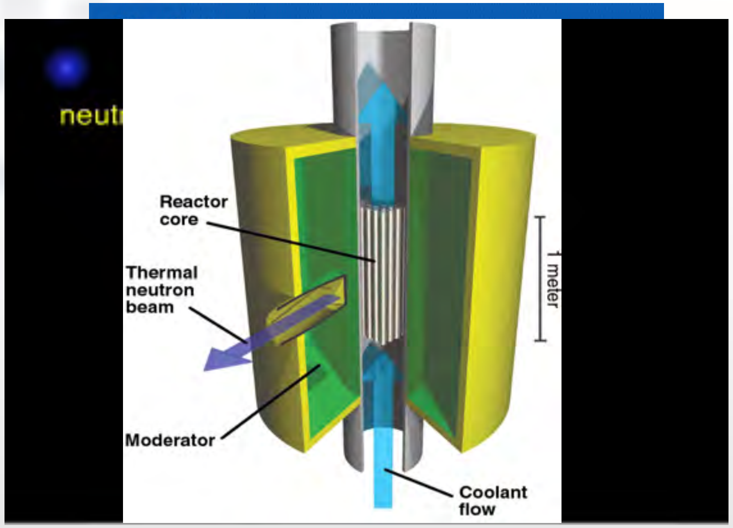
neutrons from fusion process

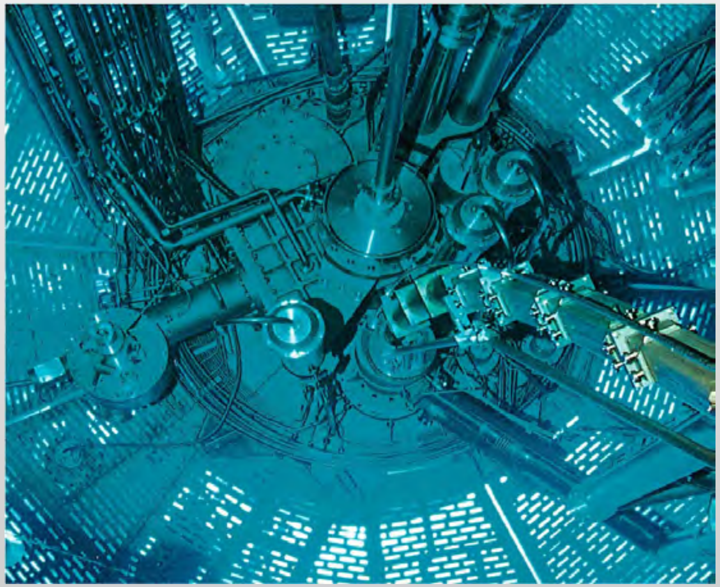
a neutron source

how does it work?

fission reactor

slow neutrons splitting nuclei





ILL reactor

D_2O moderator

hot source: graphite block 2400K

cold sources: liquid hydrogen 25K

thermal flux 1.5 10^{15} n/cm^2/sec

high power density (10 MW/litre) / achievable rate of cooling reactor core

pulsed reactors

time-of-flight methods on pulsed sources

pulsing reactivity to become supercritical

- mechanically (fissile materials or reflector)
- electron pulses in the core - photo-fission process
- combination of the two above.

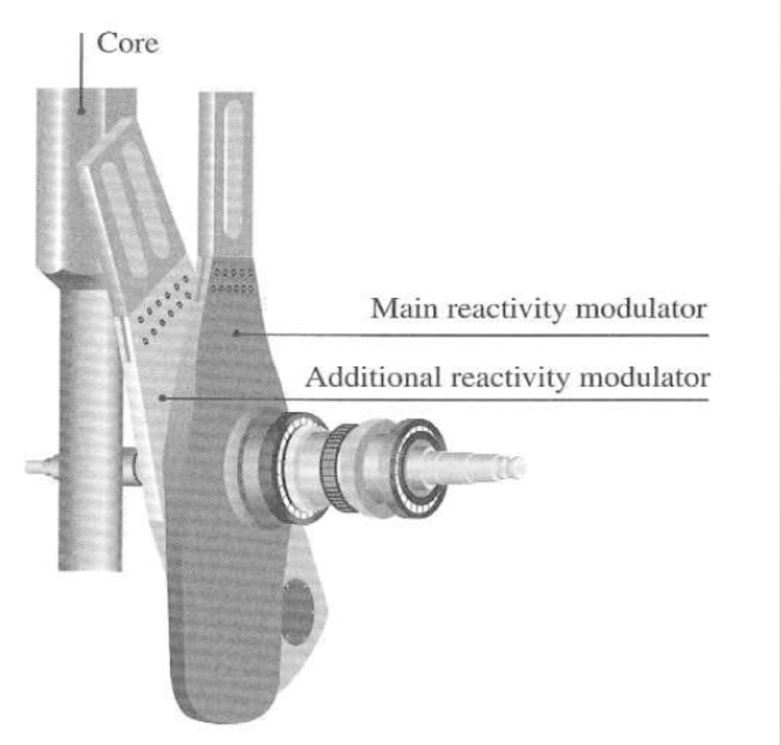
IBR-2 at Dubna, Russia

average power 2 MW

peak power 1,500 MW

rep rate 5 Hz, pulse width 215 µsec

peak flux 1.5 10^{16} n/cm^2/sec



neutrons from accelerators

pulsed sources

to overcome cooling problems

series of installations at Argonne Nat Lab, Rutherford, KEK

photo-fission

using high-energy electrons on heavy metal targets

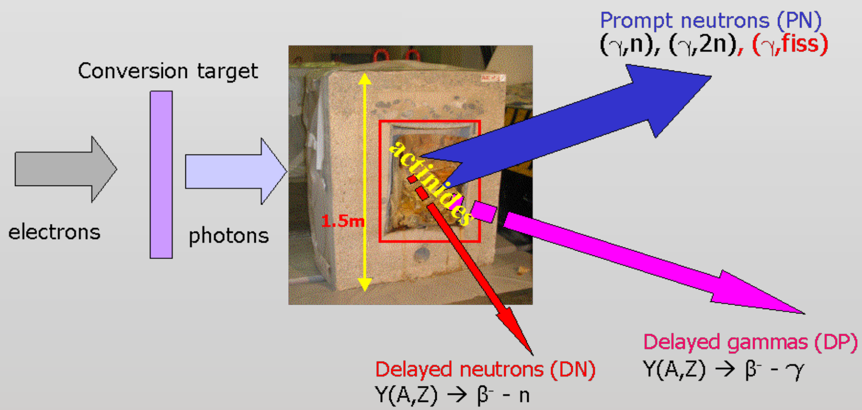
deceleration leads to Bremsstrahlung

γ-rays produce fast neutrons

not efficient

3,000MeV per neutron

intense γ-ray beams



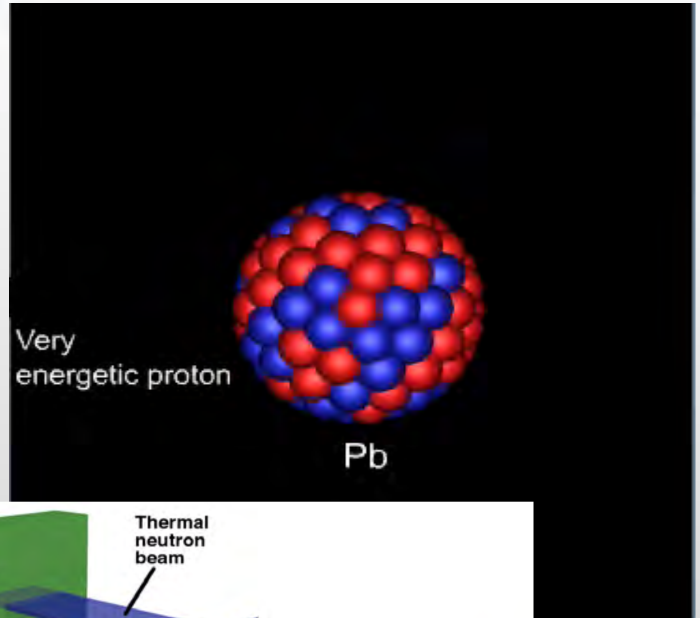
spallation sources

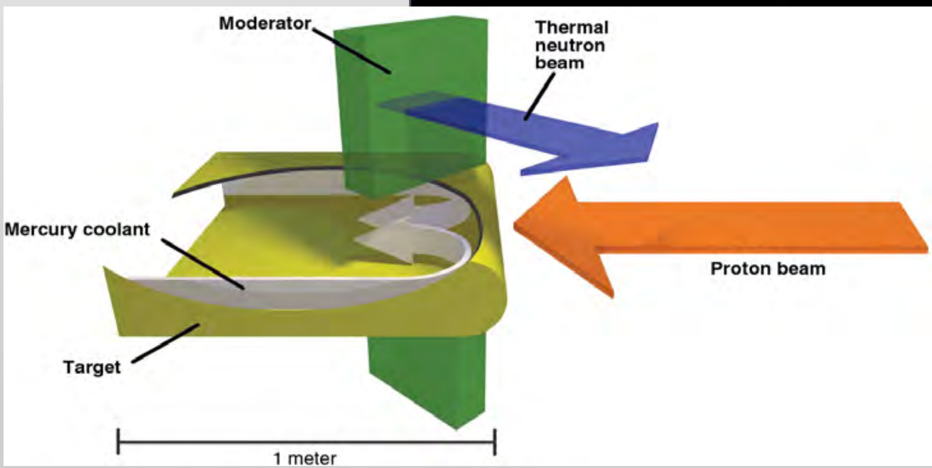
using high-energy electrons on heavy metal targets

'evaporation' of 30 fast neutrons

accelerator   proton 2.0 GeV

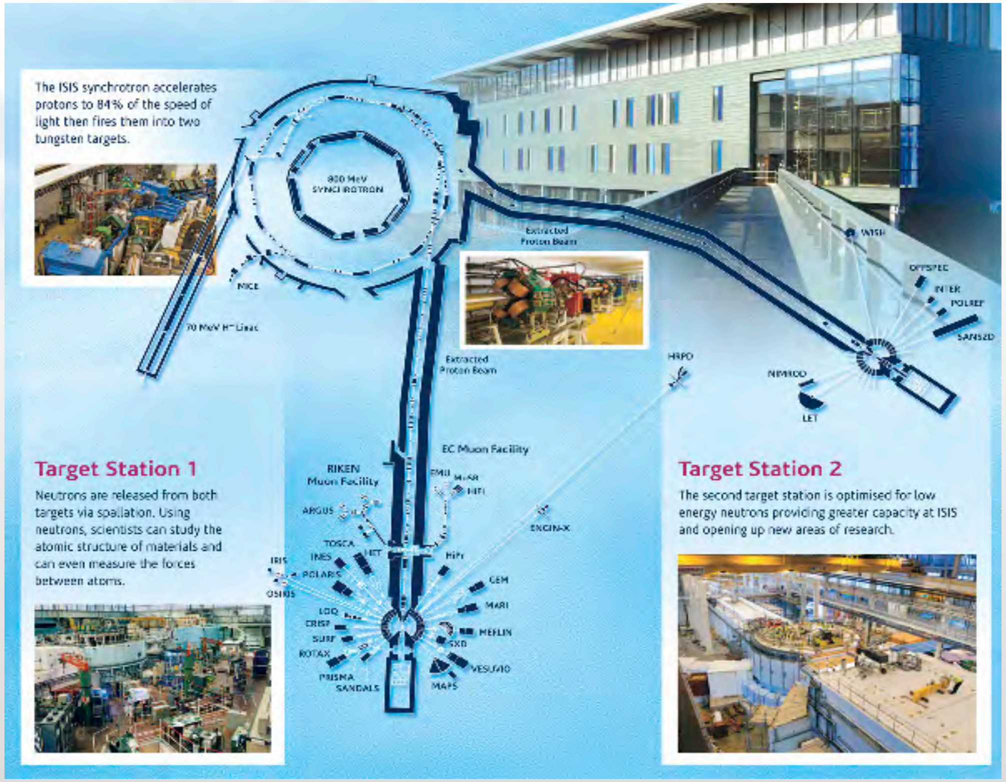
high Z metal target





ISIS facility Rutherford Laboratory

- H^- ion source
- Linac 70 Mev
- proton synchrotron 800 MeV
- repetition rate 50 Hz
- pulse width 100 ns
- power 0.200 MW
- 2 target stations different moderators



neutron pulses width ~ 10-90 µs

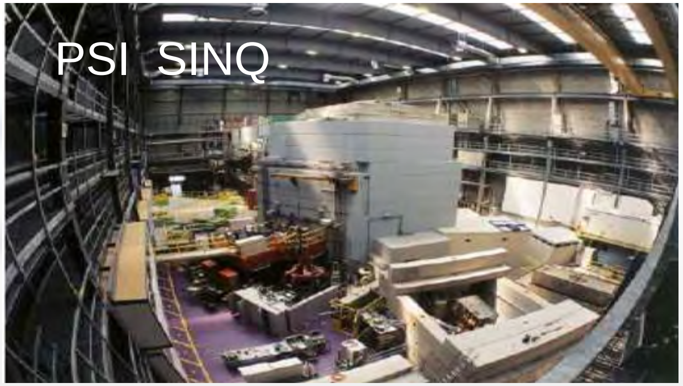
neutrons from accelerators

PSI

protons pulses 0.3ns 50.6MHz

equivalent to 0.7MW

continuous neutron source but pulsed accelerator



SNS

1 MW

short pulses

JPARC

0.8 MW 60Hz in 2012?

short pulses

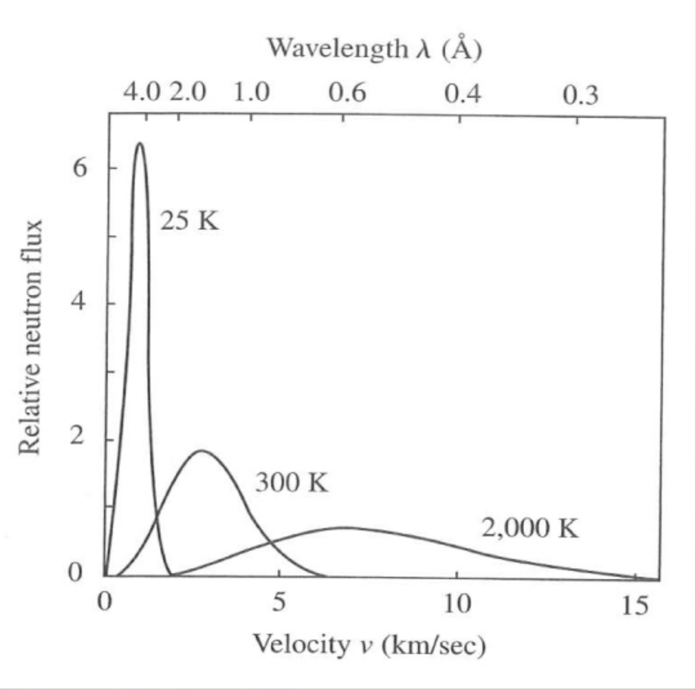
neutron moderators

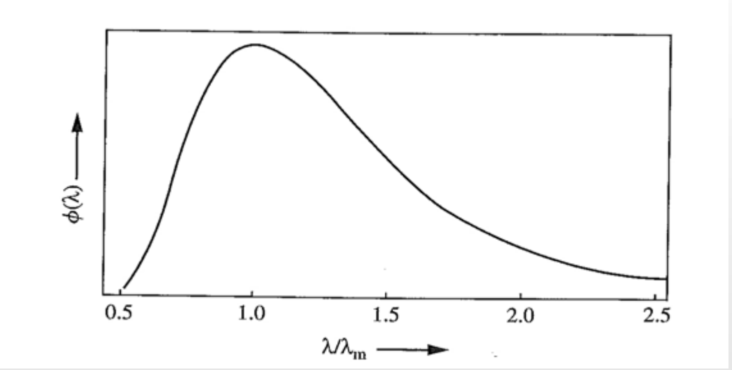
fission/spallation neutrons are in the MeV range

moderation process

thermal equilibrium with moderator

Maxwellian spectrum if thermal equilibrium



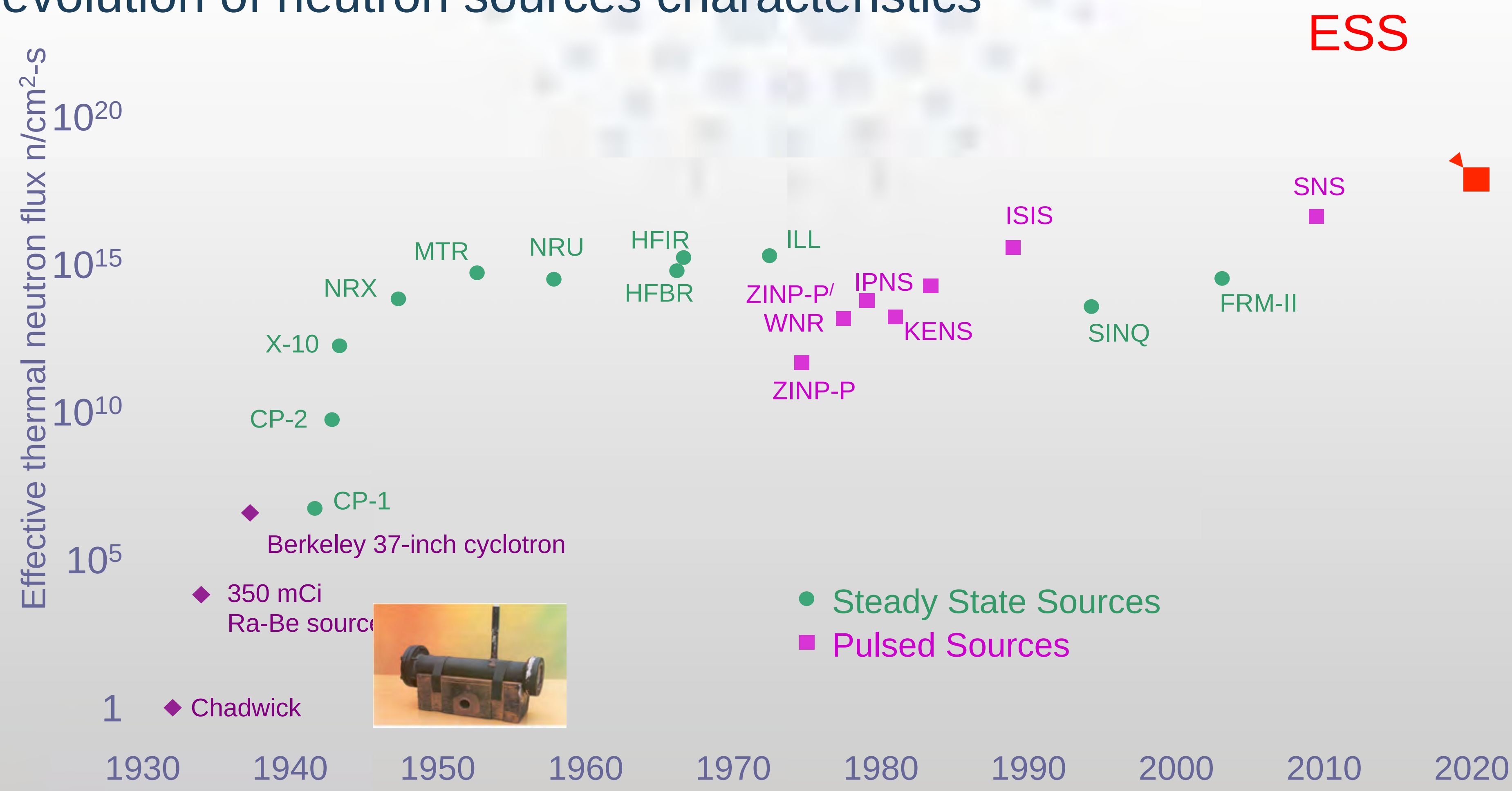


$$\lambda_m = \frac{h}{(5m_n k_B T)^{1/2}} = \frac{19.483}{(T)^{1/2}} (\mathring{A})$$

choice of moderator depends on applications

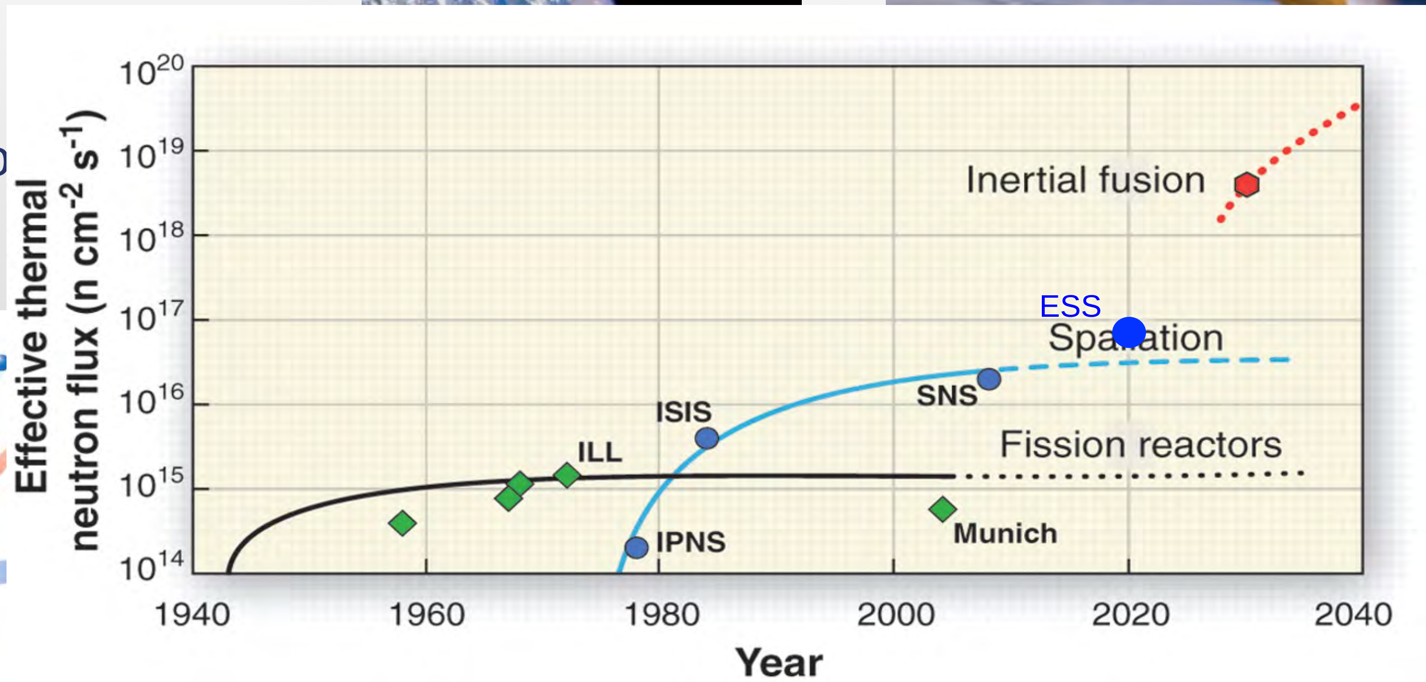
hot neutrons	<0.6 Å
thermal neutrons	1- 4 Å
cold neutrons	4-20 Å

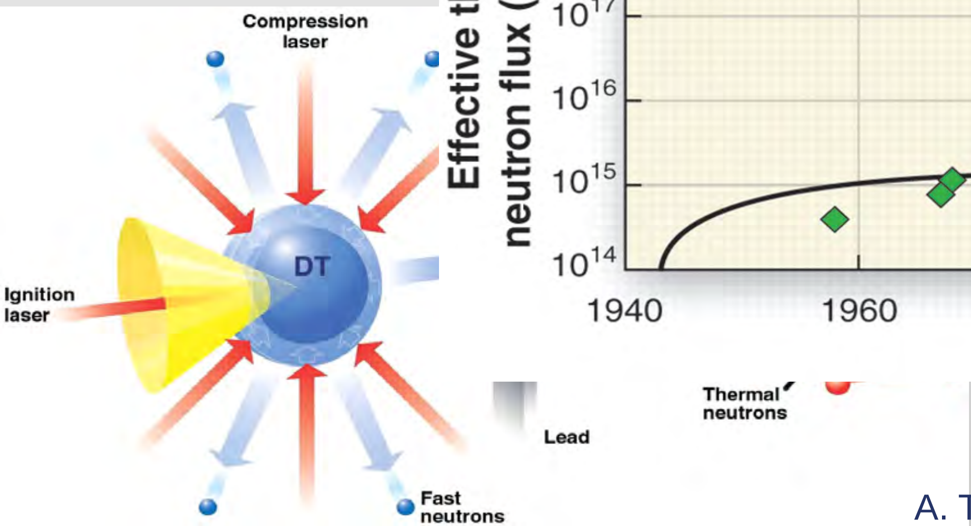
evolution of neutron sources characteristics

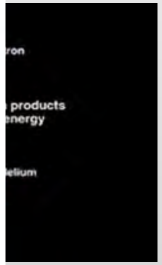


(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986) landing the moon again by 2019!

a ‘dream’ neutro



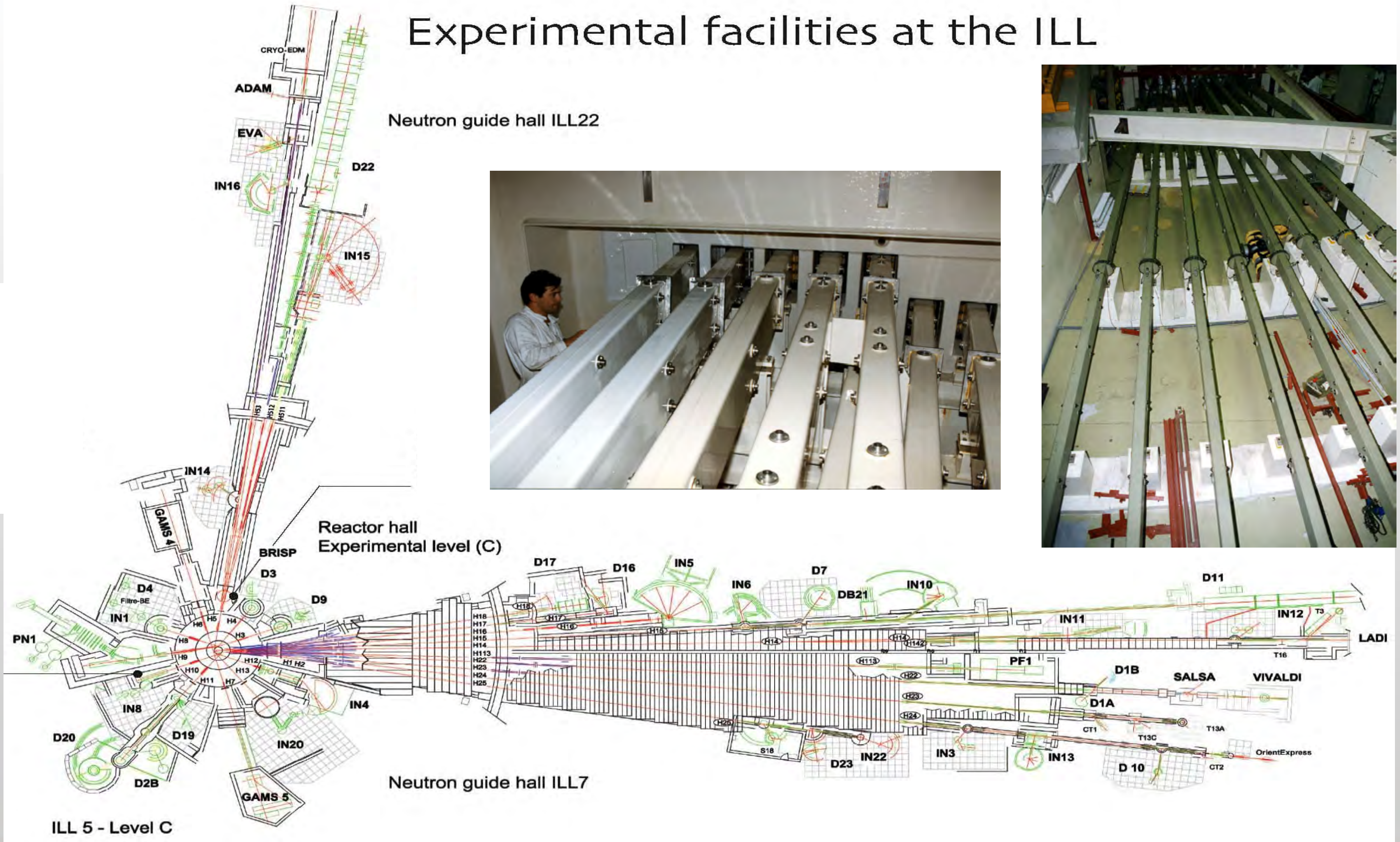




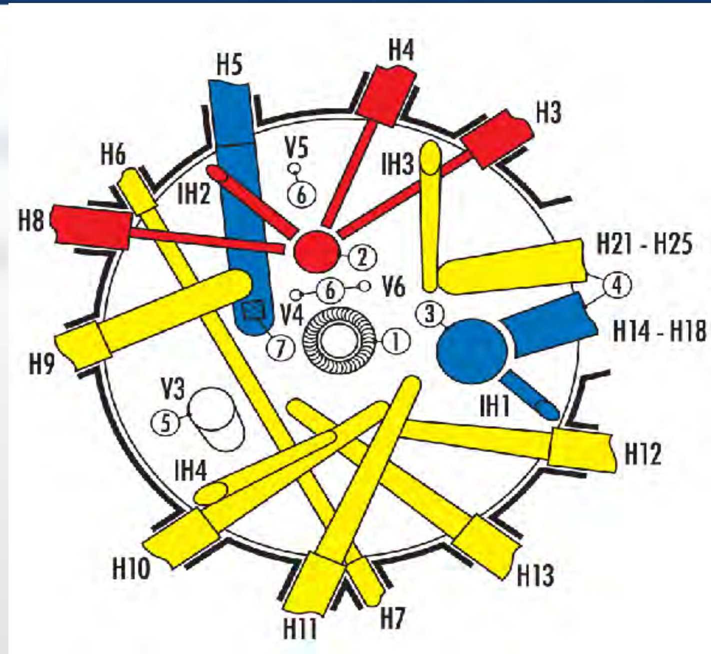
propagating thermonuclear reaction

A. Taylor et al. Science 315, 1092 (2007)

neutron guide halls



neutron optics



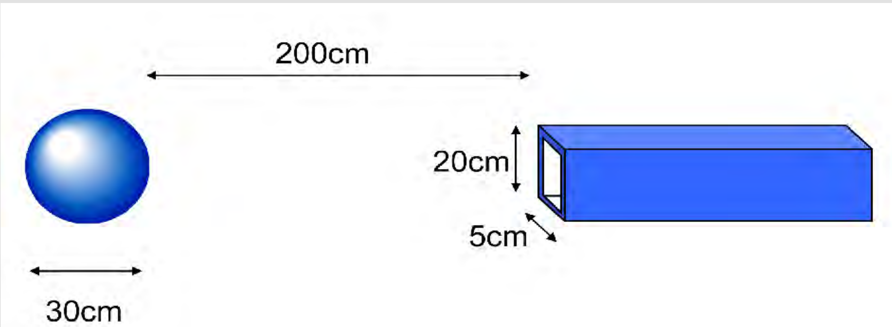
low brightness sources

~ 10^{14} n/cm^2/steradian/sec

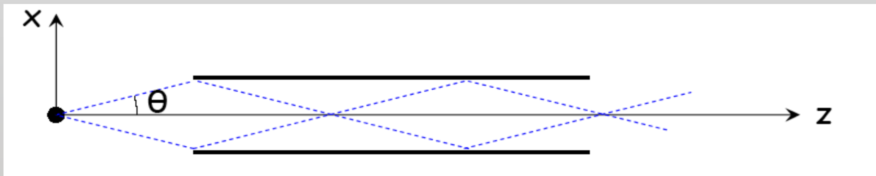
compared with a 60 W (900 lm) light bulb

~ 10^{19} photons/cm^2/steradian/sec

optimise neutron economy

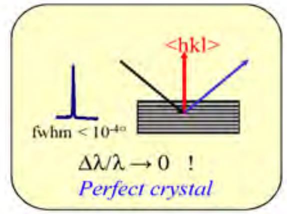


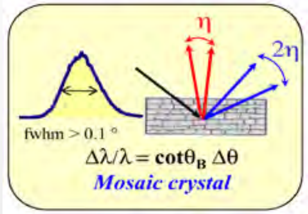
- to collect (thermal/cold) neutrons
- to transport them to instruments



a few degrees!

neutron monochromators



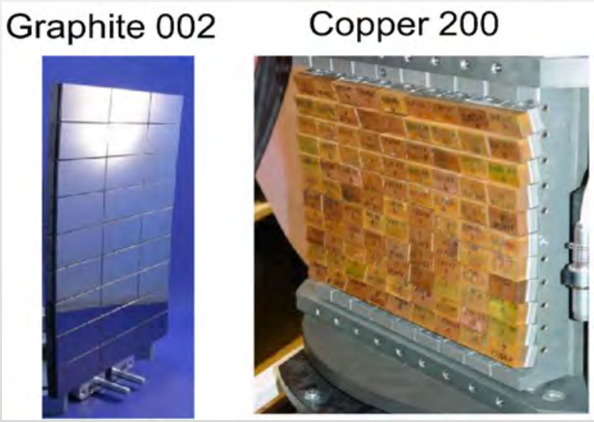


crystal monochromators

selection of wavelength bandwidth (energy)

focusing

focusing mechanics



Heusler alloy: polarising monochromator

focusing supermirrors / guides

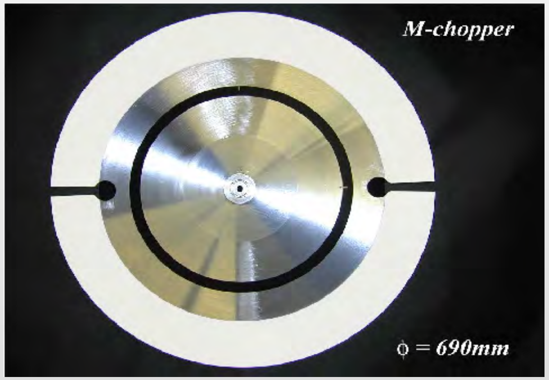
neutron velocity selectors

principle for time-of-flight

create pulse structure (even on reactors)

separate energies through velocity

select energies via time slicing



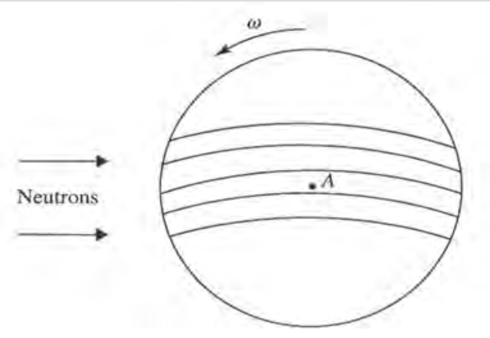
disk chopper

opening of ~ 1 degree

rotational speed 300Hz

opening of about 80 μsec

disk diameter of 700 cm (speed about 600m/s)



Fermi chopper

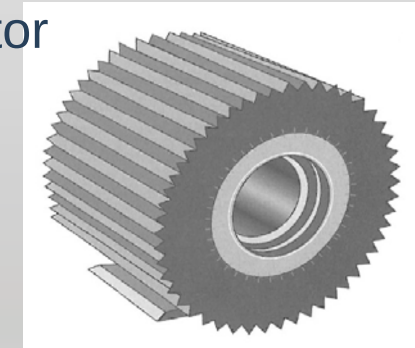
rotational speed 600Hz

opening of about 1 μsec

helical velocity selector

typical bandwidth 10%

SANS experiments

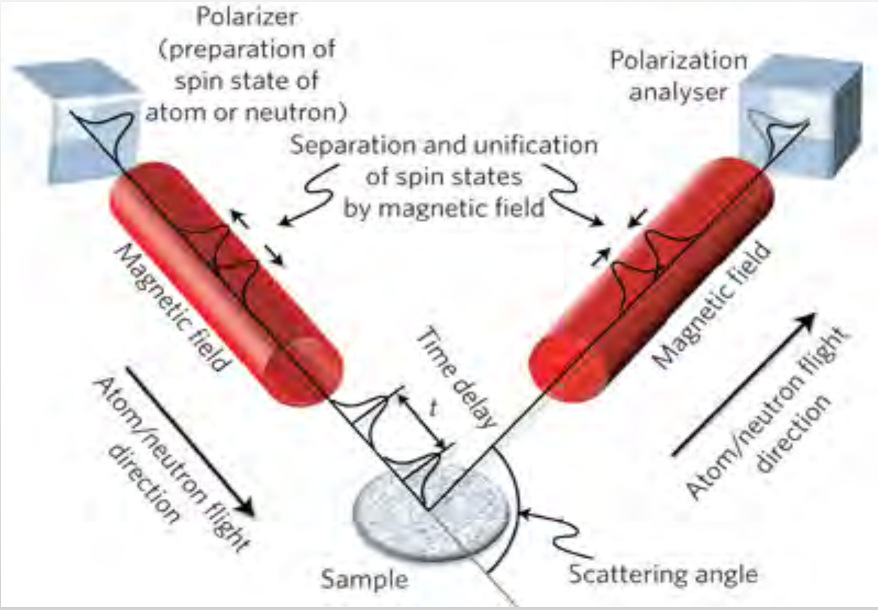


high resolution method – neutron spin echo

create neutron spin states

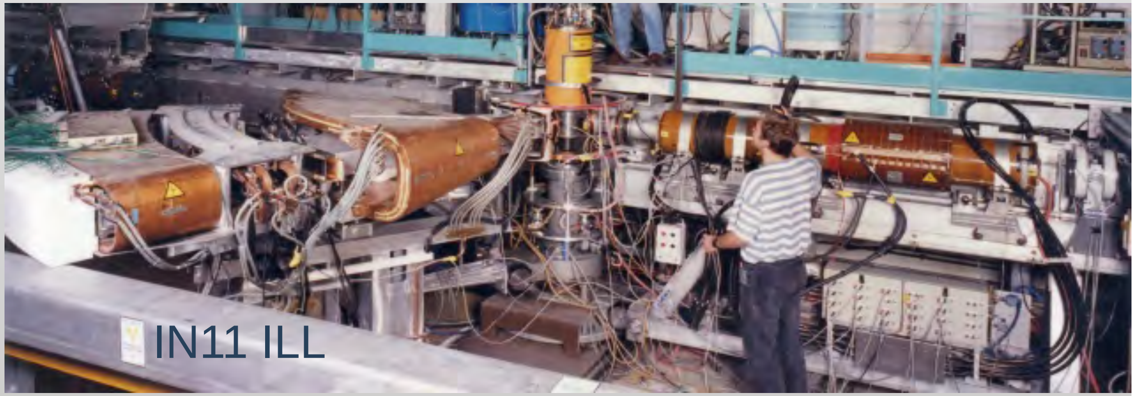
exploit Larmor precession of neutrons

vary time shift to probe time-dependent correlations



H. Hedgeland et al. Nature Phys. 5, 561 (2009)

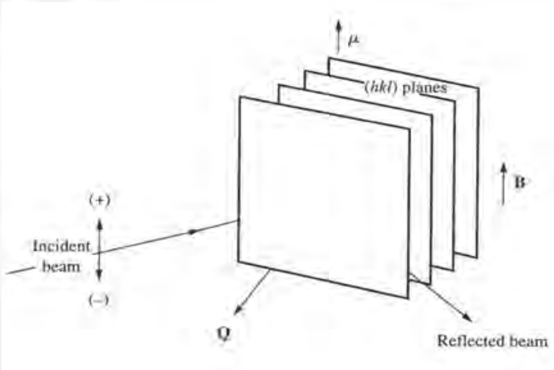
typical time scales:	0.01 - 500 ns
	400 µeV – 8 neV



IN11 ILL

neutron polarisation

production of polarised beams



Bragg reflection from magnetised crystal

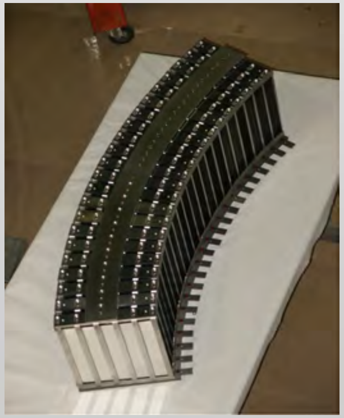
$$\frac{d\sigma}{d\Omega} = F_N^2(\mathbf{Q}) + 2(\mathbf{P}\cdot\mu)|F_N(\mathbf{Q})||F_M(\mathbf{Q})| + F_M^2(\mathbf{Q})$$

B is guide field and polarising field

up-state $\frac{d\sigma}{d\Omega} = |F_N(\mathbf{Q}) + F_M(\mathbf{Q})|^2$ $\frac{d\sigma}{d\Omega} = |F_N(\mathbf{Q}) - F_M(\mathbf{Q})|^2$ down-state

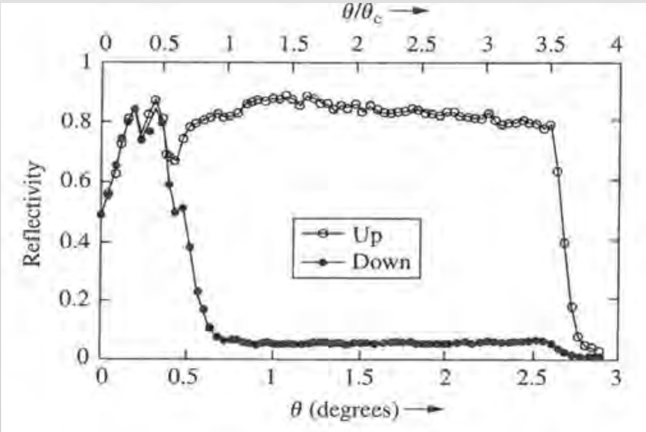
good matching for Cu_2MnAl (111), $Co_{0.92}Fe_{0.08}$ (200), ^{57}Fe (110)

total reflection from magnetised mirror



$$n' = 1 - \frac{N\lambda^2(\bar{b} \pm p)}{2\pi}$$

$$\theta_c \approx \lambda\left[\frac{N}{\pi}(\bar{b} \pm p)\right]^{1/2}$$

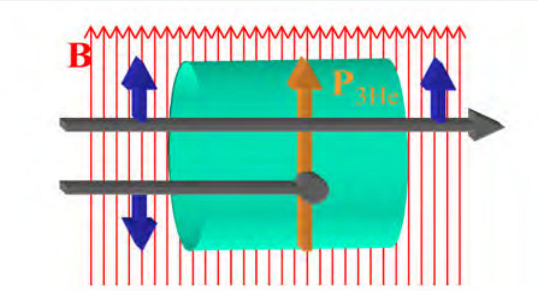


neutron polarisation

production of polarised beams

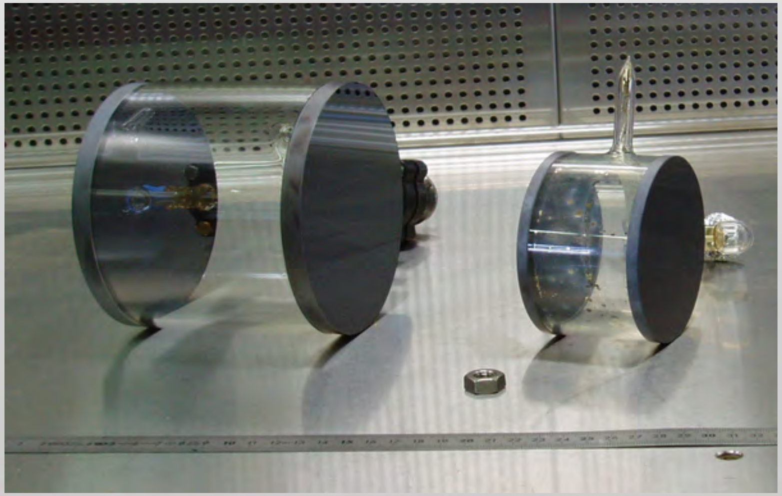
transmission through polarising filter

neutron absorption cross section of ^{3}He is highly spin-dependent



$\sigma_{\uparrow\uparrow} \approx 0$ parallel neutron spins are transmitted

$\sigma_{\uparrow\downarrow} \approx 6000\,\text{barns}$ anti-parallel neutron spins are absorbed



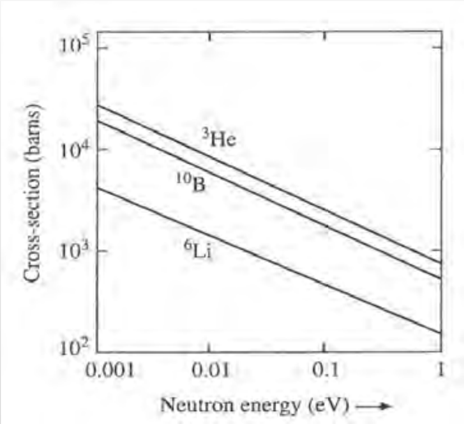
nuclear spin-polarised ^{3}He gas

neutron detection

the neutron is a weak probe! difficult to detect

thermal neutrons produce negligible ionisation

secondary ionisation due to neutron capture



emission of gamma rays or charged nuclei

most common absorbers: ^{3}He, ^{10}B and ^{6}Li

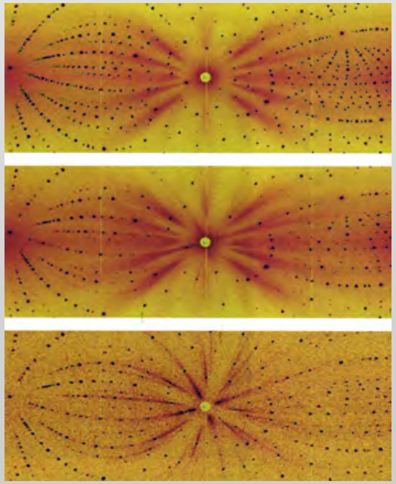


image plates

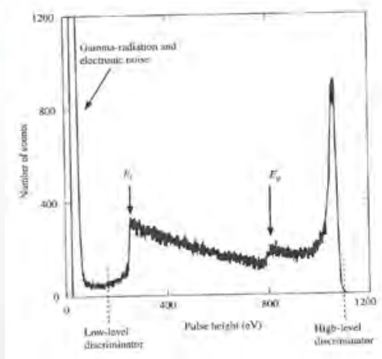
common in SRX community

need to convert neutron into photons (^{6}Li or Gd)

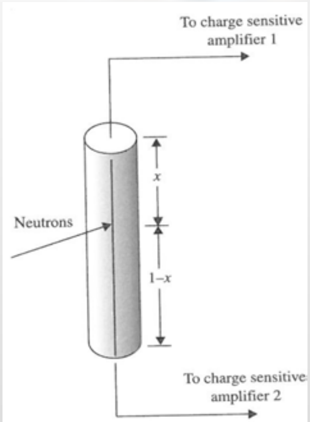
gas detectors

^{3}He gas difficult to obtain nowadays

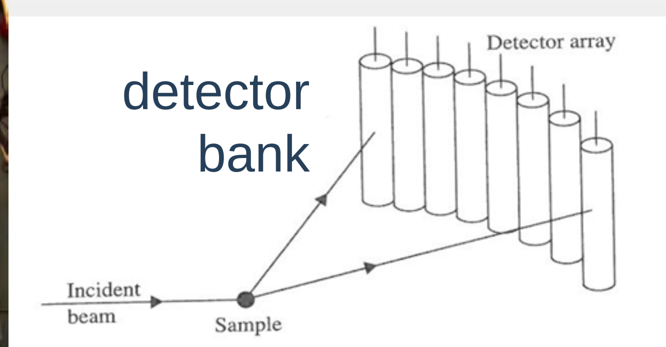
^{10}B in BF_3 toxic gas

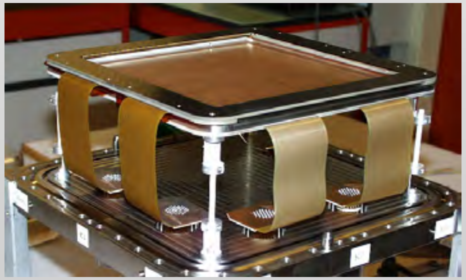


position sensitive detectors



detector bank

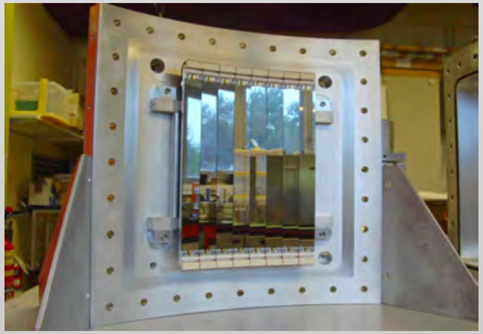




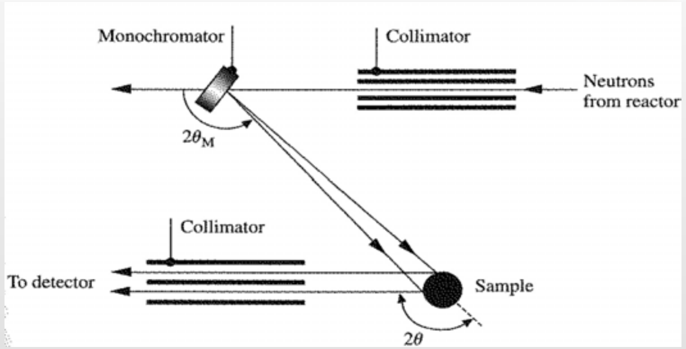
multi-wire counter

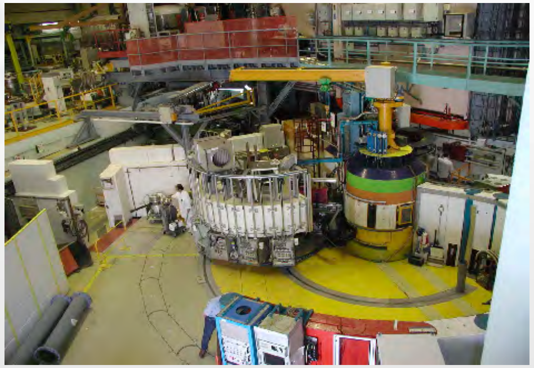
micro-pattern gas counter

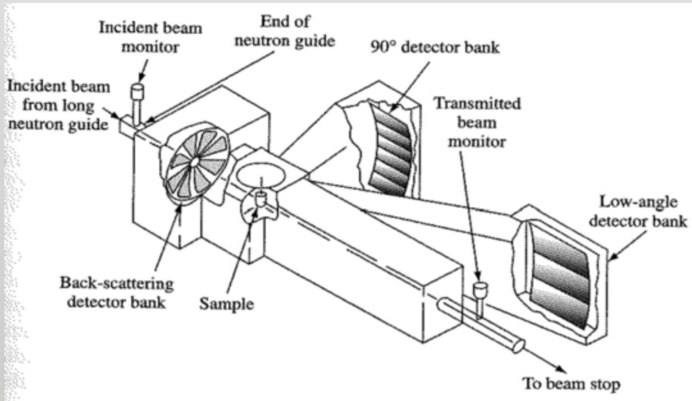
photolithography

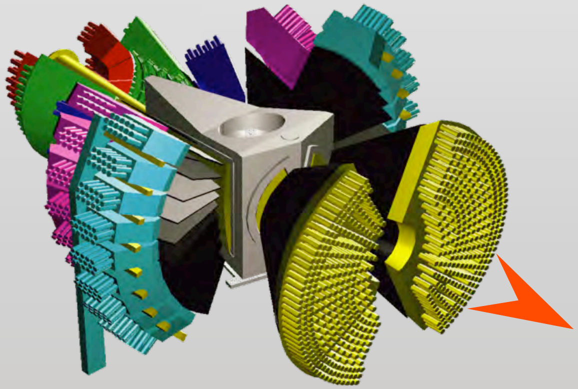


powder diffraction









powder diffraction

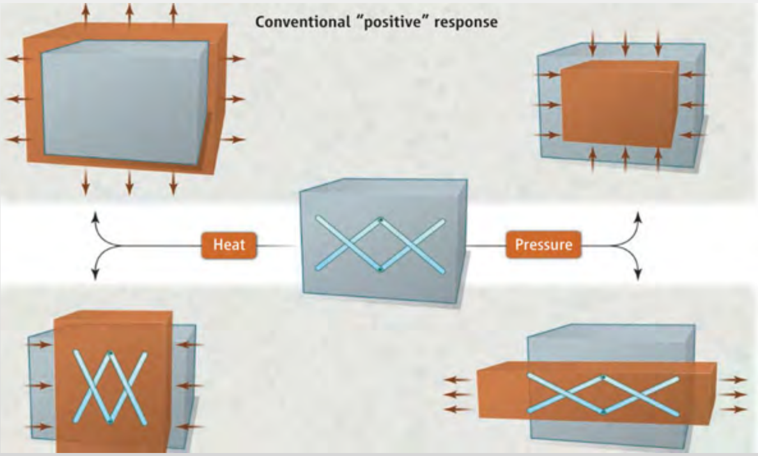
molecular crystal

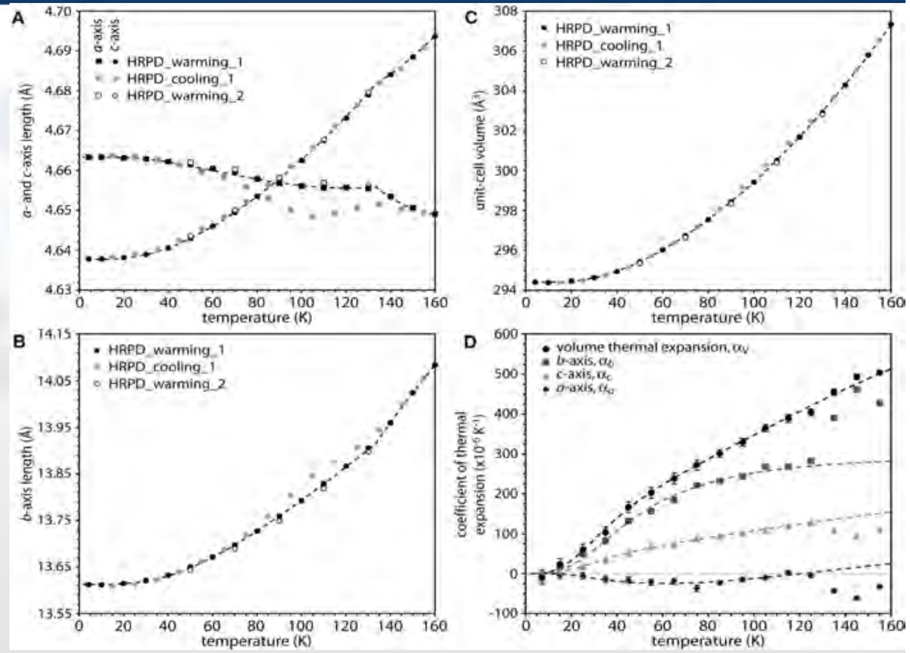
$CH_3OH.H_2O$

methanol monohydrate

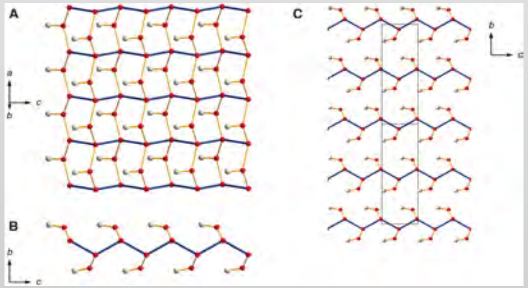
negative linear compressibility

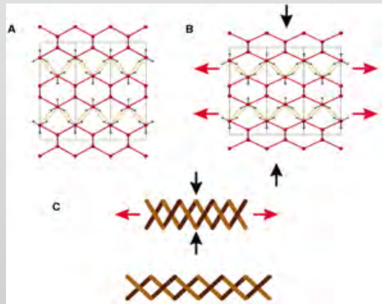
negative thermal expansion





parametric studies of lattice dimensions





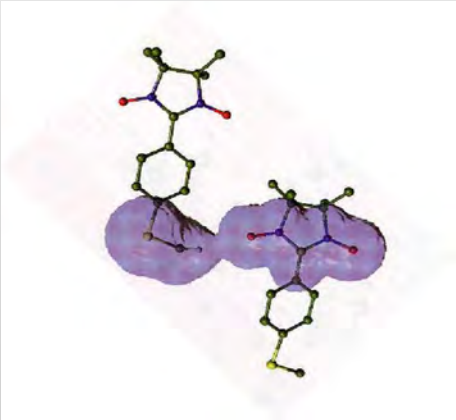
applications to nano-switches

but also planetary sciences …

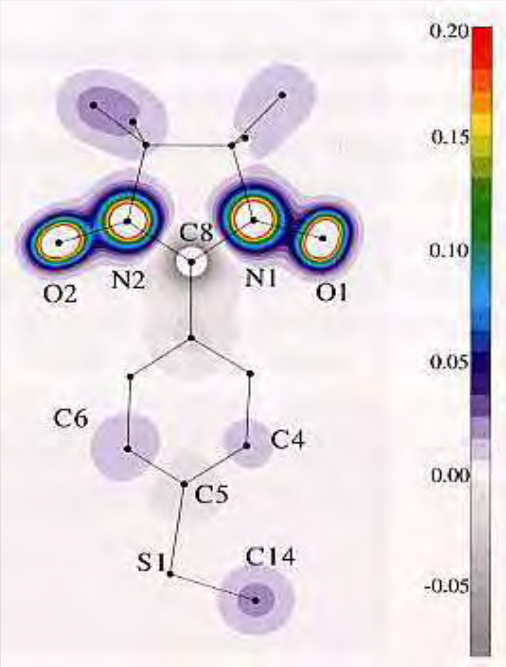
A D Fortes et al. Science 2011;331:742-746 single crystal diffraction polarised neutrons

organic materials

- molecular magnets
- 'high' T_c
- magnetic couplings driven by radicals packing

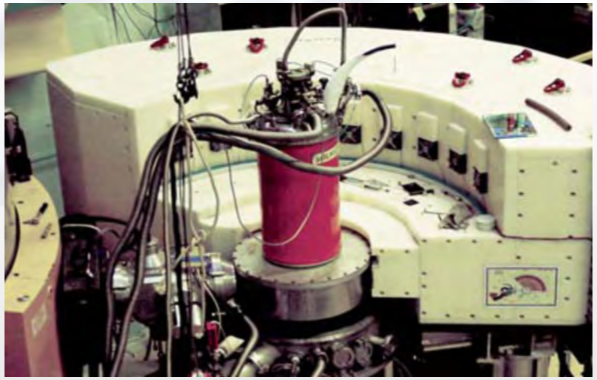


Nitrophenyl nitronyl nitroxide T_c=0.6K

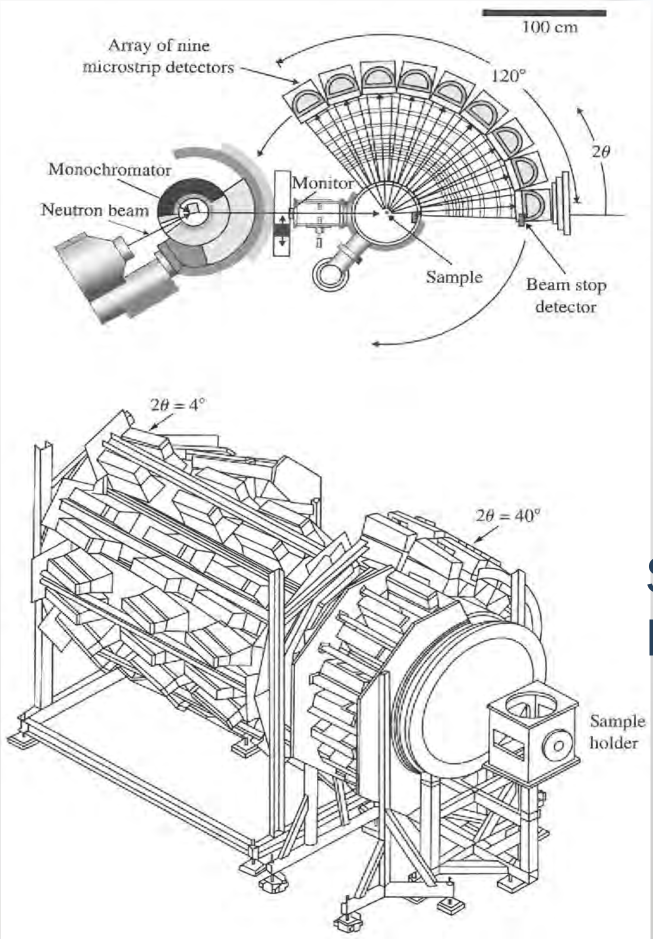


S. Pillet et al. (2001)

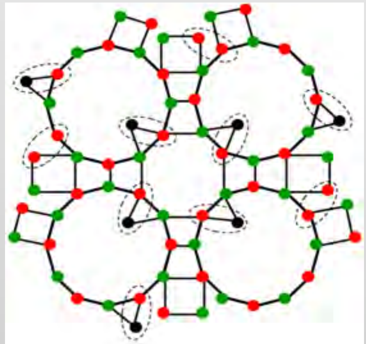
diffraction - disordered materials



D4 ILL



Sandals
ISIS



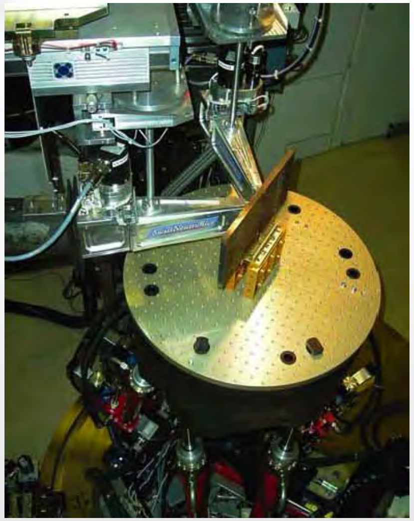
long range order observed in glasses
(chemical and topological)

neutron instruments and applications

diffraction and imaging engineering

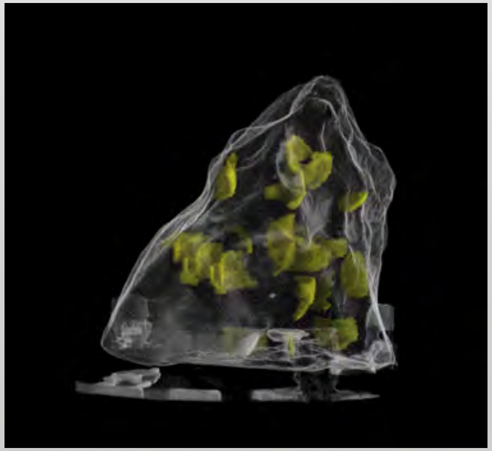
residual stresses in large mechanical parts
welds, ….

SALSA instrument ILL



neutron imaging of large objects

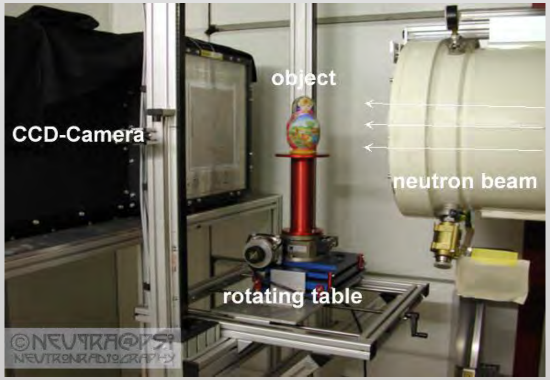
fossil with leaves



BMW engine

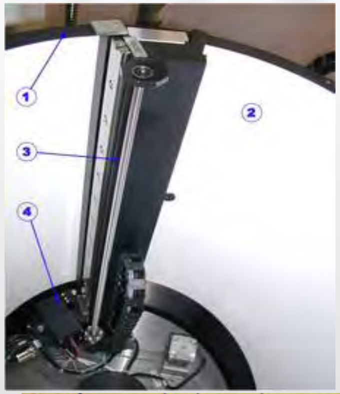
200 µsec exposures

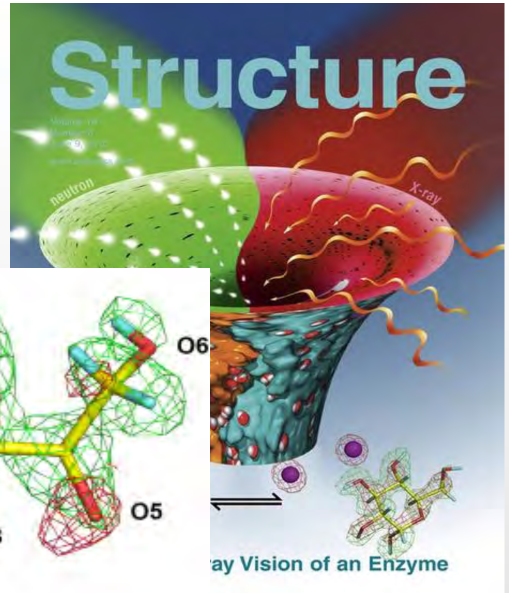
FRM-2 PSI ILL

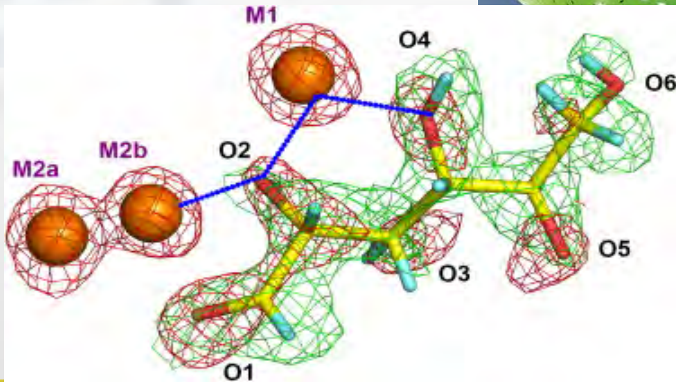


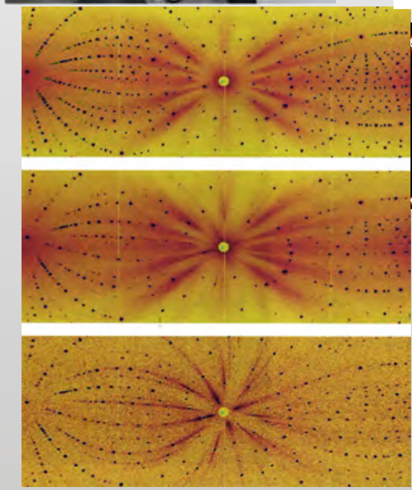
diffraction and bio-molecules

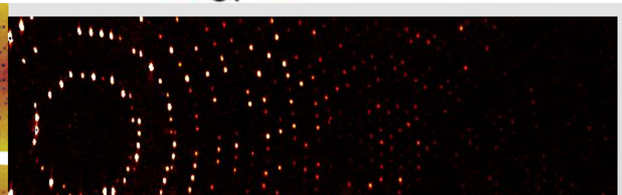
deuteration complementarity SRX neutrons









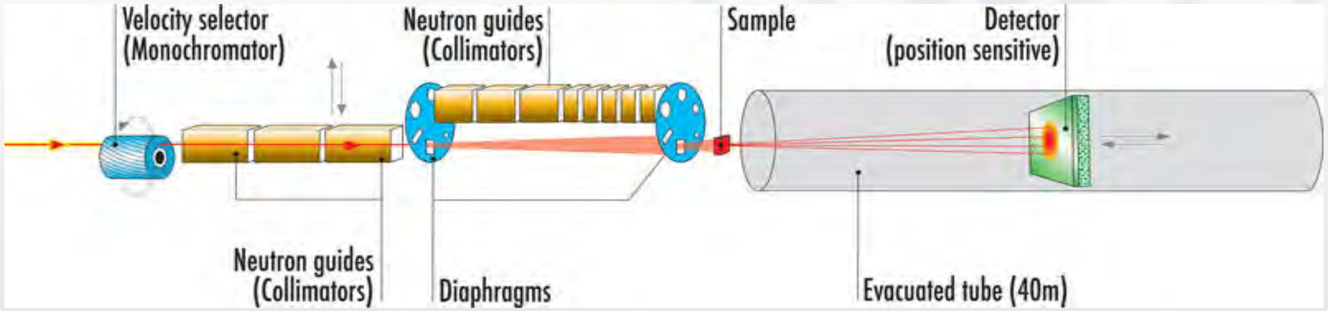


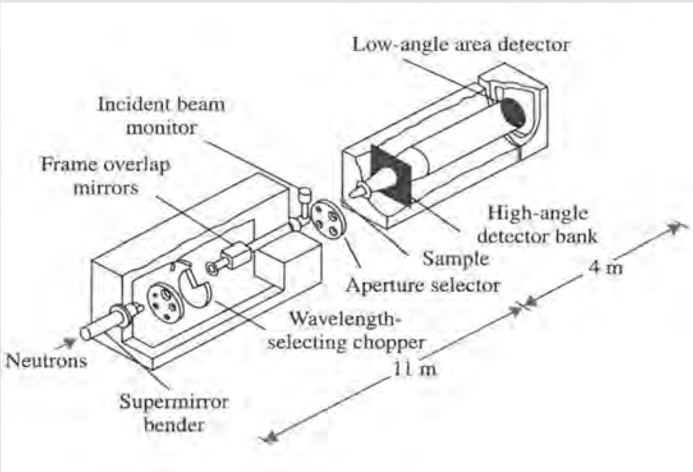
localisation and displacements of protons A.Y. Kovalevsky et a., Structure 18, 688 (2010)

instruments

small angle neutron scattering

D11
ILL

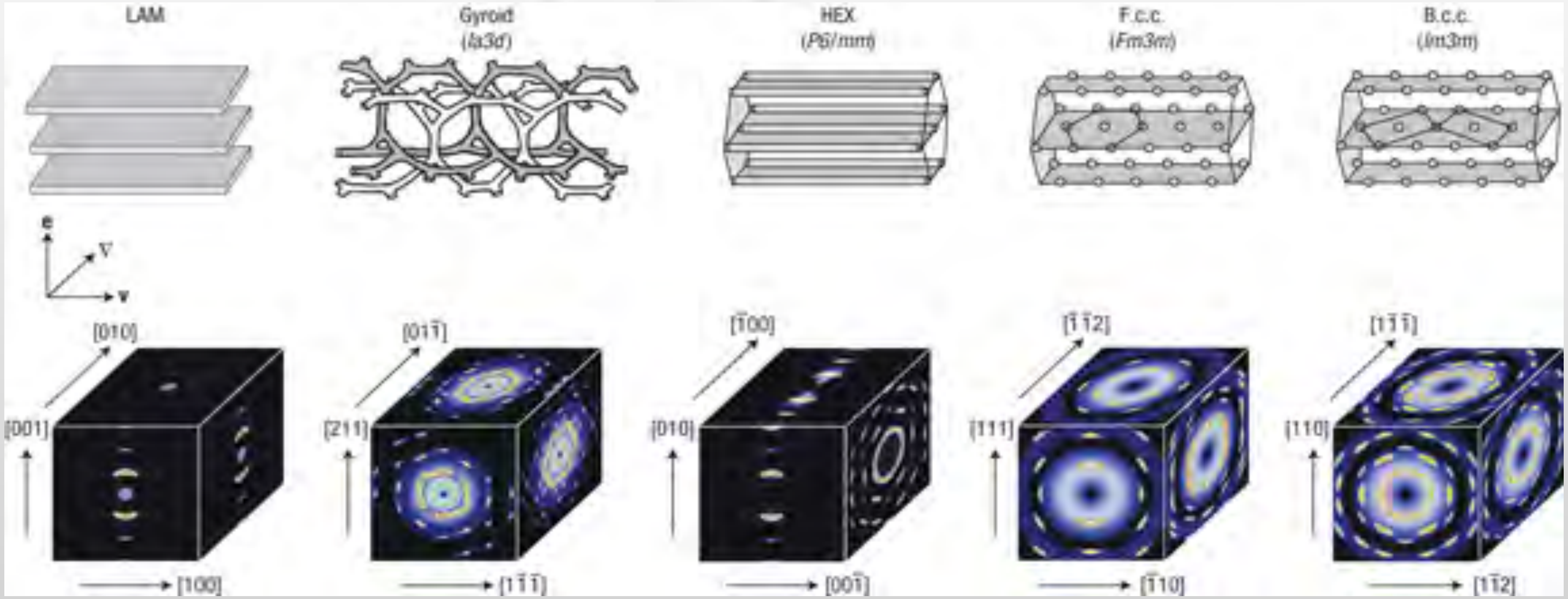




LOQ
ISIS

'soft matter' systems

unified scheme of order and mutual orientation
under 'orientation' fields: flow, shear, ….

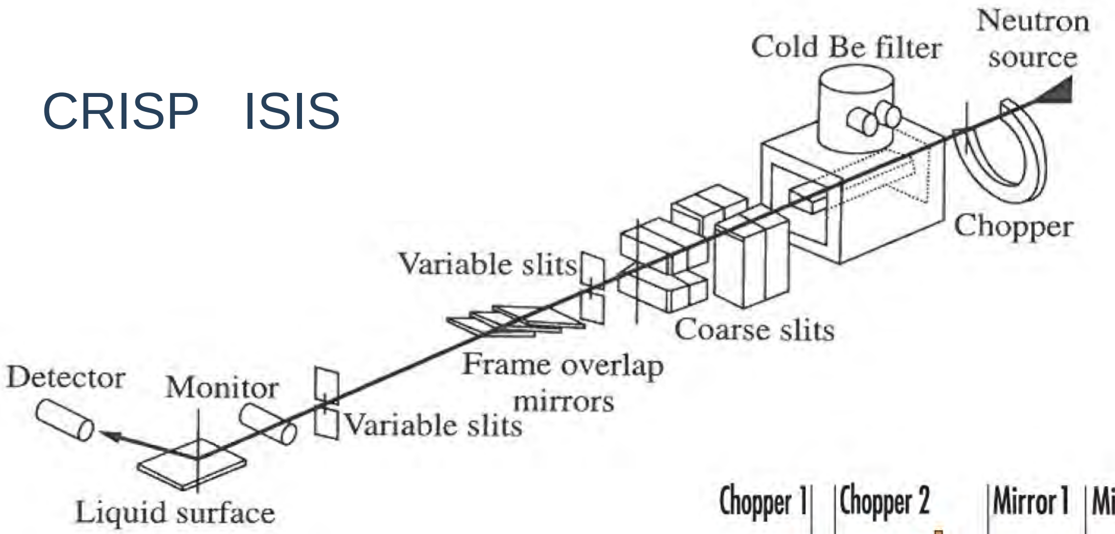


S. Förster et al. Nature Materials 6, 888 (2007)

instruments

neutron reflectometry

CRISP ISIS



Figaro ILL