NEUTRONS AND THEIR INTERACTION WITH MATTER

Overview

- History – neutrons and nuclear reactions
- Production – reactors and spallation sources
- Properties – as a particle and a probe
- Instruments – exploiting the probe to do science

A BIT OF HISTORY

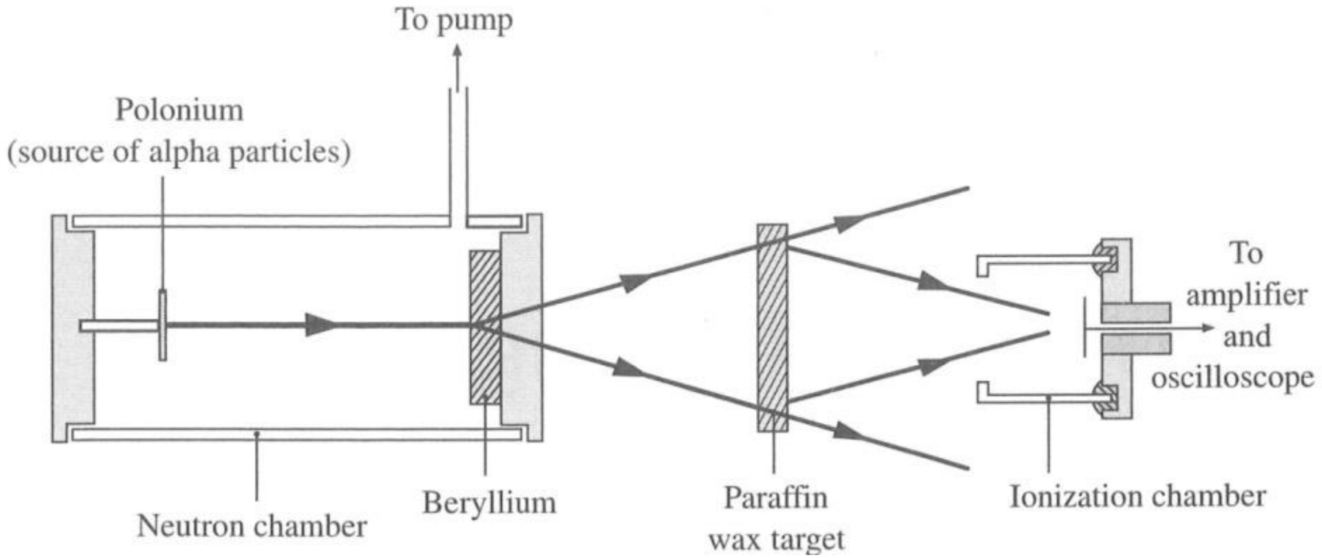
The neutron

- 1932: J. Chadwick, after work by others, discovers the 'neutron', a neutral but massive particle

$$ {}^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} $$

$$ \left(m_{He} + m_{B}\right)c^2 + T_{He} = \left(m_{C} + m_{n}\right)c^2 + T_{C} + T_{n} $$

$$ m_{n} = 1.0067 \pm 0.0012 \, \mathrm{a.m.u} $$



A BIT OF HISTORY

The nuclear reaction

- 1938: O. Hahn, F. Strassmann & L. Meitner discovered the fission of ^{235}U nuclei through thermal neutron capture
- 1939: H. v. Halban, F. Joliot & L. Kowarski showed that ^{235}U nuclei fission produced 2.4 n^0 on average – chain reaction
- 1942: E. Fermi & al. demonstrated first self-sustained chain reaction reactor

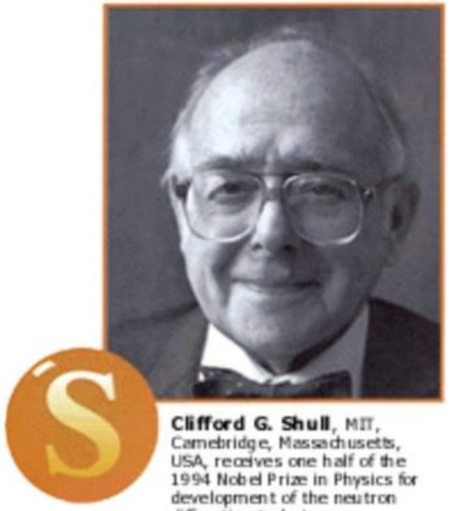
Nobel prizes, neutrons and the ILL

Chadwick, Shull & Brockhouse

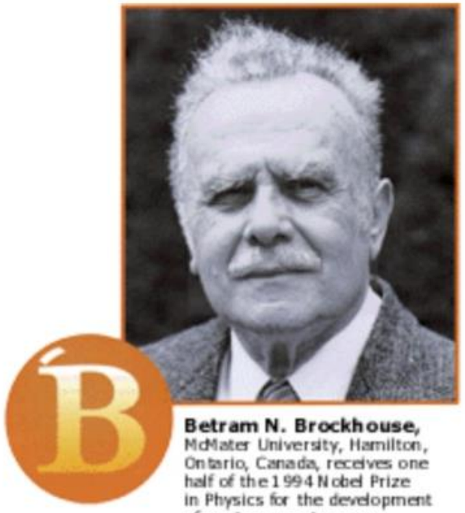
James Chadwick
(1891 - 1974)

The Nobel Prize in Physics 1994

The Royal Swedish Academy of Sciences has awarded the 1994 Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.



Clifford G. Shull, MIT, Camebridge, Massachusetts, USA, receives one half of the 1994 Nobel Prize in Physics for development of the neutron diffraction technique.



Betram N. Brockhouse, McMater University, Hamilton, Ontario, Canada, receives one half of the 1994 Nobel Prize in Physics for the development of neutron spectroscopy.

Shull made use of **elastic scattering** i.e. of neutrons which change direction without

Brockhouse made use of **inelastic scattering** i.e. of neutrons, which change

Nobel prizes, neutrons and the ILL

NEUTRONS
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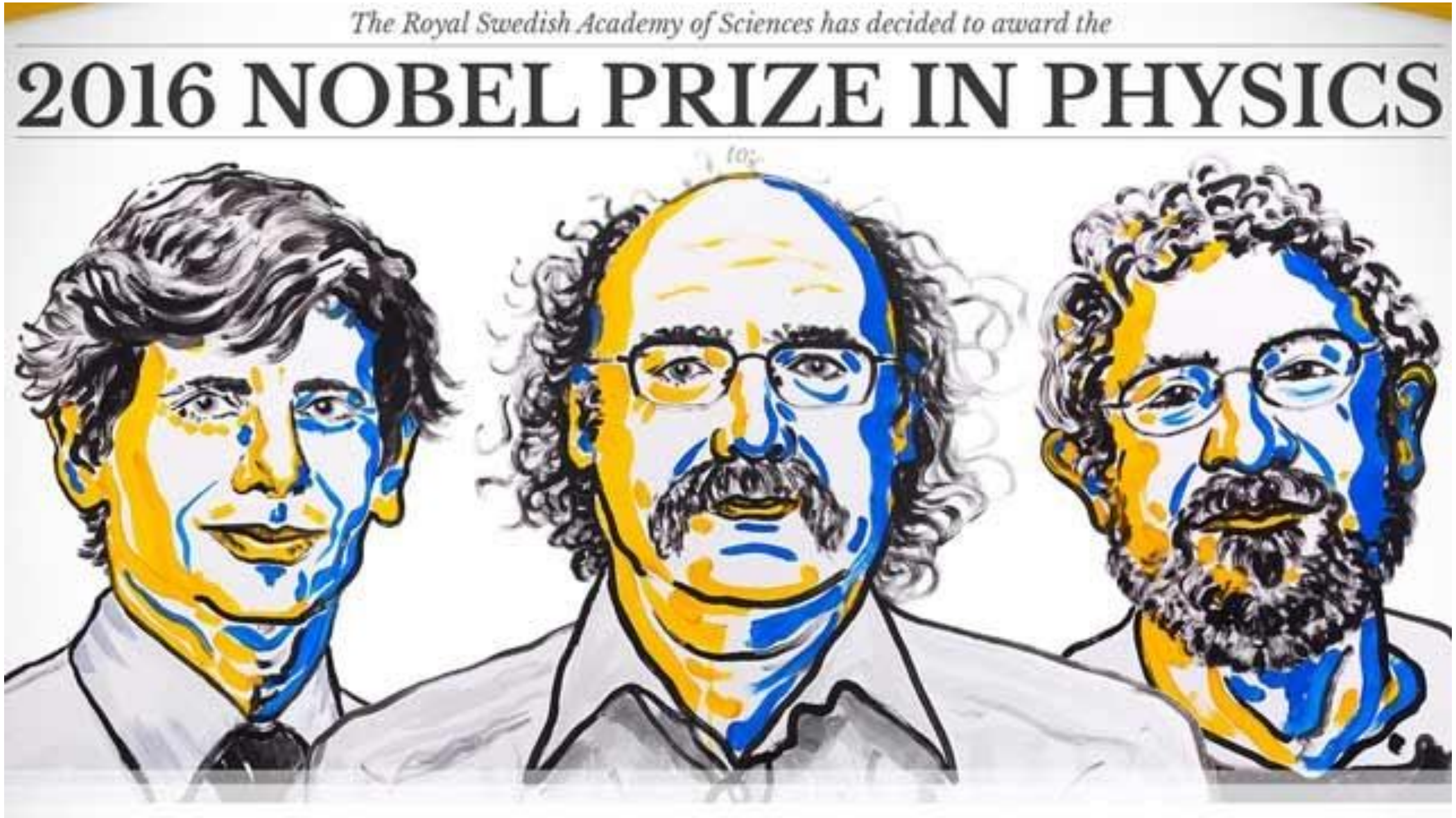
Nobel prizes, neutrons and the ILL

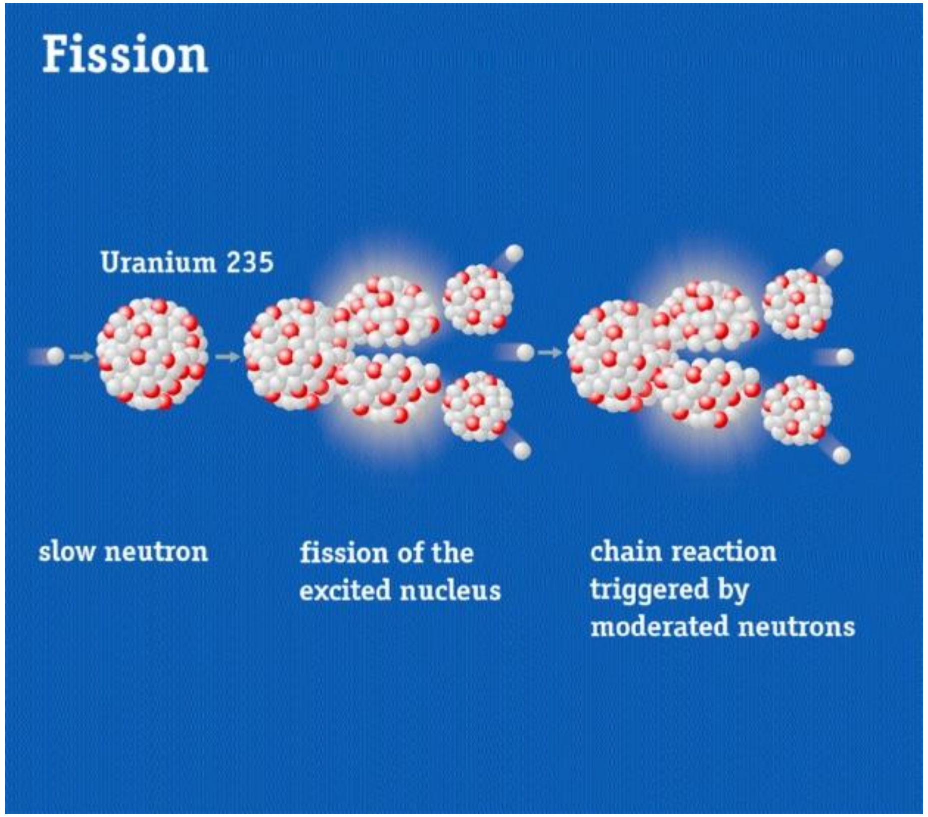
Haldane (1977 – 1981), Kosterlitz and Thouless for topological phase transitions and phases of matter (Electronic structure and excitation of 1D quantum liquids and spin chains)



NEUTRON SOURCES

Fission reactors

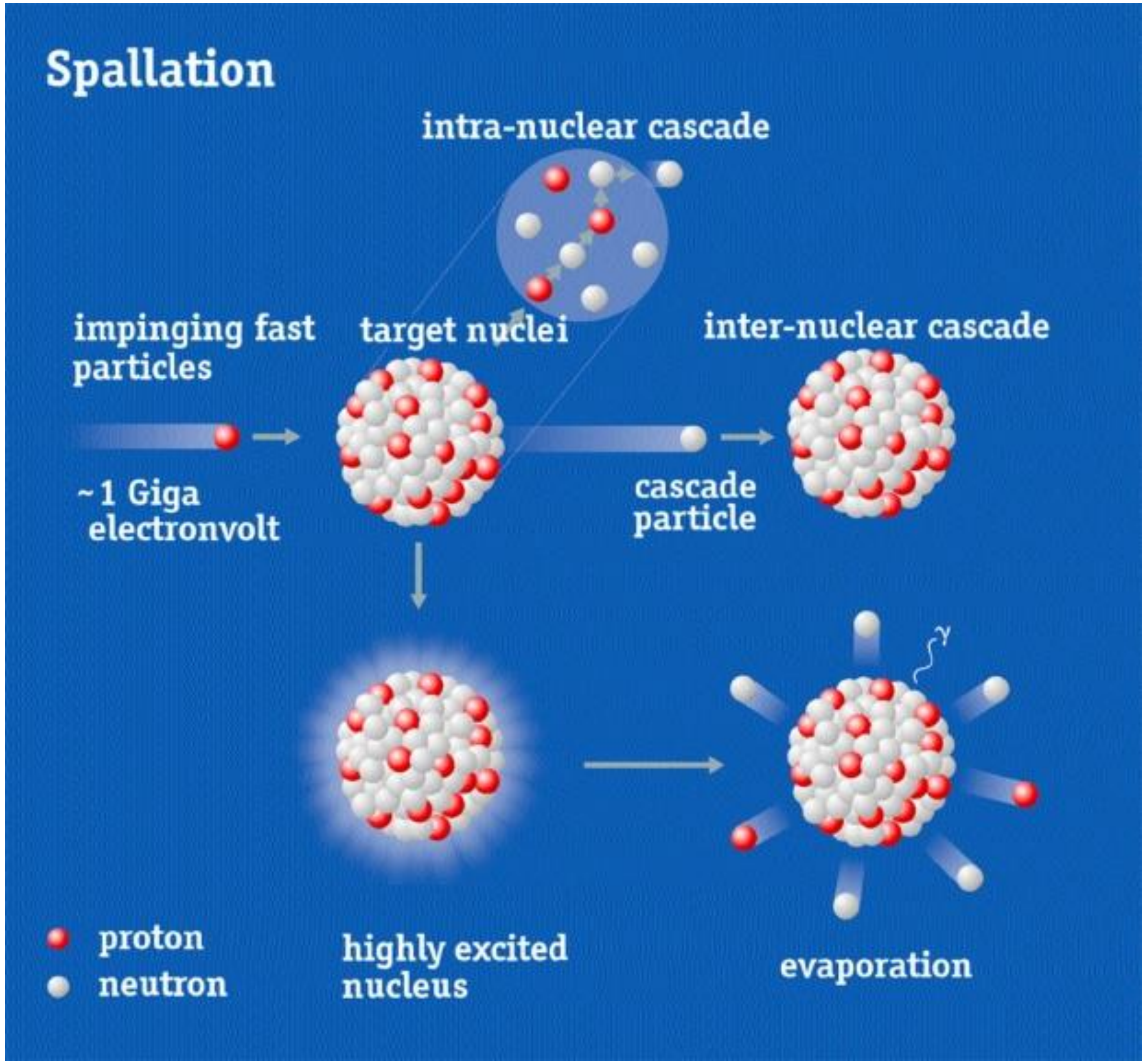
- Nuclear fission → chain reaction with excess neutrons (1n → 2.5n)
- Slow neutrons split U-235 nuclei
- Fission neutrons have MeV energies and need to be moderated (thermalized) to meV energies by scattering from water
- Thermalisation @ RT → *thermal* neutrons, @ 25K → *cold* neutrons and @ 2400 K → *hot* neutrons
- ILL – flux 1.5 x 10^{15} n/cm^2/s



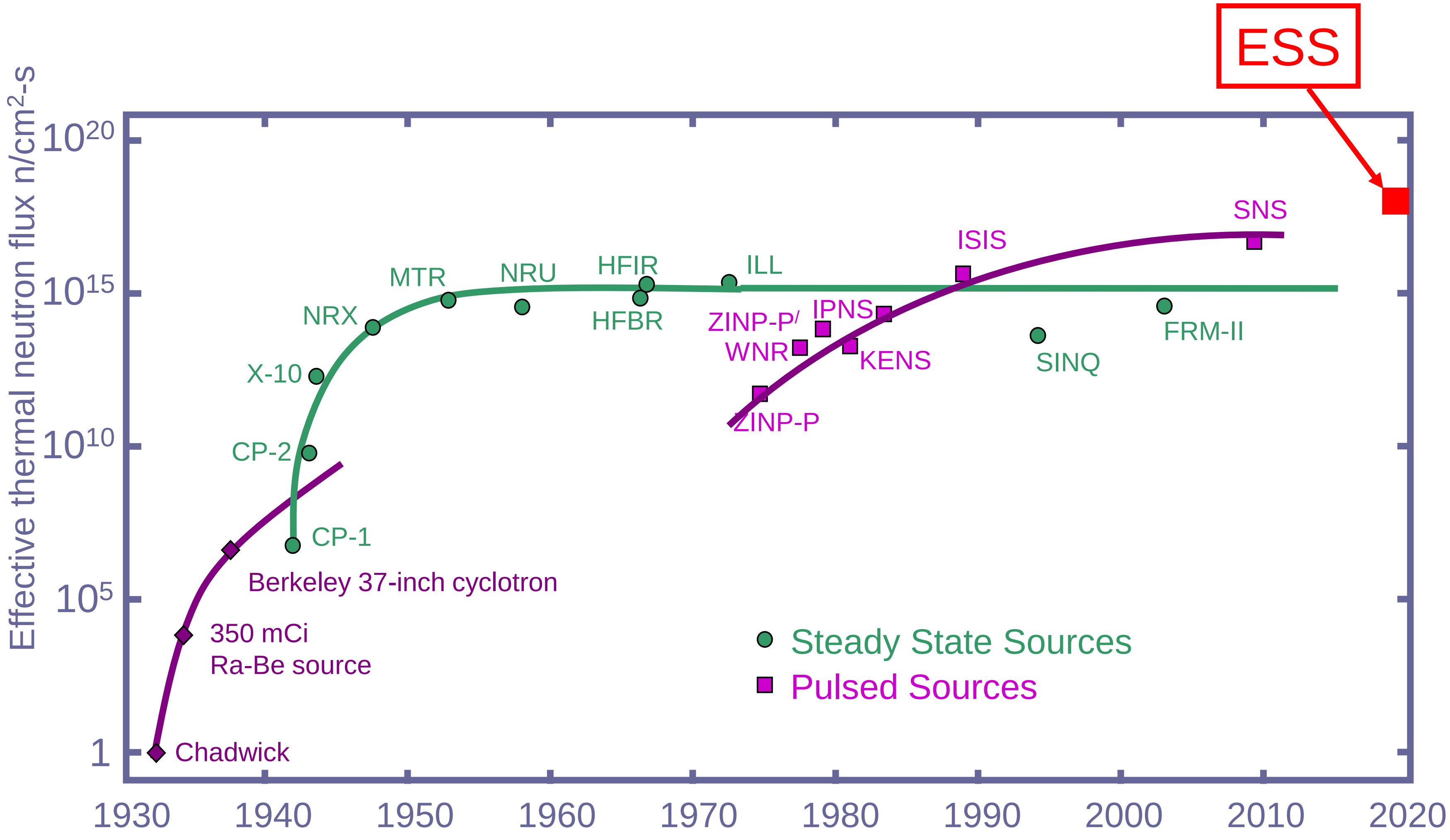
NEUTRON SOURCES

Spallation sources

- Neutrons can be produced by bombarding heavy metal targets
- 2 GeV protons (90% speed-of-light) produce spallation – evaporation of ~30 neutrons



Neutron sources



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

NEUTRONS
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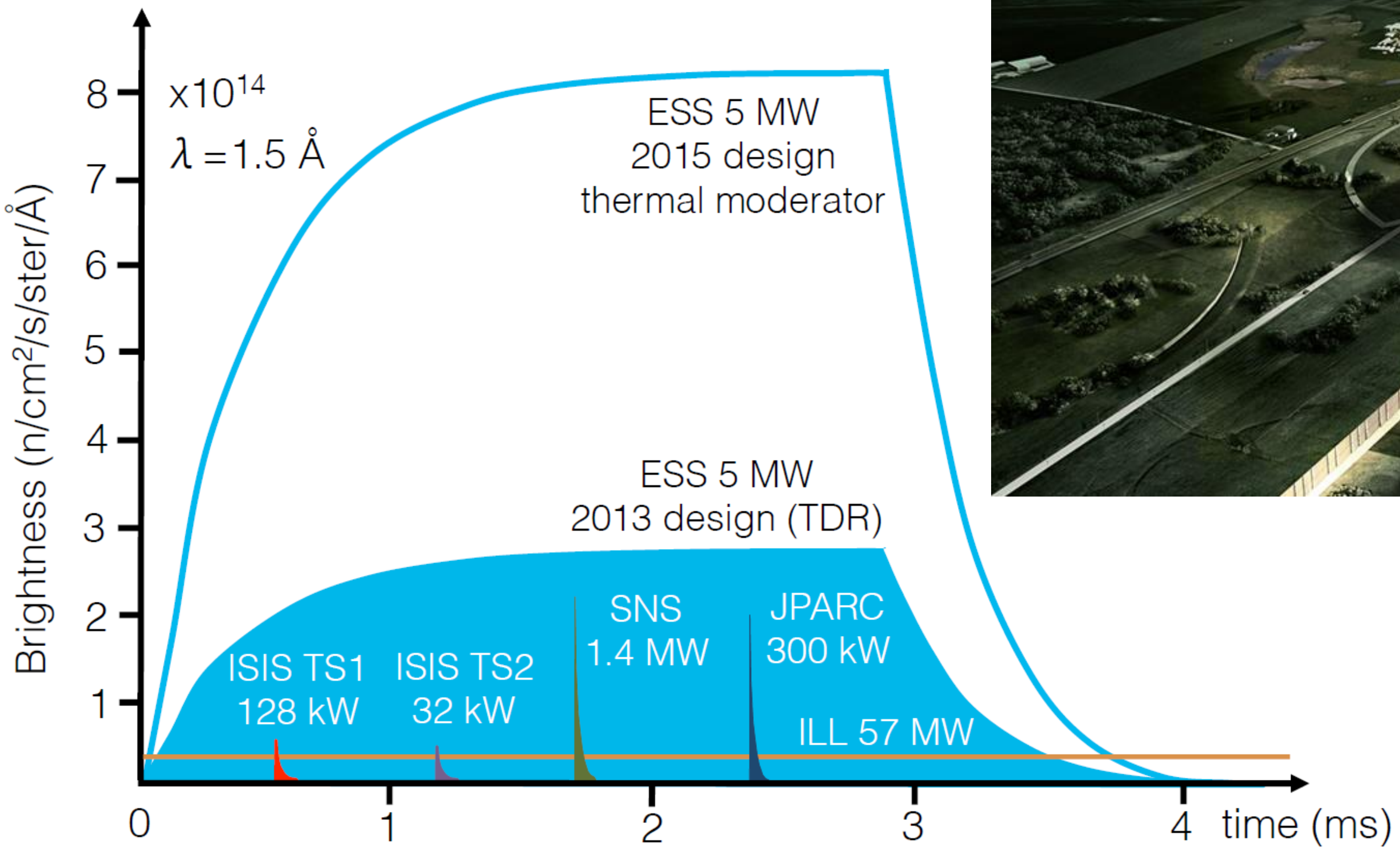
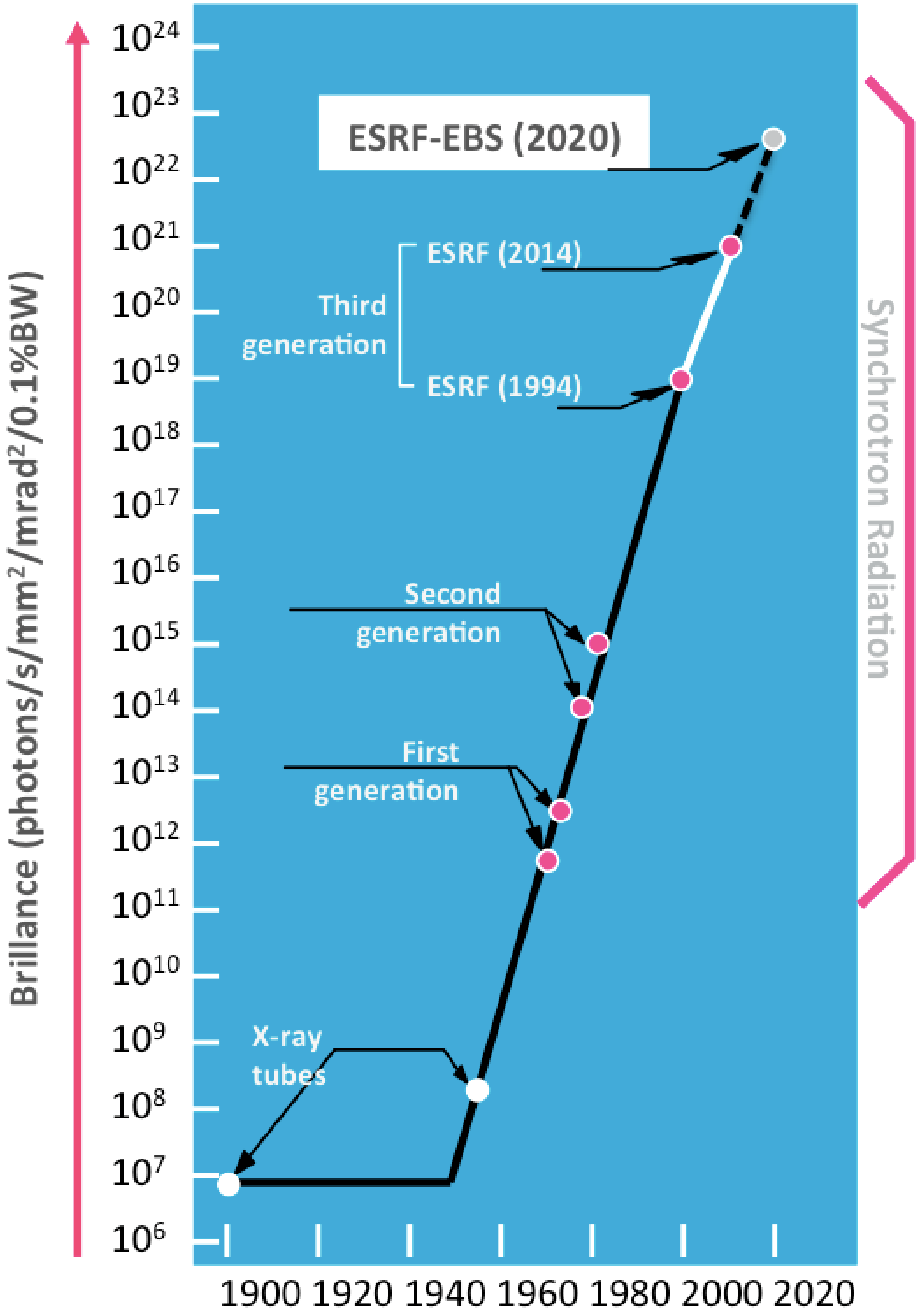
Continuous or pulsed beams

Integrated vs peak flux – ESS will have a time-integrated flux comparable to ILL



N vs X

ESRF (hard X-rays)



NEUTRONS FOR SOCIETY

The neutron

As a particle

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

  life time: 888 ± 1 sec or 880 ± 1 sec

- wave-particle duality: neutrons have particle-like and wave-like properties
- mass: m_n = 1.675 x 10^{-27} kg = 1.00866 amu. (unified atomic mass unit)
- charge = 0
- spin =1/2
- magnetic dipole moment: $\mu_n = -1.9\ \mu_N$, $\mu_p = 2.8\ \mu_N$, $\mu_e \sim 10^3\ \mu_n$,
- velocity (v), kinetic energy (E), temperature (T), wavevector (k), wavelength (λ)

NEUTRONS FOR SOCIETY

The neutron

As a particle

- velocity (v), kinetic energy (E), temperature (T), wavevector (k), wavelength (λ)

$$E = m_n v^2/2 = k_B T = (hk/2\pi)^2/2m_n = (h/\lambda)^2/2m_n$$

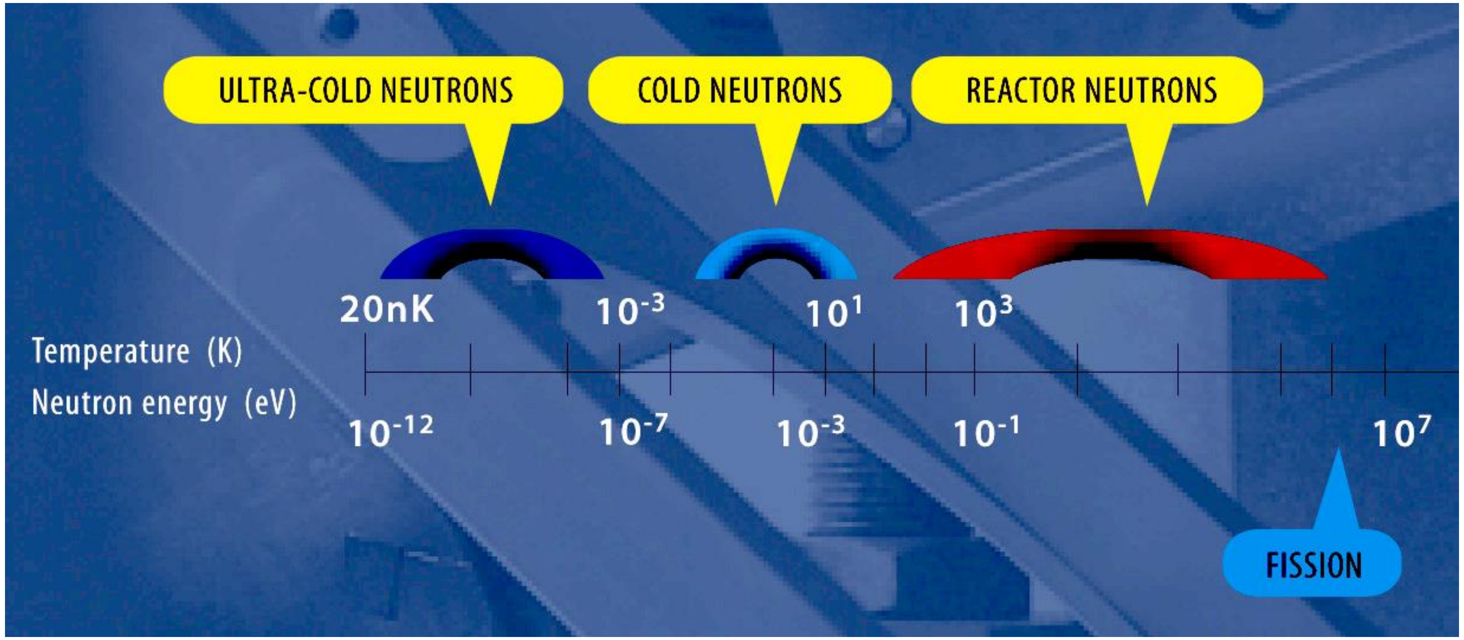
- Neutron energy determines velocity and therefore time-of-flight (*tof*) over a given distance i.e. *tof* → energy determination

$$tof = \frac{L}{v} = 253\mu\sec\cdot\lambda\left[\overset{o}{A}\right]\cdot L[m]$$

The neutron

As a probe

	Energy	Temperature (K)	Wavelength (nm)	velocity (m/s)
Ultra cold neutrons	< 10 μeV	< 0.05	> 30	< 15
Cold neutrons	100 - 5000 μeV	1 - 60	0.4 - 3	150 - 1000
Thermal neutrons	5 - 50 meV	60 - 600	0.13 - 0.4	1000 - 4000
Hot neutrons	0.05 - 0.5 eV	600 - 6000	0.04 - 0.13	4000 - 10000

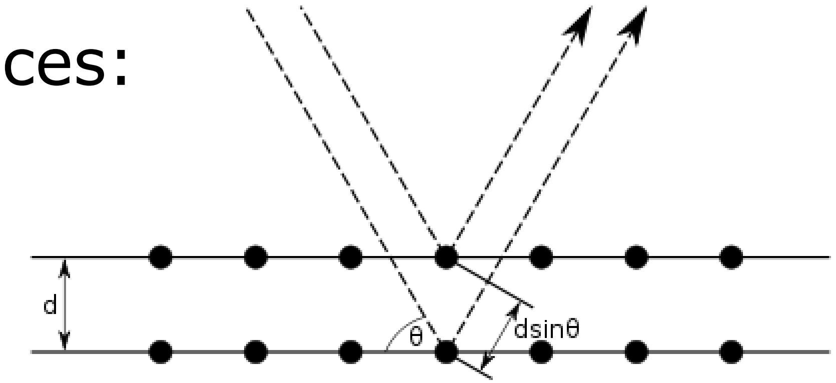


The neutron

As a probe

- Wavelengths on the scale of inter-atomic distances: *Å - nm* wavelengths to measure *Å - μm* distances/sizes

$$n\lambda = 2d\sin\Theta$$



- Energies comparable to structural and magnetic excitations: *meV* neutrons to measure *neV – meV* energies
- Neutral particle – gentle probe, highly penetrating (e.g. 30 cm of Al), no radiation damage
- Magnetic moment (nuclear spin) probes magnetism of unpaired electrons (N.B. $\mu_e \sim 1000x\ \mu_N$)

The neutron

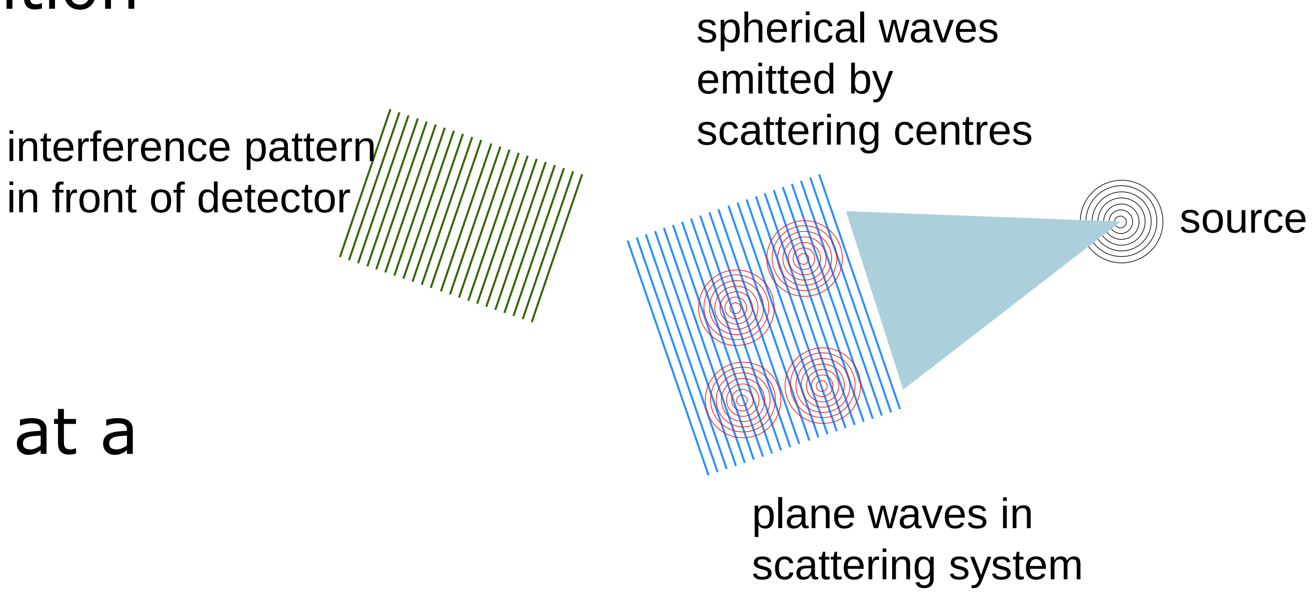
As a probe – interacting with matter – scattering from at atom

- Neutron flux at reactor core
- 1.5 x 10^{15} n/cm^2/s
- Flux at an instrument sample position
- 10^8 n/cm^2/s

→ 10^{-6} n/nm^2/s

→ 10^{-15} n/nm^2/ns

- On these time and length scales, neutrons are being scattered one at a time
- Need wave-particle duality of neutrons



The neutron

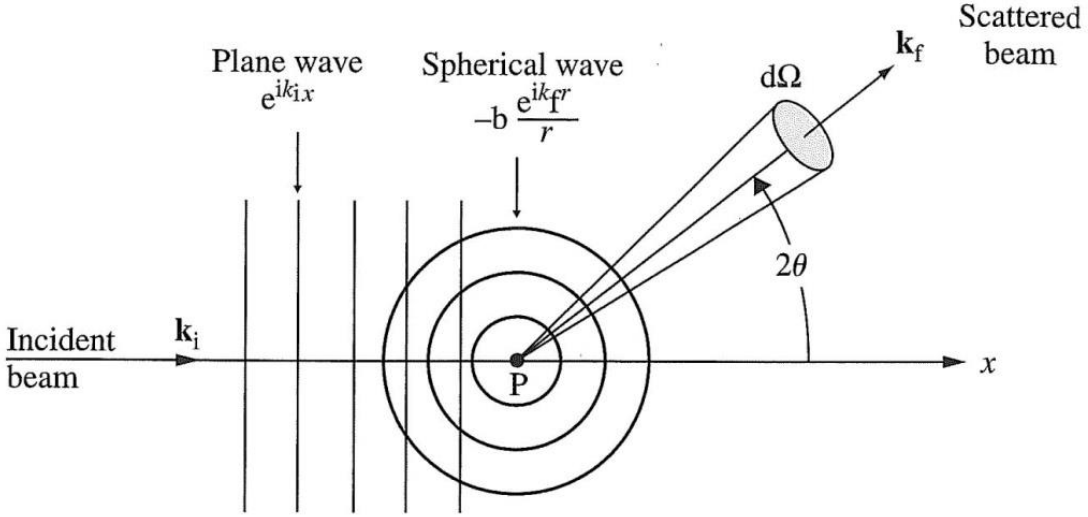
As a probe – interacting with matter – (elastic) scattering from a single fixed nucleus

$$- b \frac{e^{i\mathbf{k}_f.\mathbf{r}}}{r}$$

- Nuclear size << neutron wavelength → point-like s-wave scattering
- b is the scattering length (‘power’) in *fm*
- #neutrons scattered per second per unit solid angle Ω: $\Psi^2 r^2 d\Omega$

$$d\sigma/d\Omega = b^2$$

- σ is the cross-section: $4\pi b^2$ (in barns)



$$V(\mathbf{r}) = \frac{2p\hbar^2}{m_r} b\, d(\mathbf{r})$$

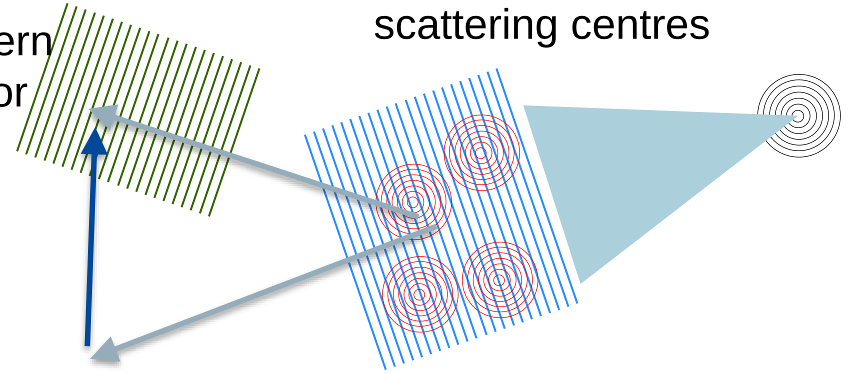
The neutron

As a probe – interacting with matter – scattering from a set of nuclei

$$\frac{d\sigma}{d\Omega} = \sum_{j,k} b_j b_k e^{i\vec{Q}.\left(\vec{R}_j - \vec{R}_k\right)}$$

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

- Q is called momentum transfer
- Q-dependence (eg angle) gives info about atomic positions



NEUTRONS FOR SOCIETY

The neutron

As a probe – interacting with matter – scattering from a set of identical nuclei – coherent and incoherent scattering

- Set of *N* similar atoms/ions – spins/isotopes are *uncorrelated* at different sites
- *b* depends on spin/isotope
- Average is ‹*b*›
- Incoherent scattering gives a *Q* independent background
- But it can be useful to probe the dynamics of single particles (later)

$$\frac{d\sigma}{d\Omega} = \langle b \rangle^2 \sum_{j,k} e^{iQ\cdot(R_j - R_k)} + \left(\langle b^2 \rangle - \langle b \rangle^2 \right) N$$

$$\sigma_{coh} = 4\pi \langle b \rangle^2 \qquad \sigma_{coh} = 4\pi b_{coh}{}^2$$

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

The neutron

As a probe – interacting with matter – scattering from a set of identical nuclei – coherent and incoherent scattering

- If single isotope and zero nuclear spin, no incoherent scattering
- If single isotope and non-zero nuclear spin *I*
- nucleus+neutron spin: *I+1/2* and *I-1/2* scattering length b^+ and b^-
- To reduce incoherent scattering (background):
  - use isotope substitution
  - use zero nuclear spin isotopes
  - polarise nuclei and neutrons

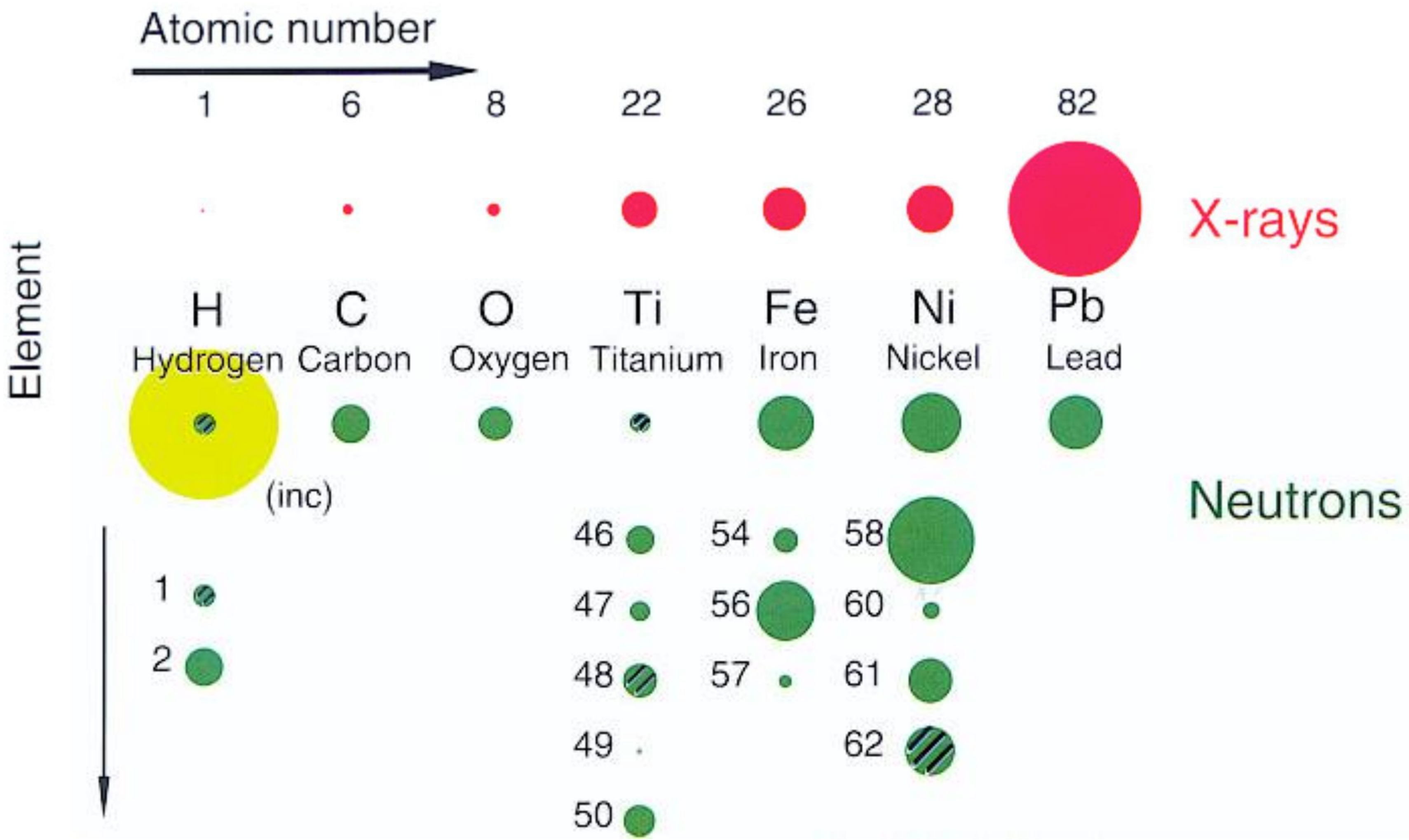
$$\langle b \rangle = \frac{1}{2I+1}\left[(I+1)b^{+} + Ib^{-}\right]$$

$$\langle b^2 \rangle - \langle b \rangle^2 = \frac{I(I+1)}{(2I+1)^2}\left(b^{+} - b^{-}\right)^2$$

NEUTRONS FOR SOCIETY

The neutron

Scattering lengths



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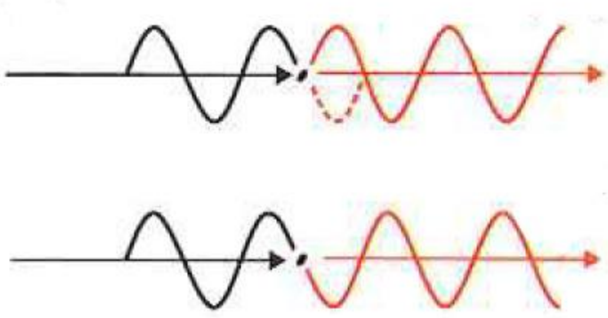
THE NEUTRON

Scattering lengths can be positive or negative (nuclear physics)

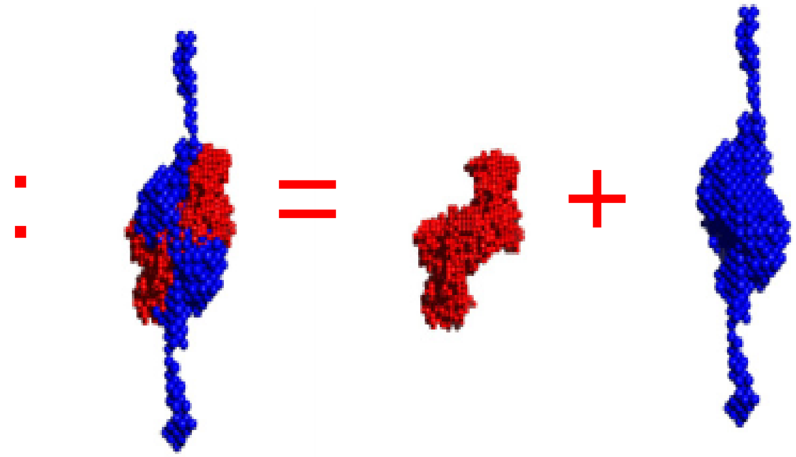
- Positive *b* (most nuclei): phase change
- Negative *b*: no phase change at scattering point

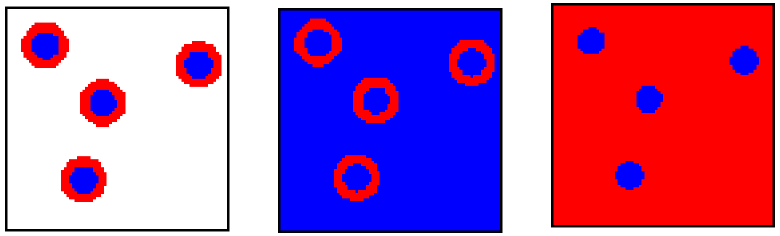


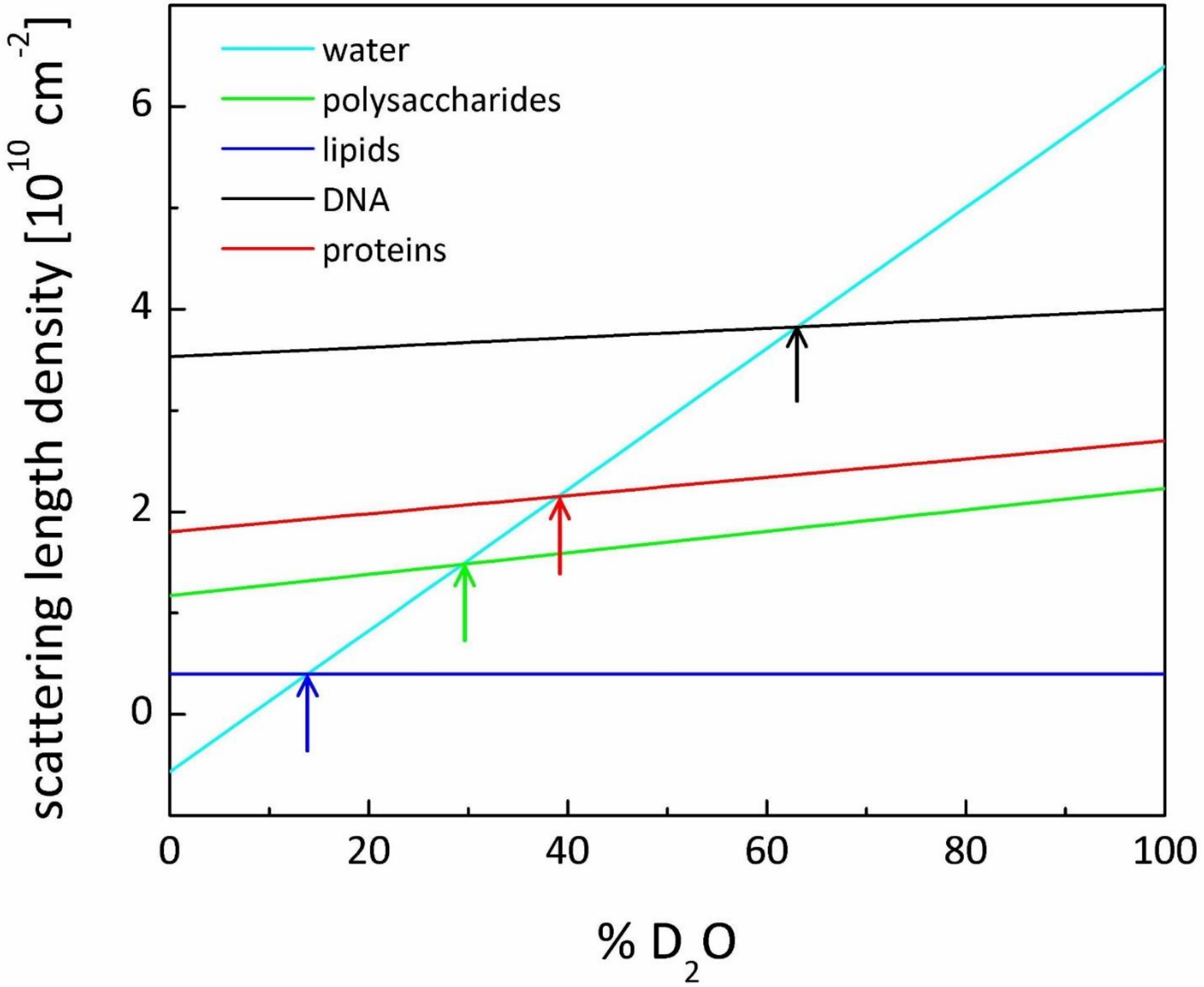
ZSymbA	p or $T_{1/2}$	I	b_c	b_+	b_-	c	σ_{coh}	σ_{inc}	σ_{scatt}	σ_{abs}
0-N-1	**10.3 MIN**	**1/2**	**-37.0(6)**	**0**	**-37.0(6)**		**43.01(2)**		**43.01(2)**	**0**
1-H			**-3.7409(11)**				**1.7568(10)**	**80.26(6)**	**82.02(6)**	**0.3326(7)**
1-H-1	99.985	1/2	-3.7423(12)	10.817(5)	-47.420(14)	+/-	1.7583(10)	80.27(6)	82.03(6)	0.3326(7)
1-H-2	0.0149	1	6.674(6)	9.53(3)	0.975(60)		5.592(7)	2.05(3)	7.64(3)	0.000519(7)
1-H-3	12.26 Y	1/2	4.792(27)	4.18(15)	6.56(37)		2.89(3)	0.14(4)	3.03(5)	$<$ 6.0E-6
2-He			**3.26(3)**				**1.34(2)**	**0**	**1.34(2)**	**0.00747(1)**
2-He-3	0.00013	1/2	5.74(7)	4.374(70)	9.835(77)	E	4.42(10)	1.532(20)	6.0(4)	5333.0(7.0)
2-He-4	0.99987	0	3.26(3)				1.34(2)	0	1.34(2)	0
3-Li			**-1.90(3)**				**0.454(10)**	**0.92(3)**	**1.37(3)**	**70.5(3)**
3-Li-6	7.5	1	2.0(1)	0.67(14)	4.67(17)	+/-	0.51(5)	0.46(5)	0.97(7)	940.0(4.0)
3-Li-7	92.5	3/2	-2.22(2)	-4.15(6)	1.00(8)	+/-	0.619(11)	0.78(3)	1.40(3)	0.0454(3)

The neutron

Scattering lengths can be positive or negative
→ Contrast matching





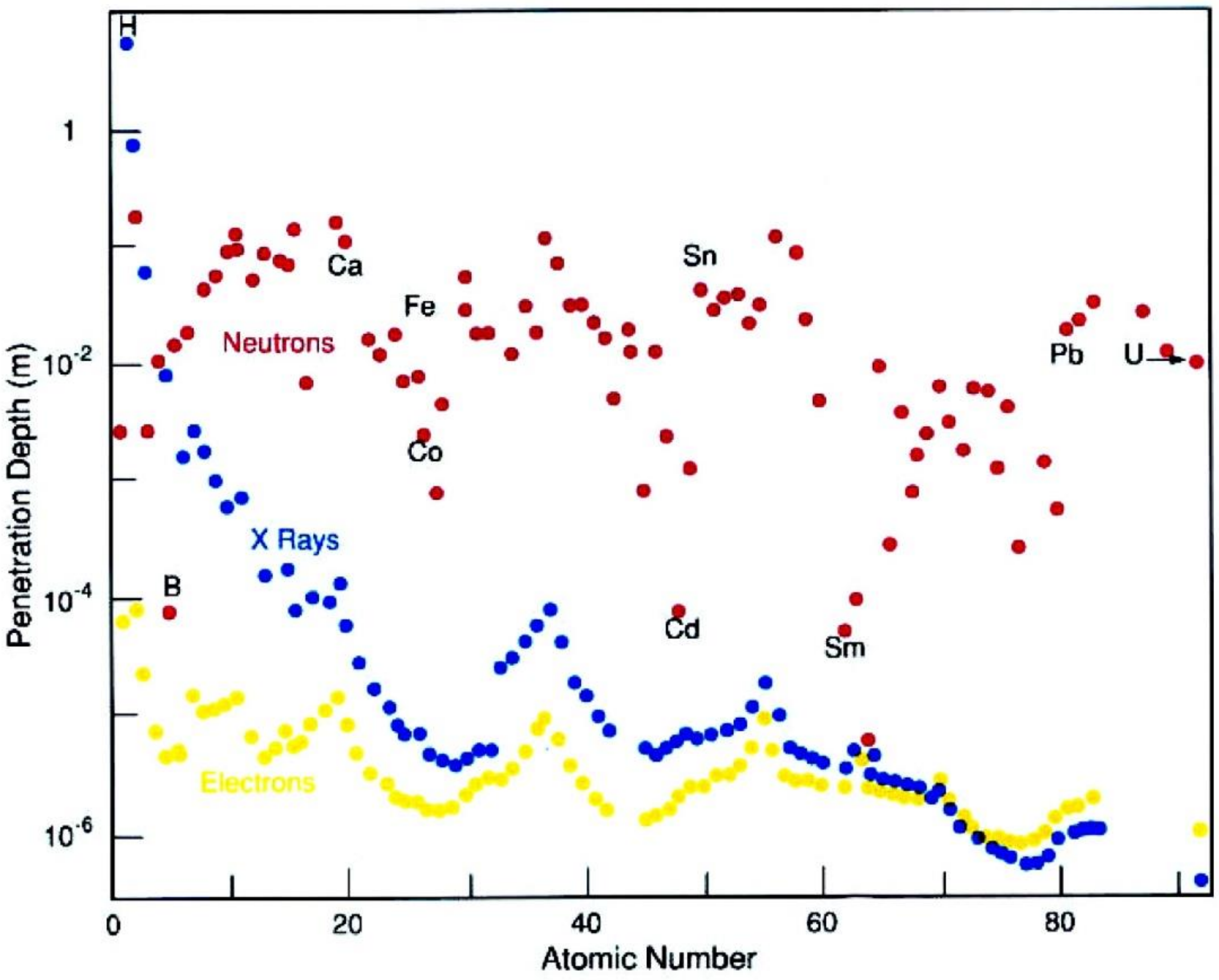


The neutron

As a probe – interacting with matter - absorption

- Absorption – neutron capture
- Several strong absorbers:

  He, Li, B, Cd, Gd,…
- Isotope dependent – choose to your advantage



NEUTRONS FOR SOCIETY

THE NEUTRON

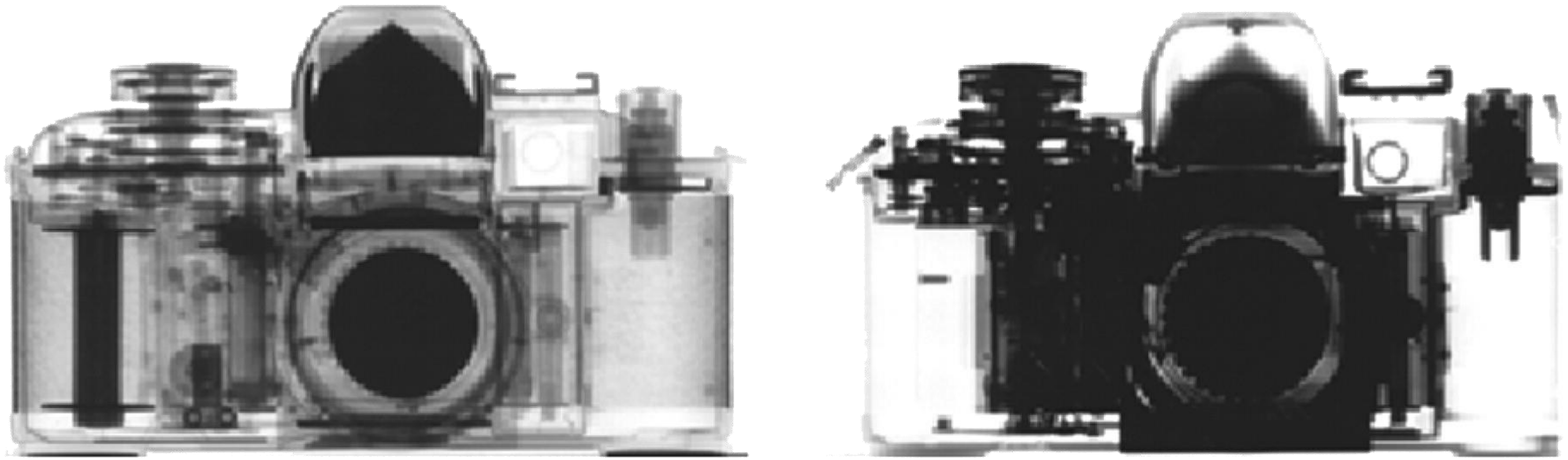
As a probe – interacting with matter - absorption - Neutron detection

- How to detect a weakly interacting, neutral particle?
- With a neutron absorber and measure the resulting signal

$$ {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + \mathrm{p} + 0.764\ \mathrm{MeV} $$

The neutron

Scattering and absorption cause attenuation of a neutron beam → imaging



NEUTRONS X-RAYS

NEUTRONS FOR SOCIETY

The neutron

Scattering and absorption cause attenuation of a neutron beam → imaging

NEUTRONS FOR SOCIETY

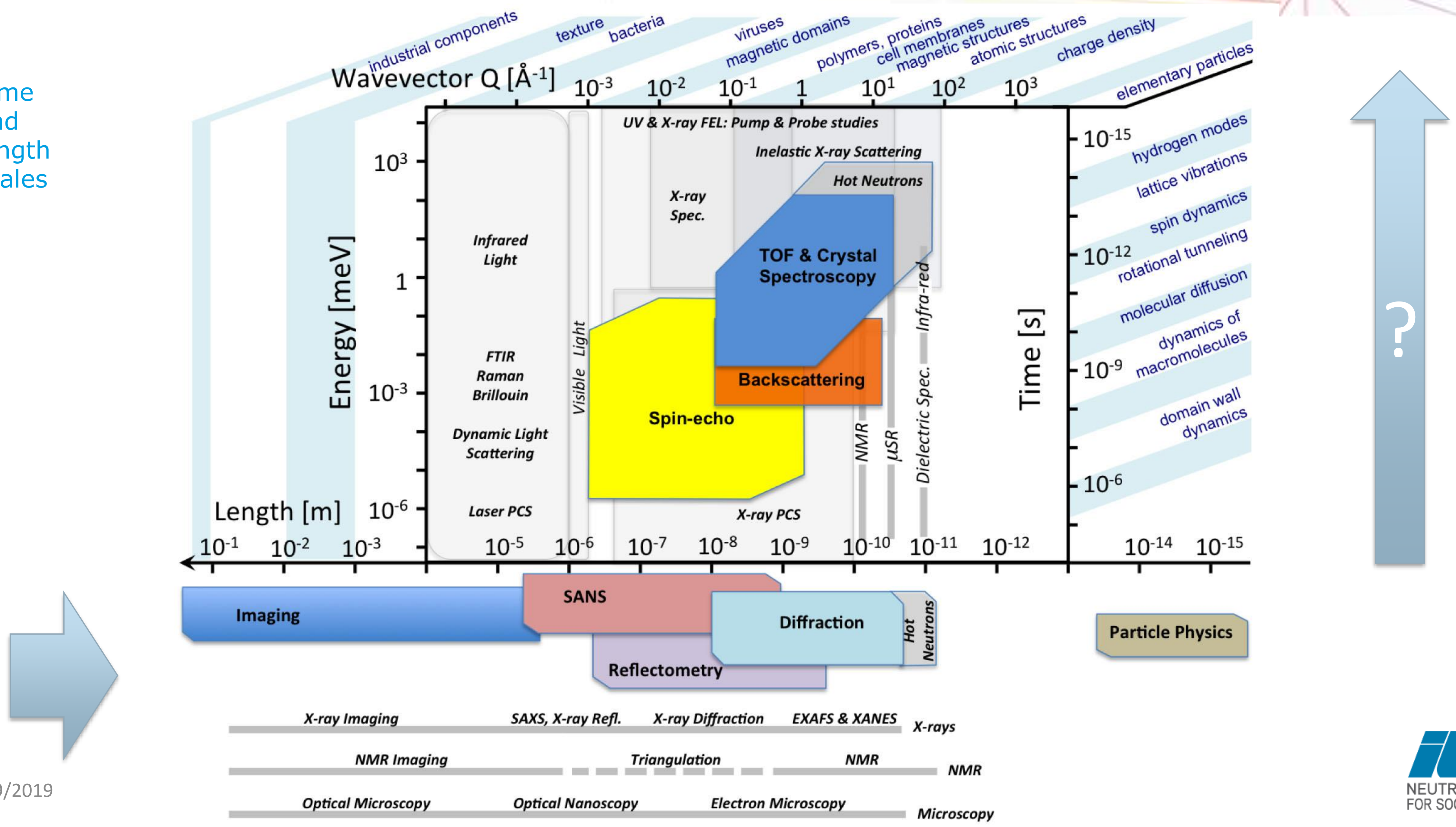
The neutron

As a probe – interacting with matter - summary

- Interaction with nuclei:
  - short range interaction → angle independent scattering (no form factor)
  - scattering length can be positive or negative (→ contrast variation)
  - depends on isotope (→ selectivity) and nuclear spin
  - Coherent and incoherent scattering – strength and weakness
  - Scattering contrast different from X-rays, favours light atoms
- A gentle probe - meV neutron beam does not cause radiation damage like a ~10 keV photon beam (what about XFEL!)
- Magnetic moment probes magnetism of unpaired electrons

Instruments & science

Time and length scales



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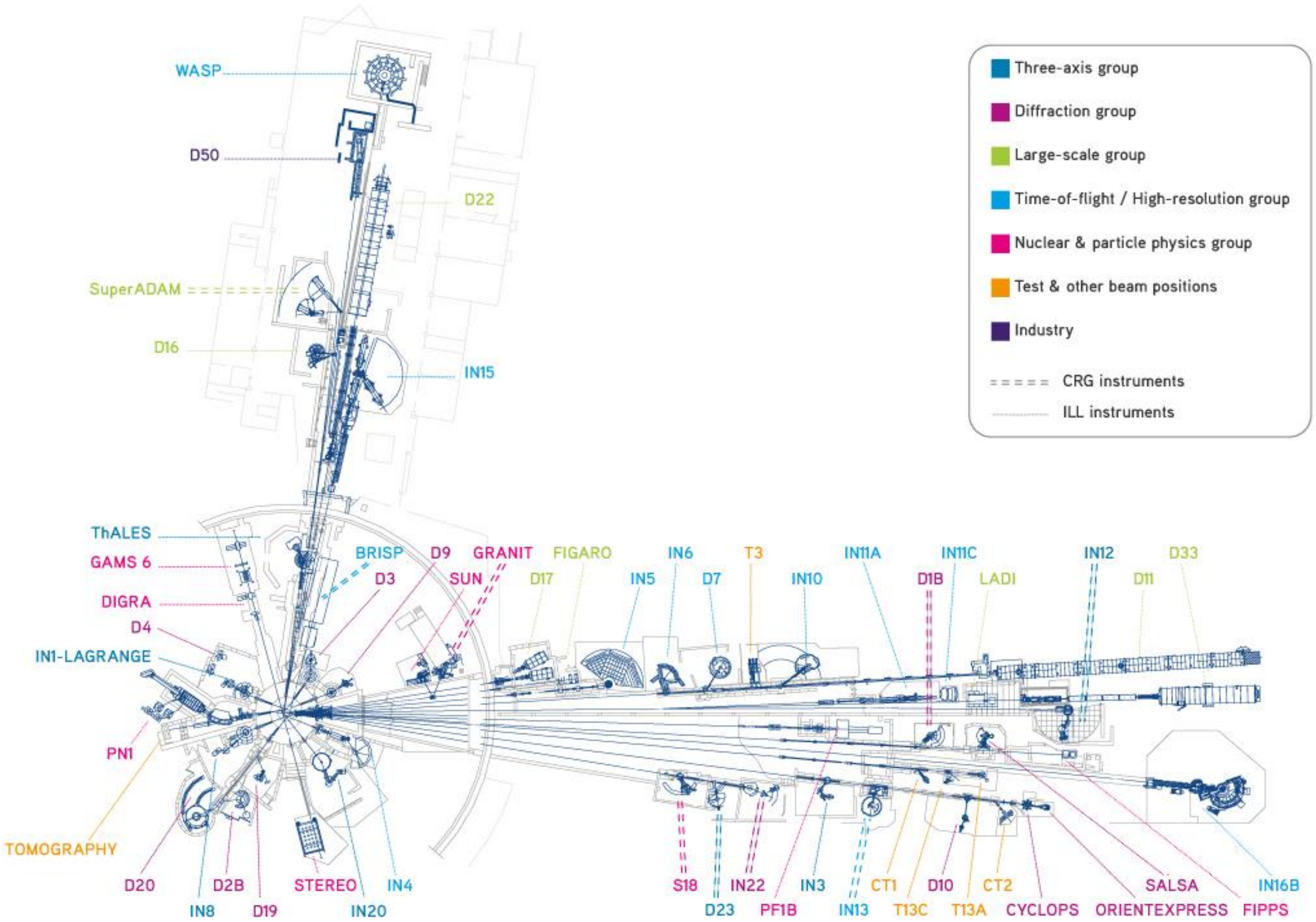
THE ILL'S INSTRUMENT SUITE



NEUTRONS FOR SOCIETY

GENERAL EXPRESSION FOR SCATTERING FROM A COMPLEX SYSTEM

Deriving the general scattering function

Based on

- Born approximation – kinematic theory: neutron wavefunction un-perturbed inside sample
- Fermi's Golden Rule to calculate transitions of neutron (k) and system (λ) from initial and final state
- Hamiltonian to describe the system states (λ)

$$\frac{d\sigma}{d\Omega} = \frac{\sum_{k_f \, in \, d\Omega} W_{k_i,\lambda_i \to k_f,\lambda_f}}{\Phi \; d\Omega}$$

$$\sum_{k_f \, in \, d\Omega} W_{k_i,\lambda_i \to k_f,\lambda_f} = \frac{2\pi}{\hbar} \rho_{\mathbf{k}_f} \left| \langle \mathbf{k}_f \lambda_f | V | \mathbf{k}_i \lambda_i \rangle \right|^2$$

$$\left(\frac{d^2\sigma}{dE_f \, d\Omega} \right)_{\lambda_i \to \lambda_f} = \frac{k_f}{k_i} \left(\frac{m_n}{2\pi\hbar^2} \right)^2 \left| \langle \mathbf{k}_f \lambda_f | V | \mathbf{k}_i \lambda_i \rangle \right|^2 \delta\left(E_i - E_f + E_{\lambda_i} - E_{\lambda_f} \right)$$

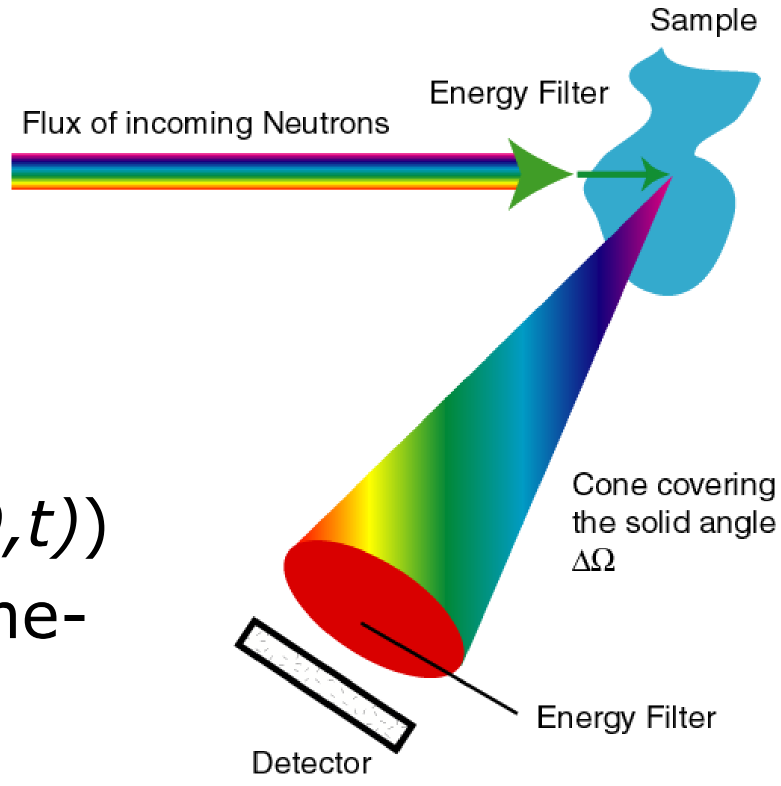
General expressions for scattering from a set of moving atoms

Deriving the scattering function – end up with (after much algebra and manipulations!)

$$\left(\frac{d^2\sigma}{dEd\Omega}\right)=\frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{jk}b_jb_k\int_{-\infty}^{+\infty}\left\langle \exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_k(t)\right\}\right\rangle\exp(i\omega t)dt$$

$$\left(\frac{d^2\sigma}{dEd\Omega}\right)=\frac{k_f}{k_i}\frac{1}{2\pi\hbar}S(\vec{Q},\omega)$$

- Experiment measures double differential cross-section which is simply related to $S(Q,\omega)$ (or $I(Q,t)$)
- $S(Q,\omega)$ is the double Fourier transform of the time-dependent pair-correlation function



GENERAL EXPRESSIONS FOR SCATTERING FROM A SET OF MOVING ATOMS

Deriving the scattering function – end up with – coherent & incoherent contributions

- For a simple system with a single element but different *b*'s

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{coh} = \frac{\sigma_{coh}}{4\pi}\frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{jk}\int_{-\infty}^{+\infty}\left\langle \exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_k(t)\right\}\right\rangle \exp(-i\omega t)dt$$

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{incoh} = \frac{\sigma_{incoh}}{4\pi}\frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{j}\int_{-\infty}^{+\infty}\left\langle \exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_j(t)\right\}\right\rangle \exp(-i\omega t)dt$$

- Scattering function determined by positions *R* of different atoms at different times *t*
- Incoherent scattering can be useful: it measures the correlation between the same atom at different times → single particle dynamics - diffusion

NEUTRONS FOR SOCIETY

GENERAL SCATTERING EXPERIMENT

Scattering triangle – handling Q and ω

- $\boldsymbol{Q=k_f - k_i}$, $\hbar\omega = E_f - E_i$ ($E \sim k^2$, $k = 2\pi/\lambda$)

- Elastic scattering:

  vary Q without changing ω

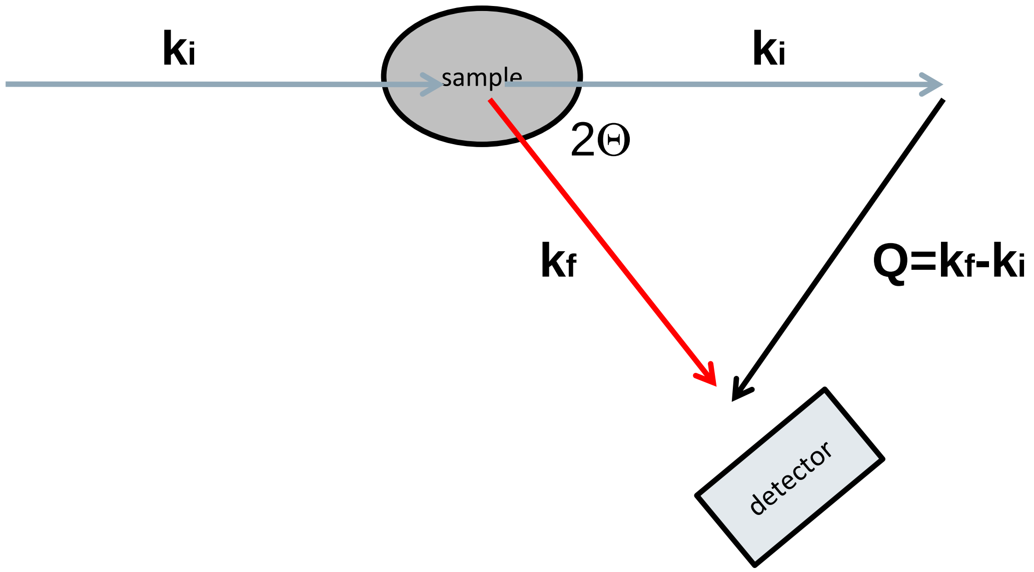
  $E_i = E_f$ vary 2Θ *(monochromatic)*

  vary $|E|$ fix 2Θ *(t.o.f.)*

- Quasi/in-elastic scattering:

  vary ω, normally Q will also change

  vary E_i or E_f and/or 2Θ



GENERIC INSTRUMENT

Energy selection

- How to measure the energy of a neutron beam?
- Or, how to monochromate a beam?
- Measure λ with Bragg reflection

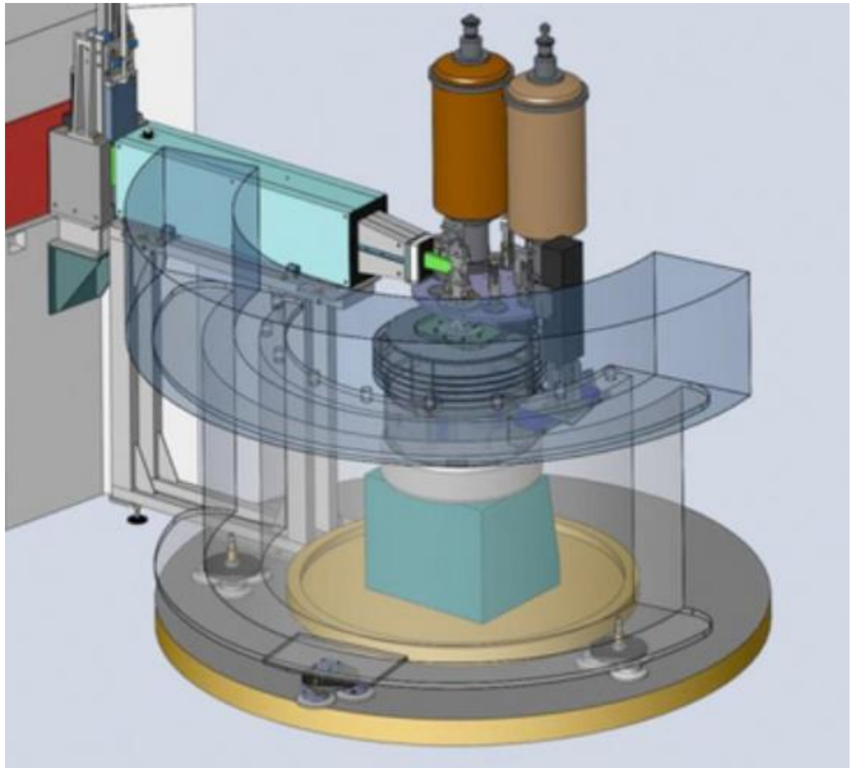
  $n\lambda = 2d\sin\Theta$

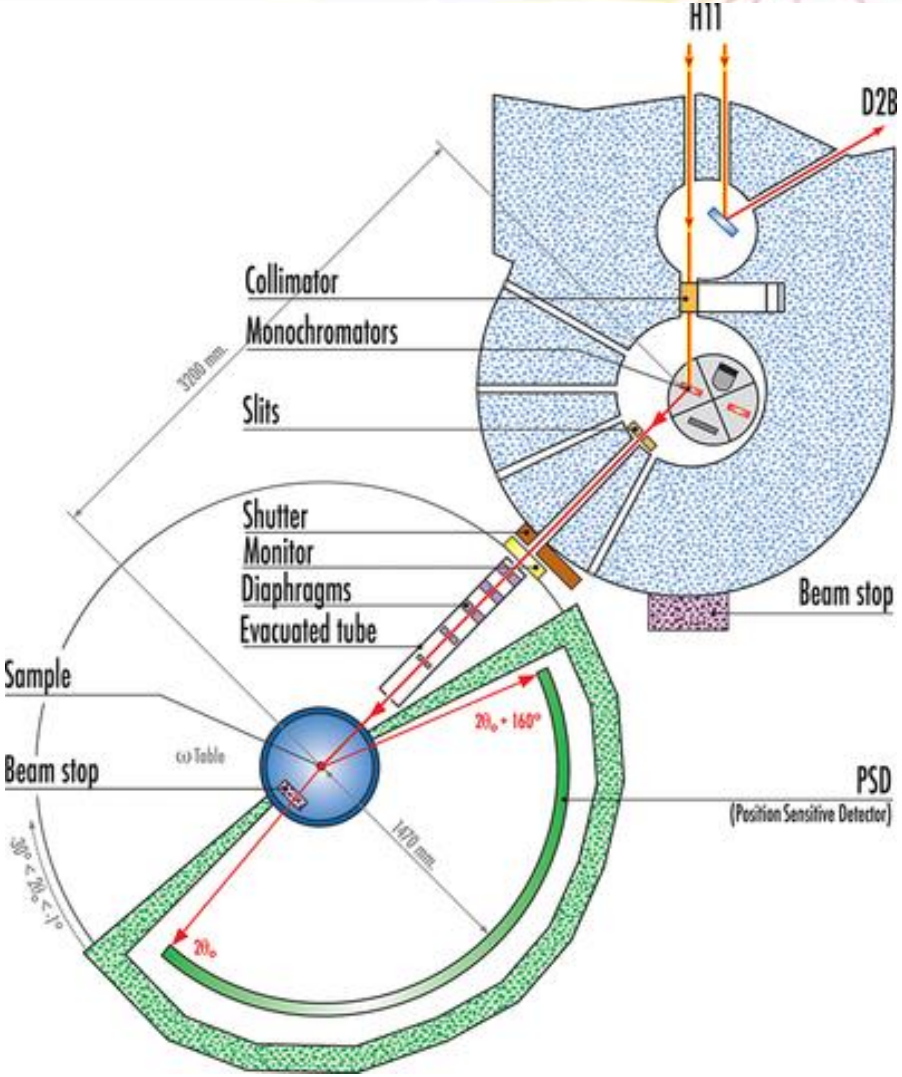
  d = distance between scattering planes
- Use neutron *t.o.f.* (or precession of neutron magnetic moments in a magnetic field)

$$tof = \frac{L}{v} = 253\mu\sec\cdot\lambda\left[\overset{o}{A}\right]\cdot L[m]$$

DIFFRACTION

Instruments (don't measure the final energy!) – D2b & LADI

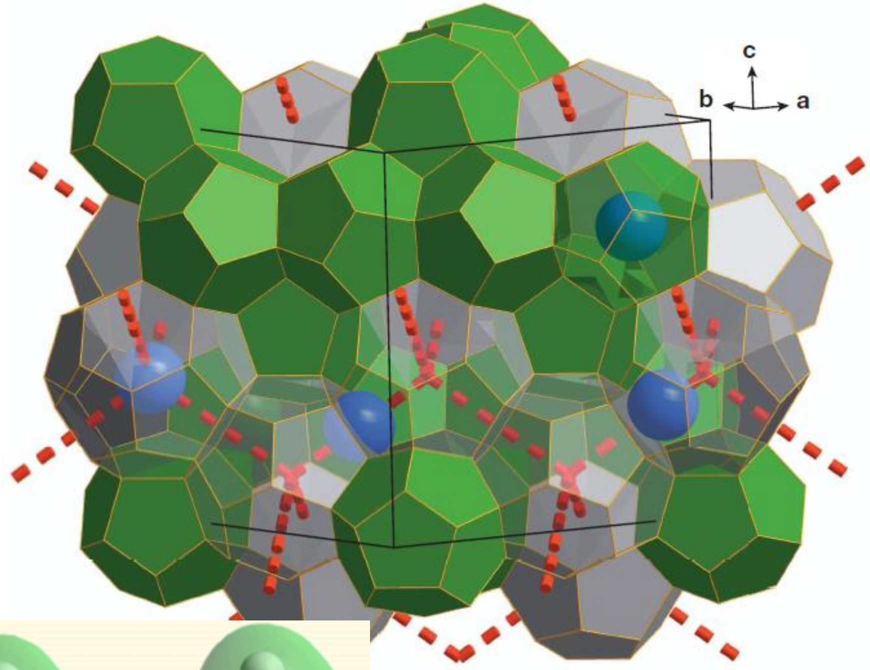


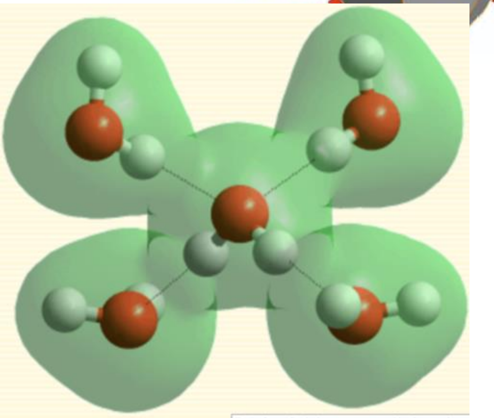


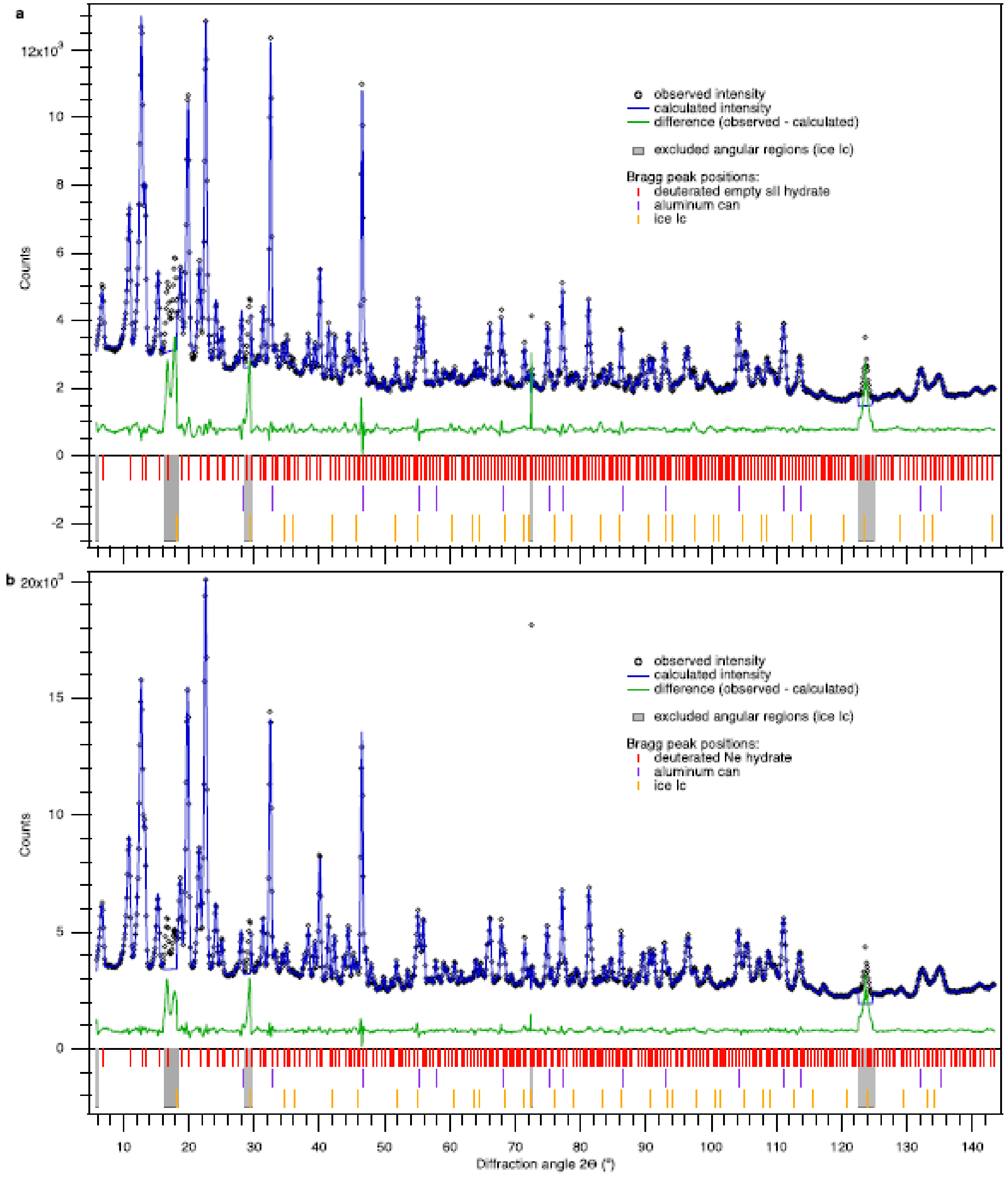
NEUTRONS FOR SOCIETY

DIFFRACTION

Example – Formation and properties of ice XVI obtained by emptying a type sII clathrate hydrate





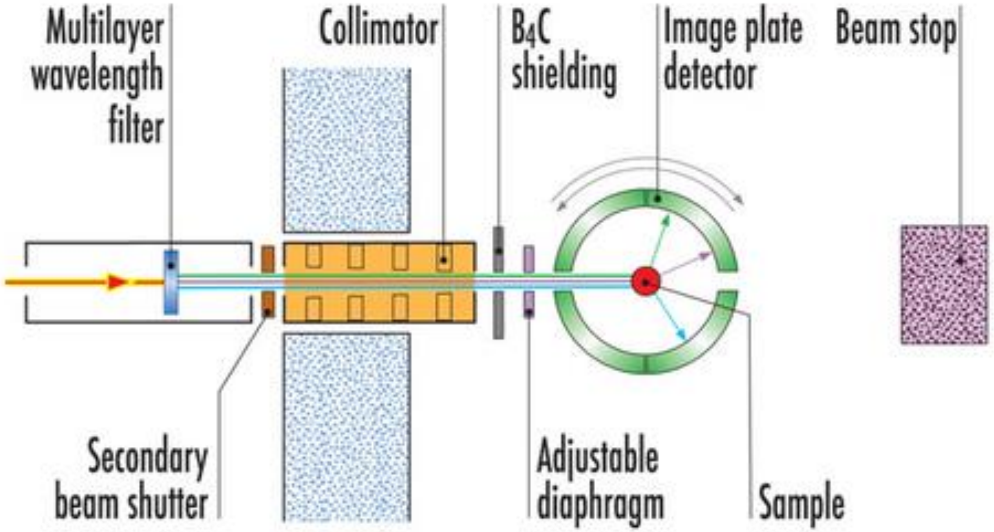


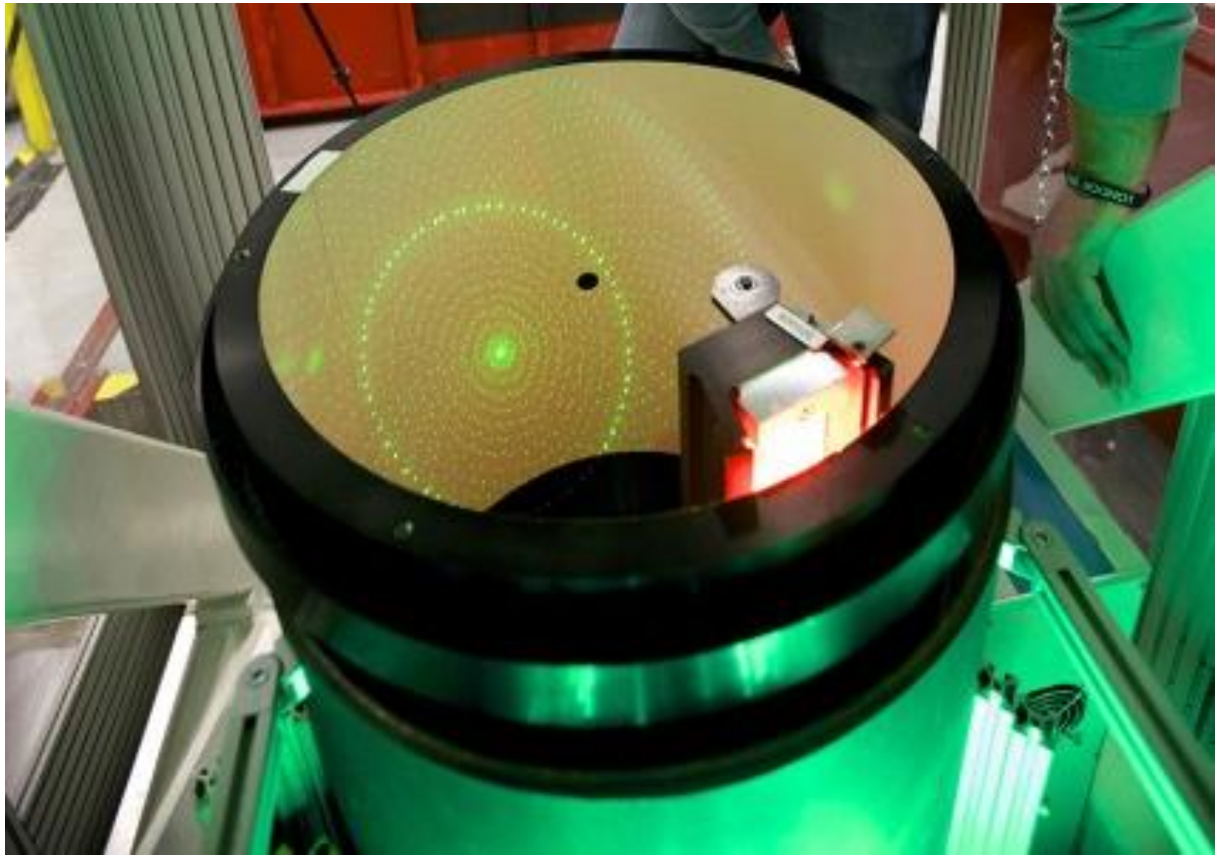
Extended Data Figure 2 | Diffraction patterns of Ne-filled and empty hydrate. **a**, **b**, Rietveld fit (obtained using FullProf software[42]) to diffraction pattern of empty sII D_2O hydrate (**a**) and Ne D_2O hydrate (**b**) taken at 5 K ($\lambda \approx 1.1226$ Å) on D20, ILL/Grenoble. The observed intensity is represented by open black circles, the calculated intensity as a blue line, the difference of both by a green line, grey shading marks the angular regions excluded in the refinement, red lines mark the positions of Bragg peaks of the hydrate, violet lines those of the aluminium sample can and orange lines those of ice Ic.

NEUTRONS FOR SOCIETY

DIFFRACTION

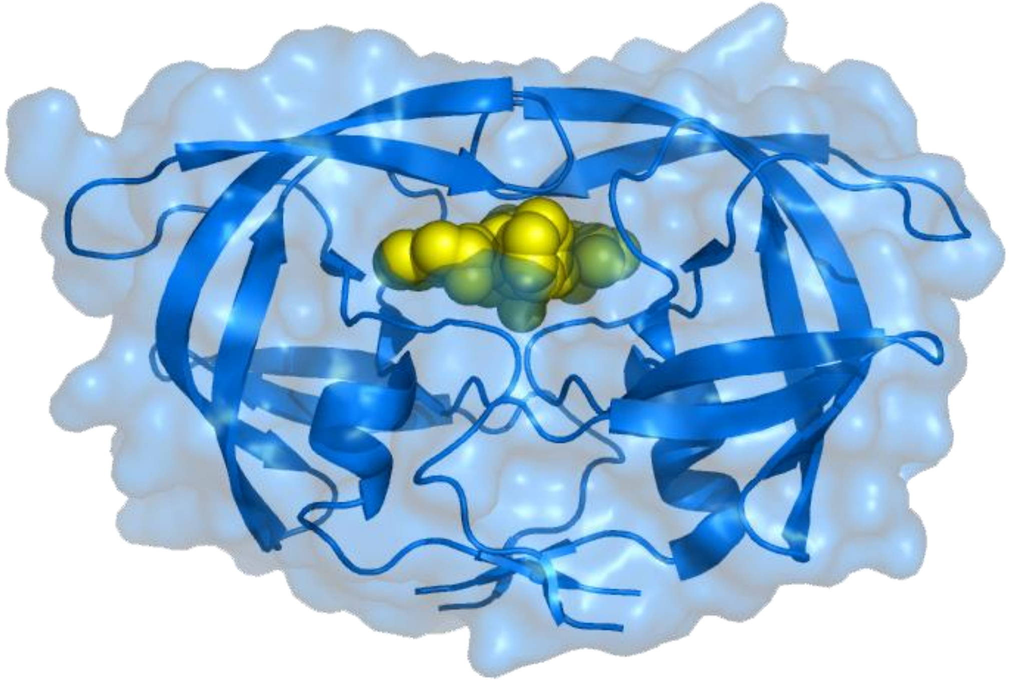
Instruments (don't measure the final energy!) – D2b & LADI

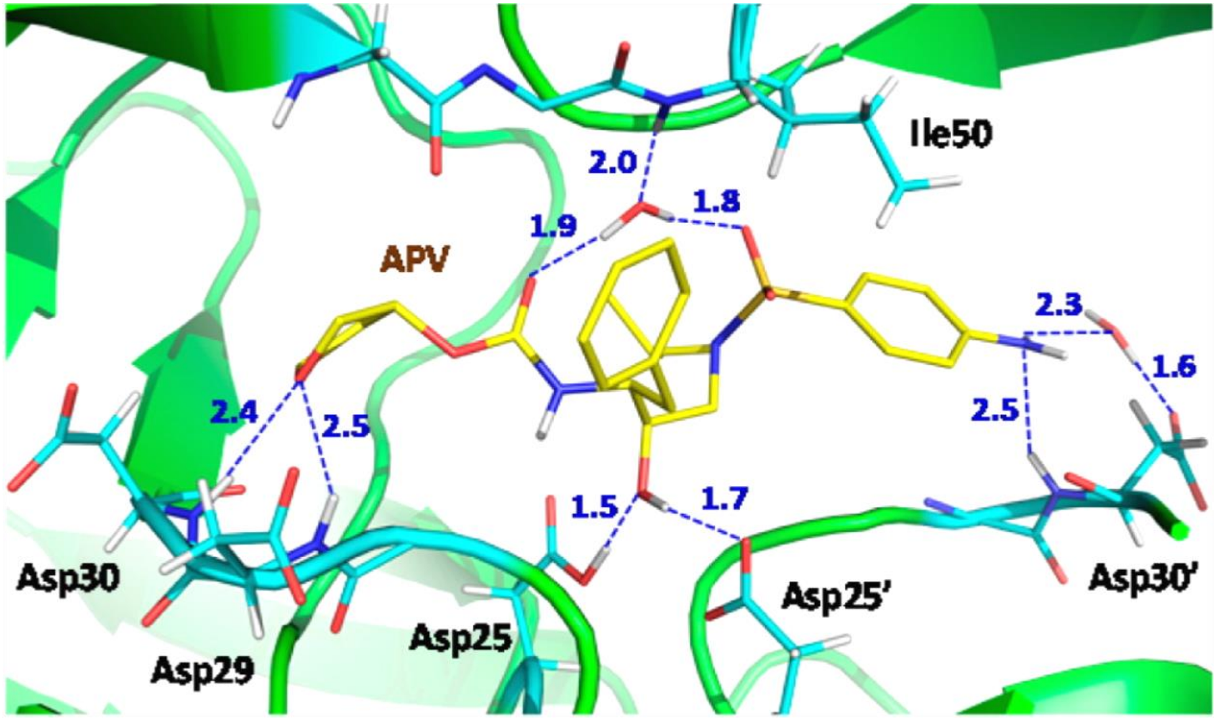




DIFFRACTION

Example – Improving drug design: HIV-1 Protease in complex with clinical inhibitors (sample ~50 μg)





SPECTROSCOPY – TIME/FREQUENCY DOMAIN

Simplified expressions for the scattering function – coherent scattering

In previous scattering expressions

$R=R_0+\delta R(t)$

For normal modes: $\delta R(t)$ → displacement vectors ***e*** & frequencies ω

Coherent scattering - Phonons:

- Short range coupling gives long range correlations
- Dispersion as a function of ***q*** (or wavelength) – guitar string!

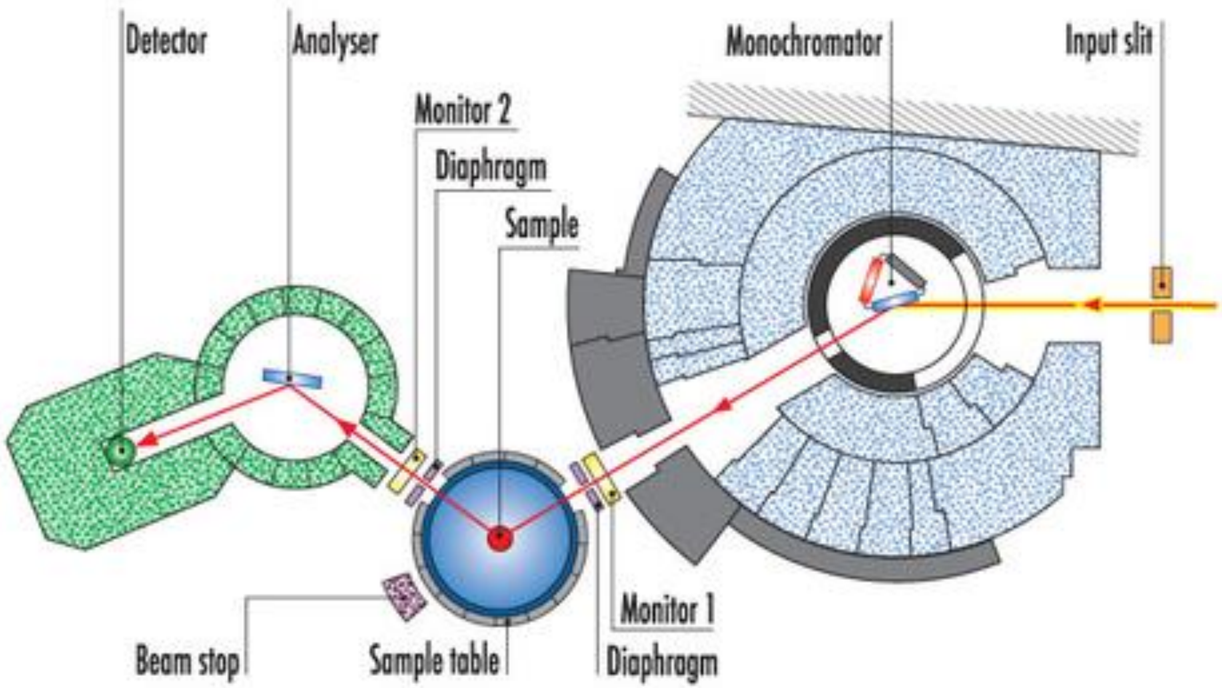
$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{coh\pm1} = \frac{\sigma_{coh}}{4\pi}\frac{k_f}{k_i}\frac{(2\pi)^3}{v_0}\frac{1}{2M}\exp(-2W)\sum_s\sum_\tau\frac{\left(\vec{Q}\cdot\vec{e}_s\right)}{\omega_s}\langle n_s+1/2\pm1/2\rangle$$

$$\times\delta(\omega\mp\omega_s)\delta\left(\vec{Q}\mp\vec{q}-\vec{\tau}\right)$$

NEUTRONS FOR SOCIETY

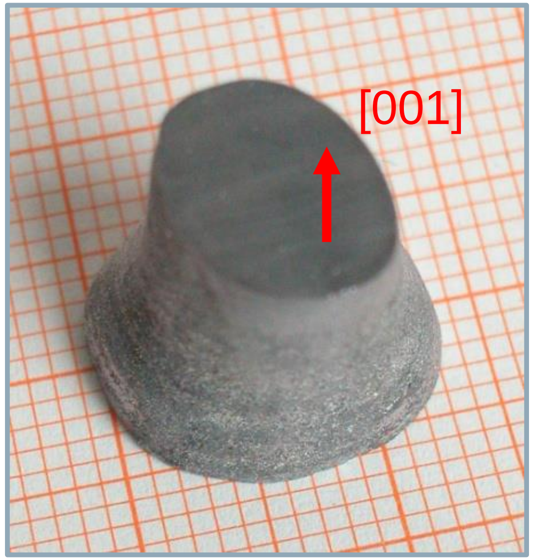
Spectroscopy – time/frequency domain

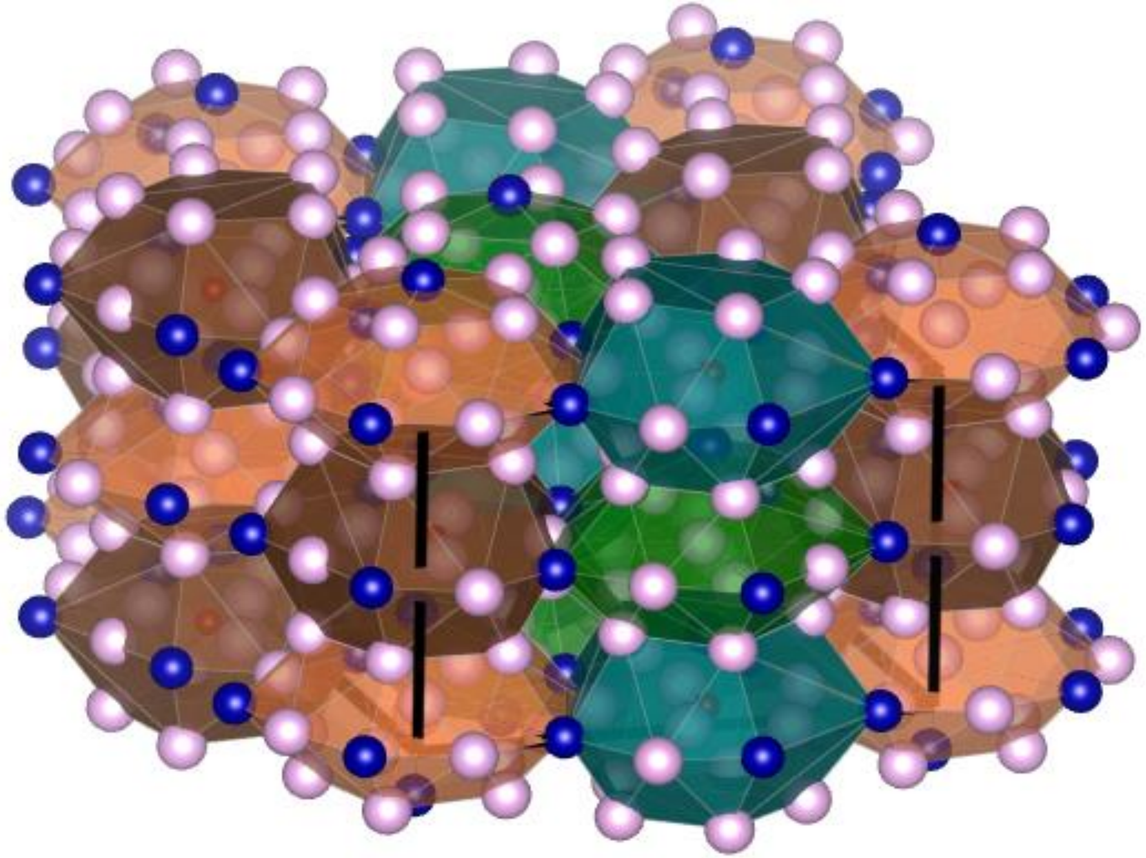
Instruments – varying k_i & k_f – TAS, TOF



Spectroscopy – time/frequency domain

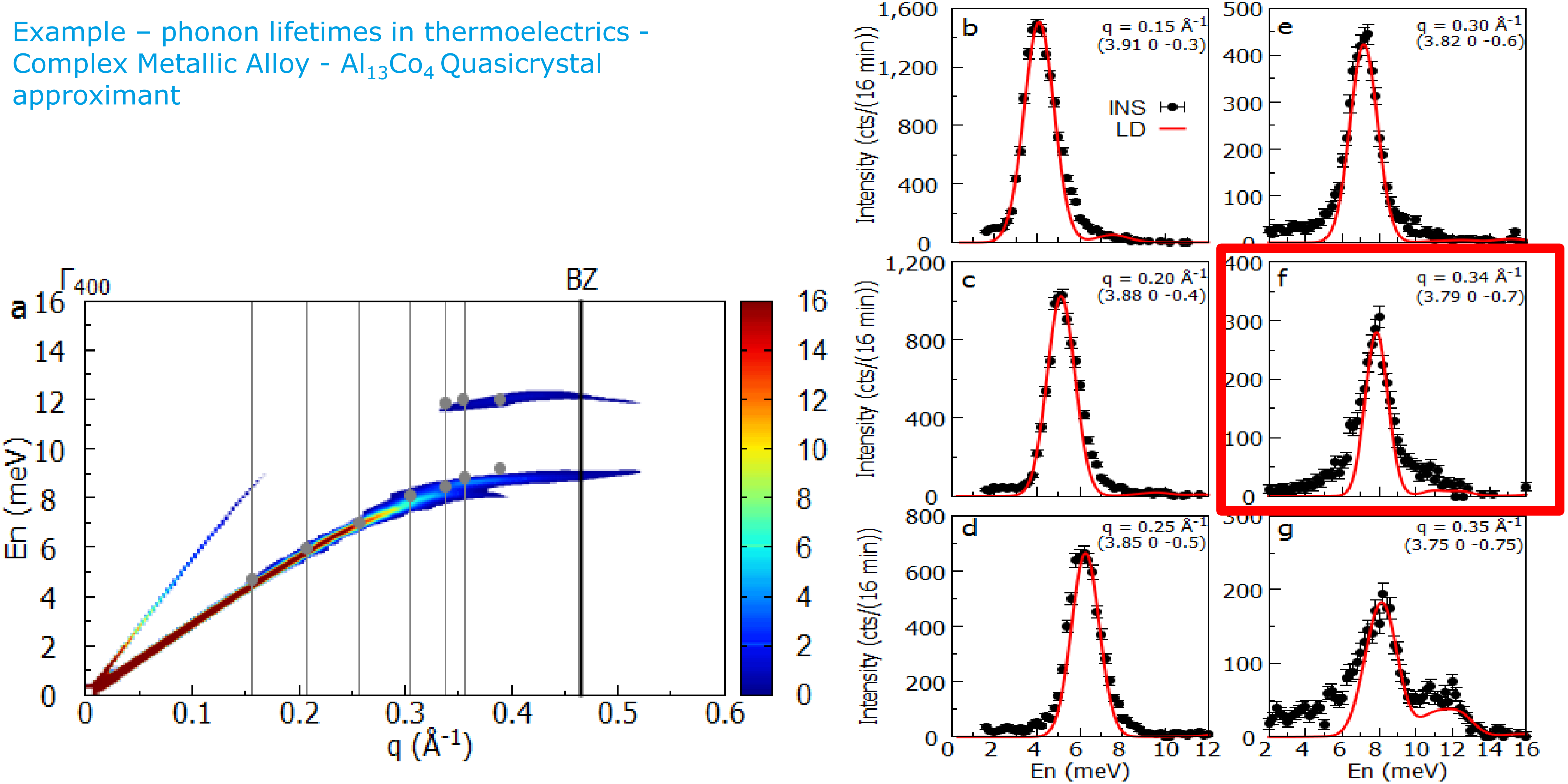
Example – phonon lifetimes in thermoelectrics - Complex Metallic Alloy - $Al_{13}Co_4$ Quasicrystal approximant





Spectroscopy – time/frequency domain

Example – phonon lifetimes in thermoelectrics - Complex Metallic Alloy - $Al_{13}Co_4$ Quasicrystal approximant



NEUTRONS FOR SOCIETY

SPECTROSCOPY – TIME/FREQUENCY DOMAIN

Simplified expressions for the scattering function – incoherent scattering

In previous scattering expressions

$R = R_0 + \delta R(t)$

For normal modes: $\delta R(t)$ → displacement vectors **e** & frequencies ω

Incoherent scattering - Internal (molecular) modes:

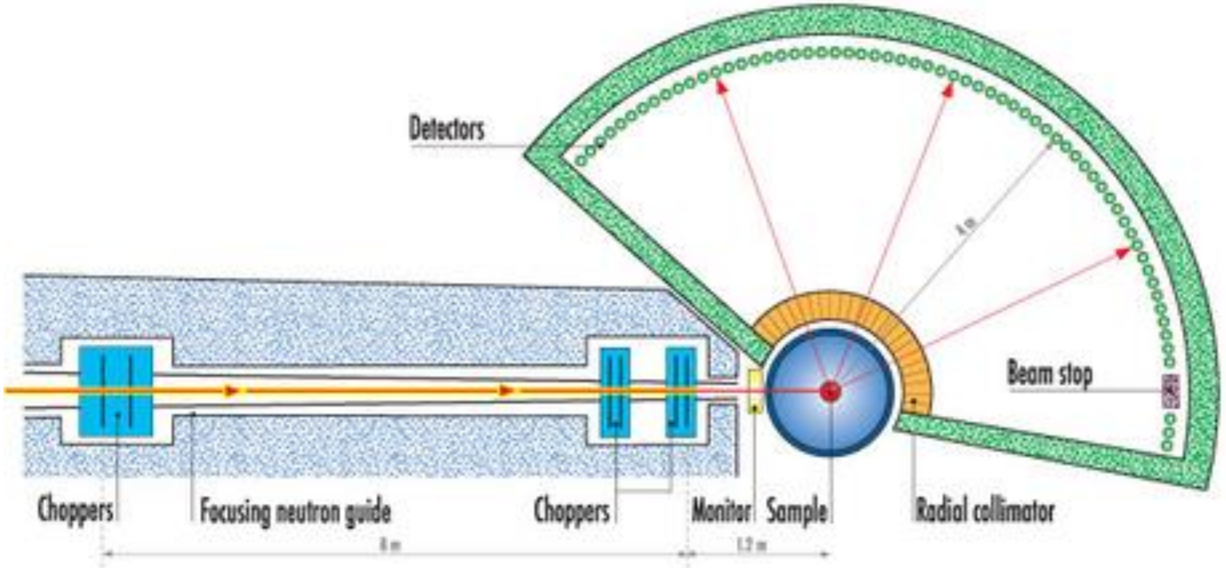
- No long range correlations due to weak coupling
- No dispersion

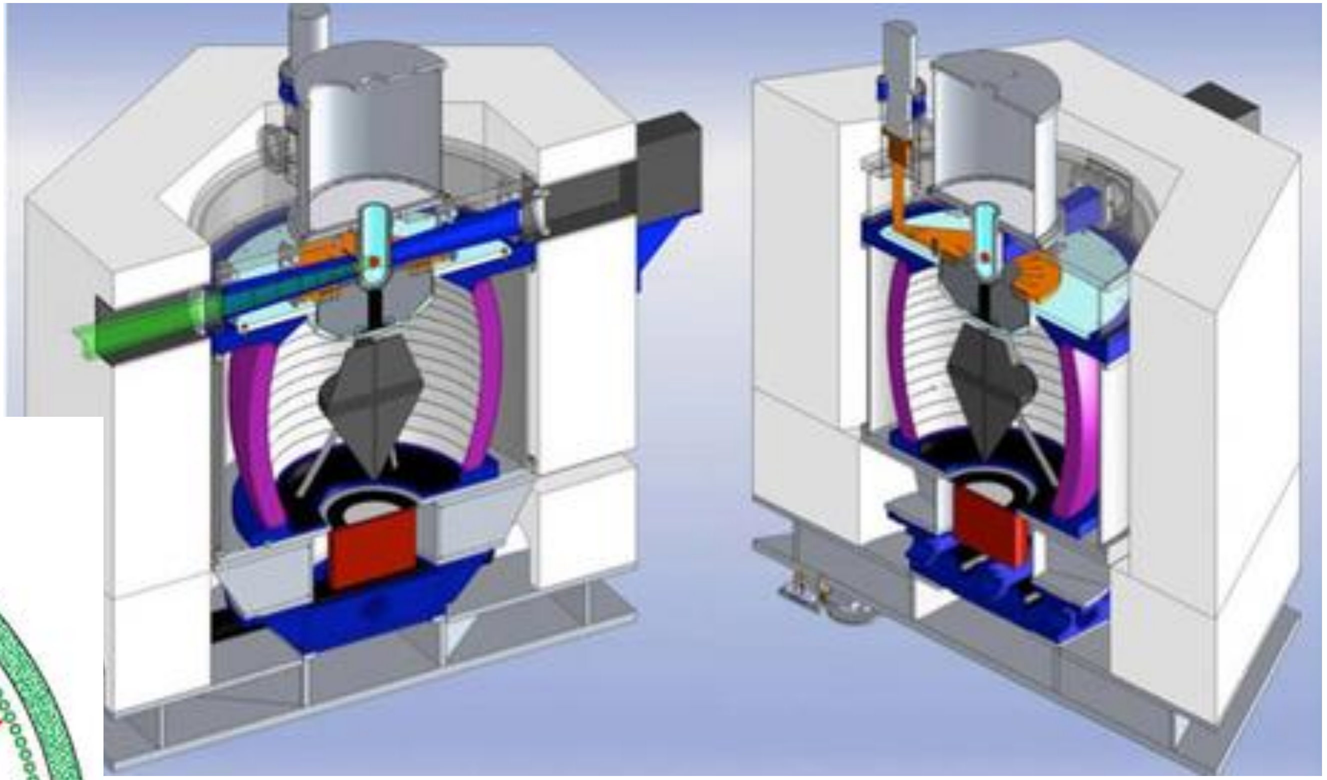
$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{incoh\pm 1} = \frac{k_f}{k_i}\sum_s \delta(\omega \mp \omega_s)\frac{\langle n_s + 1/2 \pm 1/2\rangle}{2\omega_s}\sum_r \frac{(\sigma_{incoh})_r}{4\pi}\frac{1}{M_r}\left|\vec{Q}\cdot \vec{e}_r\right|^2 \exp(-2W_r)$$

NEUTRONS FOR SOCIETY

Spectroscopy – time/frequency domain

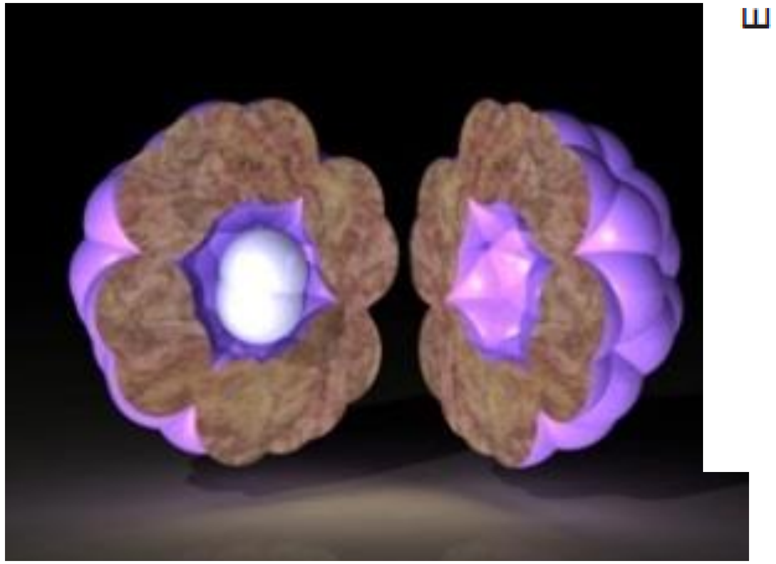
Instruments – TOF, Lagrange

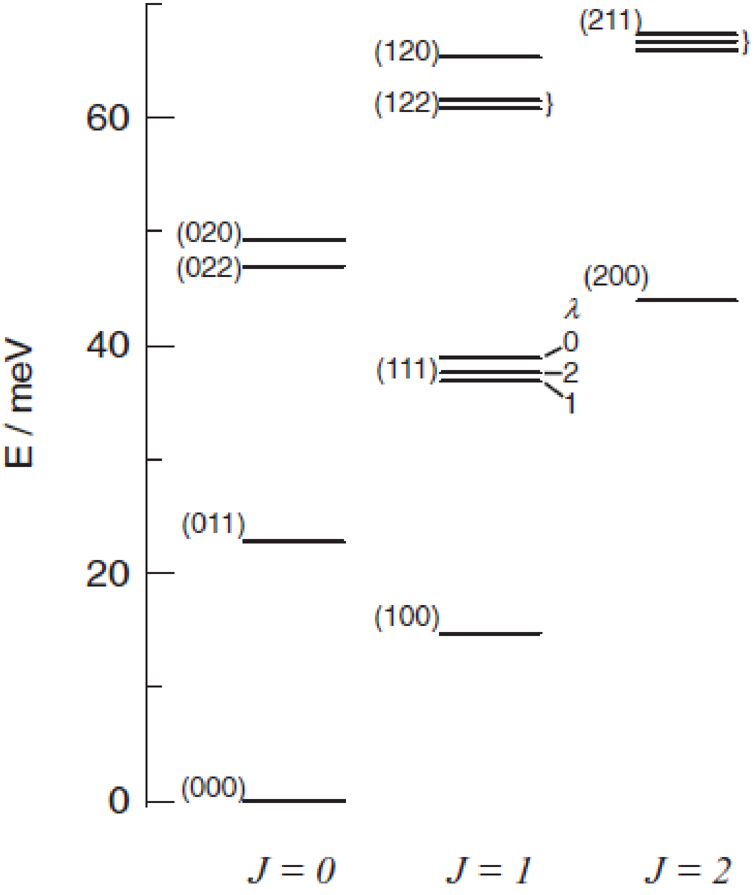


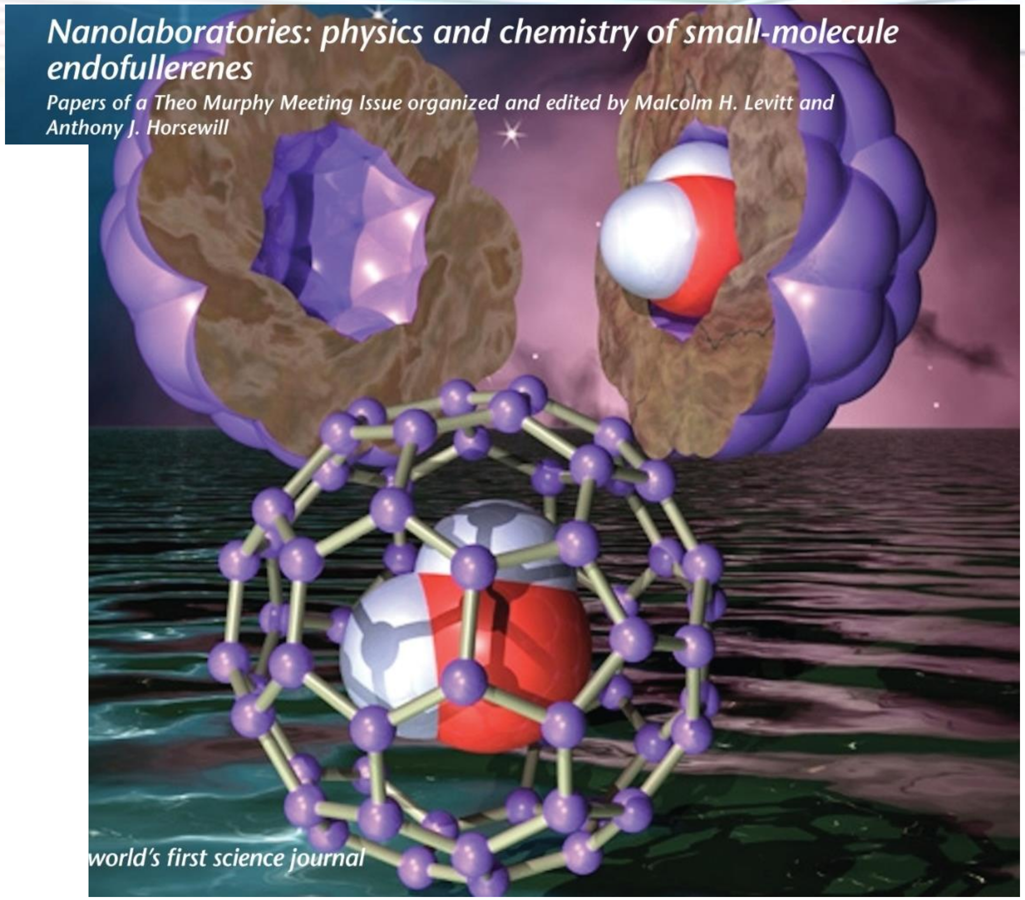


Spectroscopy – time/frequency domain

Example – endofullerenes

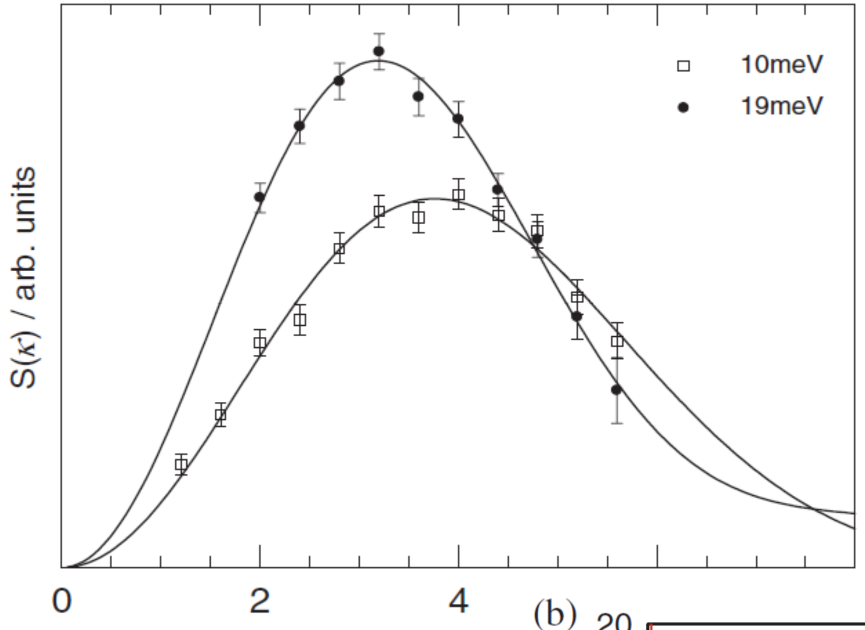


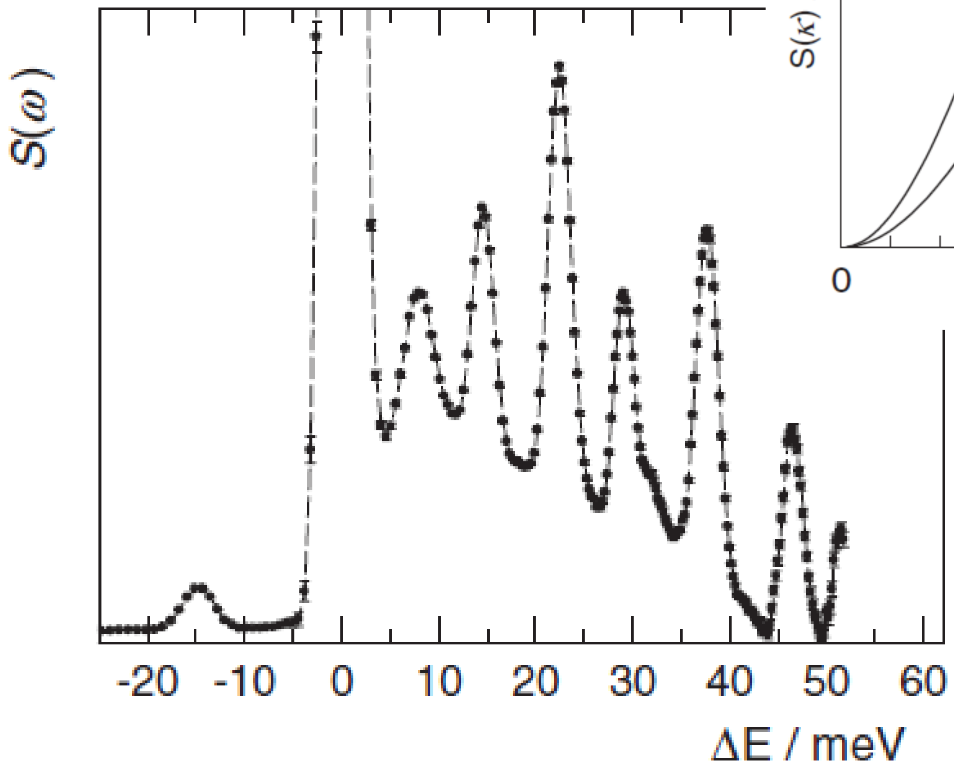


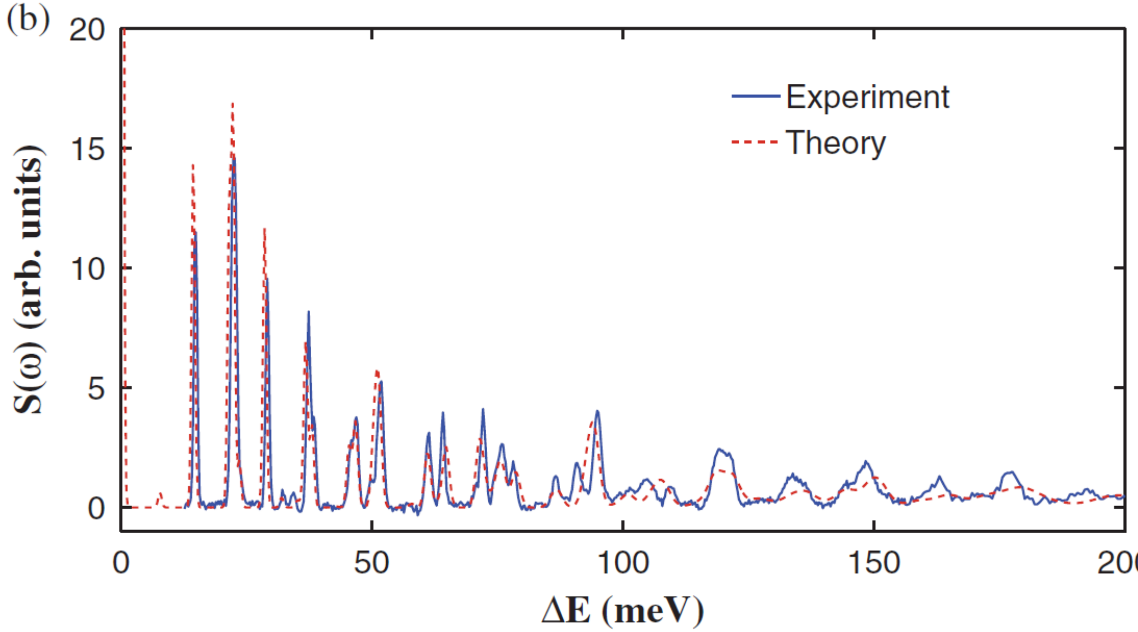


SPECTROSCOPY – TIME/FREQUENCY DOMAIN

Example – endofullerenes

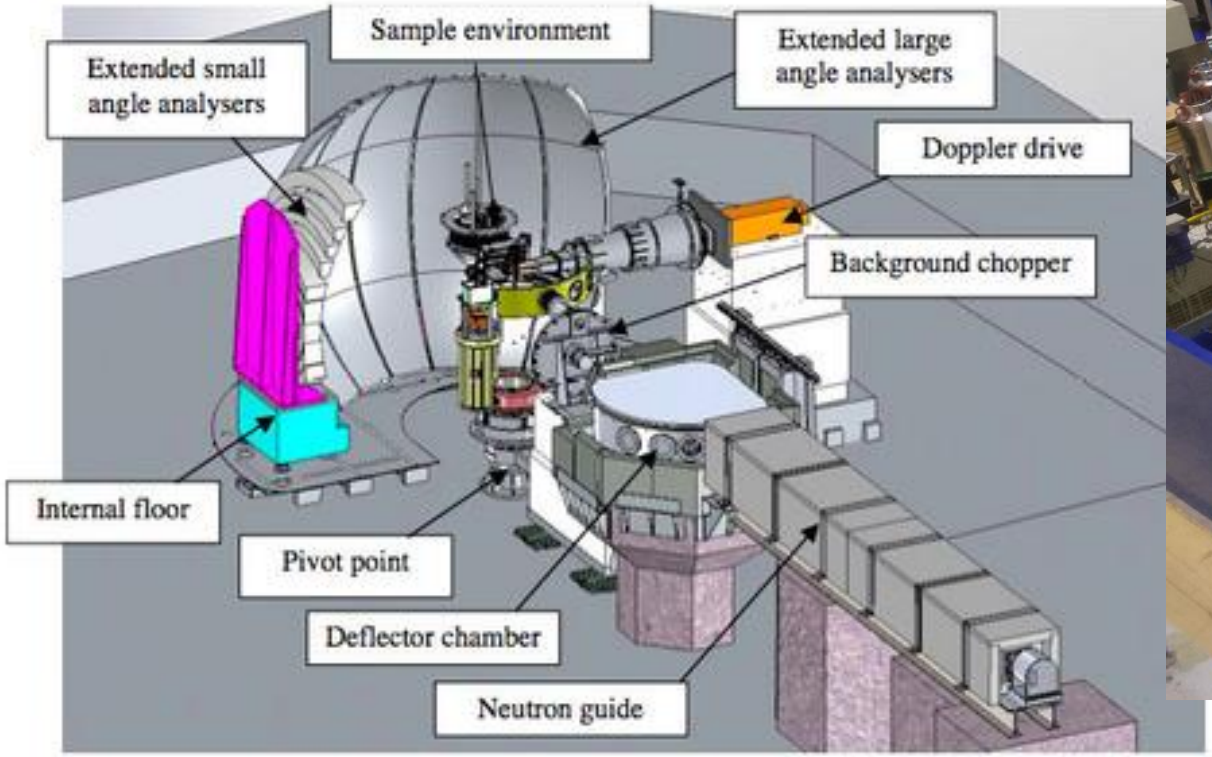


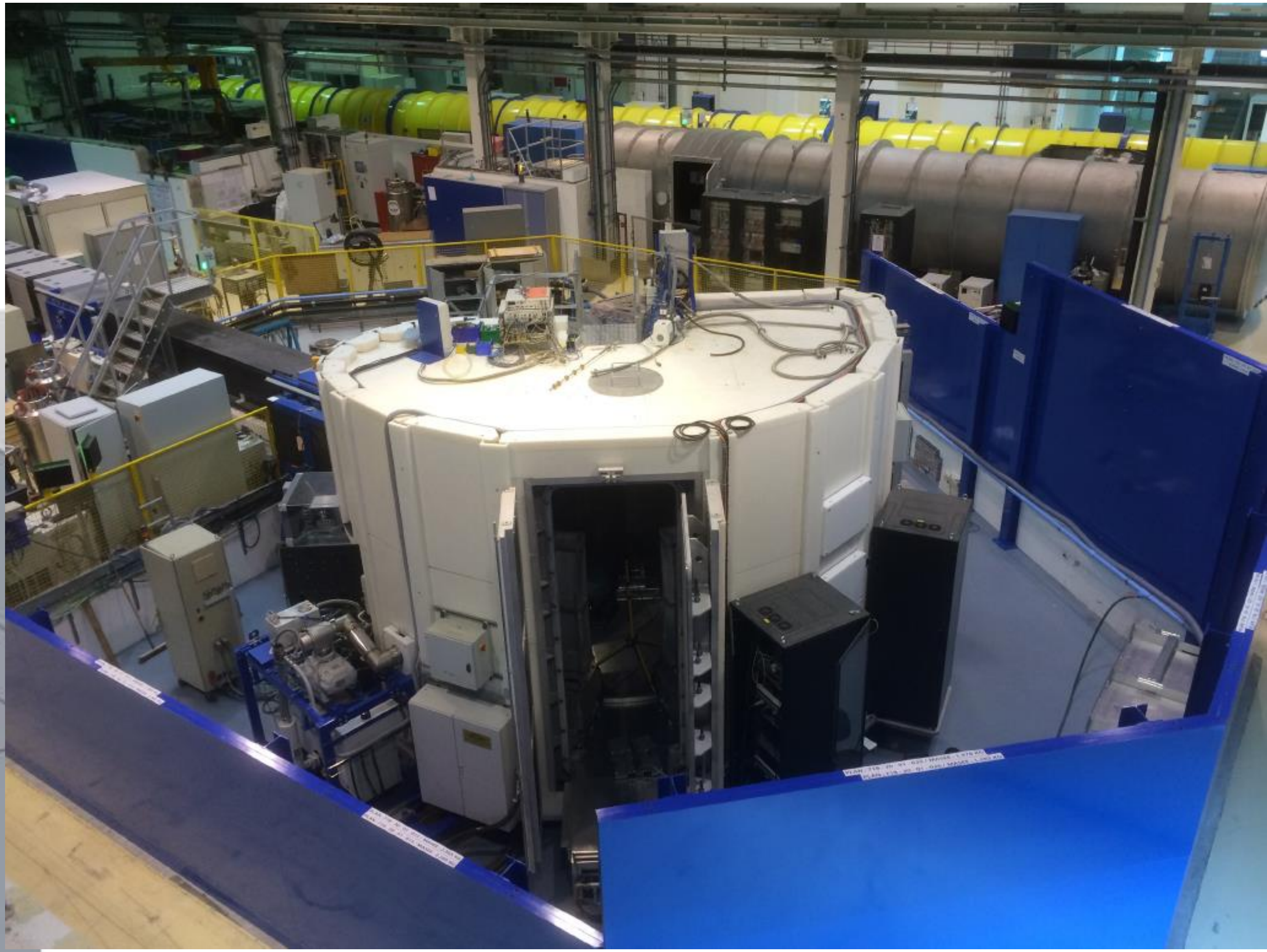




SPECTROSCOPY – TIME/FREQUENCY DOMAIN

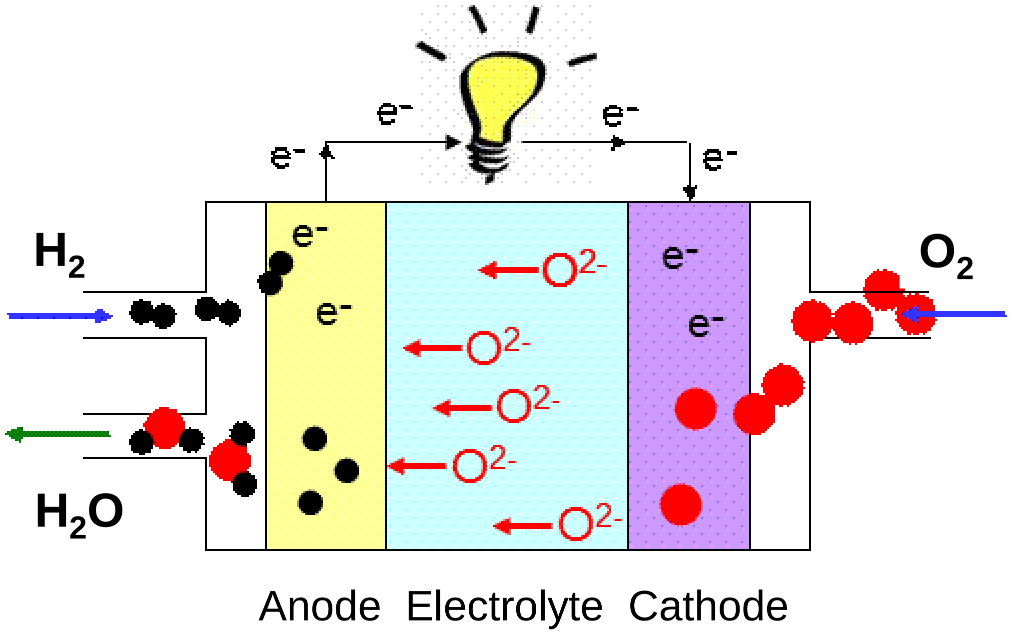
Instruments – Back-Scattering

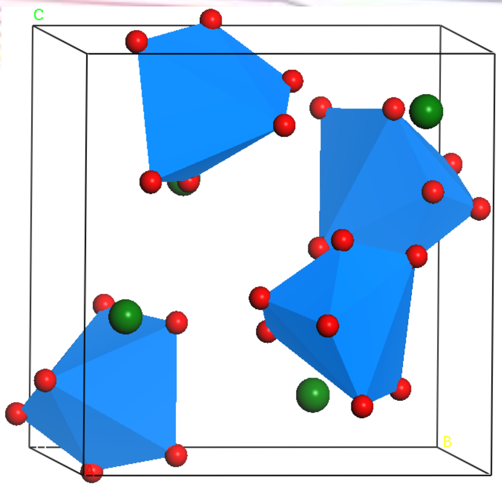


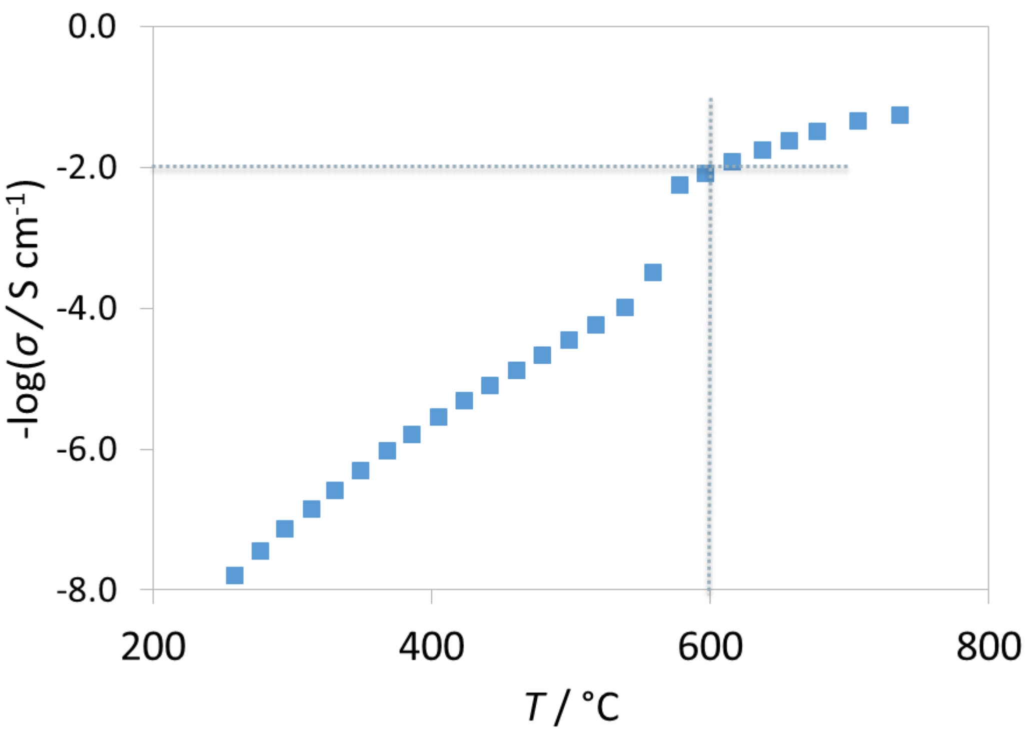


SPECTROSCOPY – TIME/FREQUENCY DOMAIN

Example – oxide ion conductors

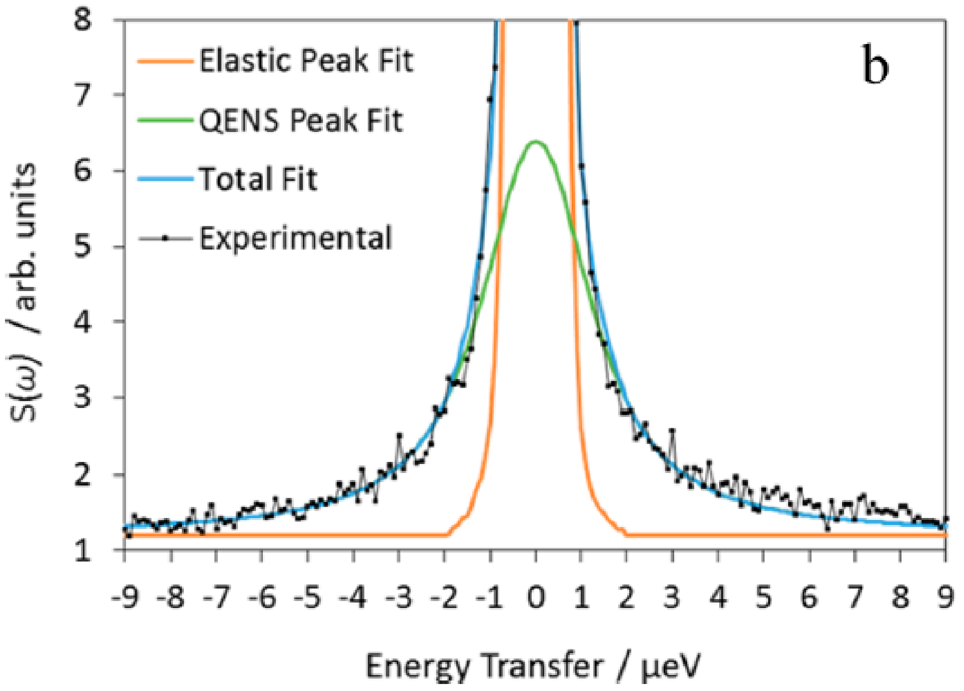


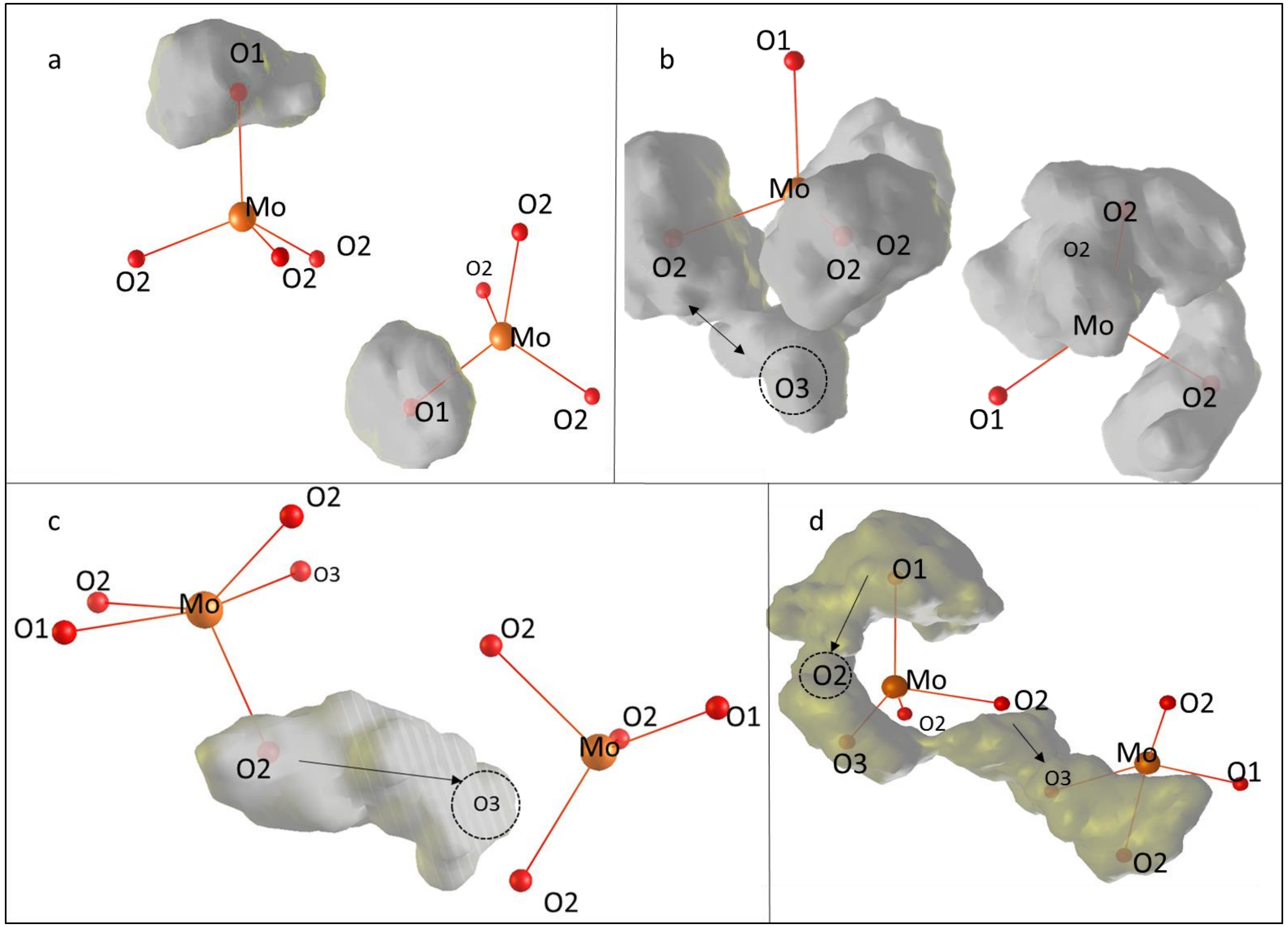




Spectroscopy – time/frequency domain

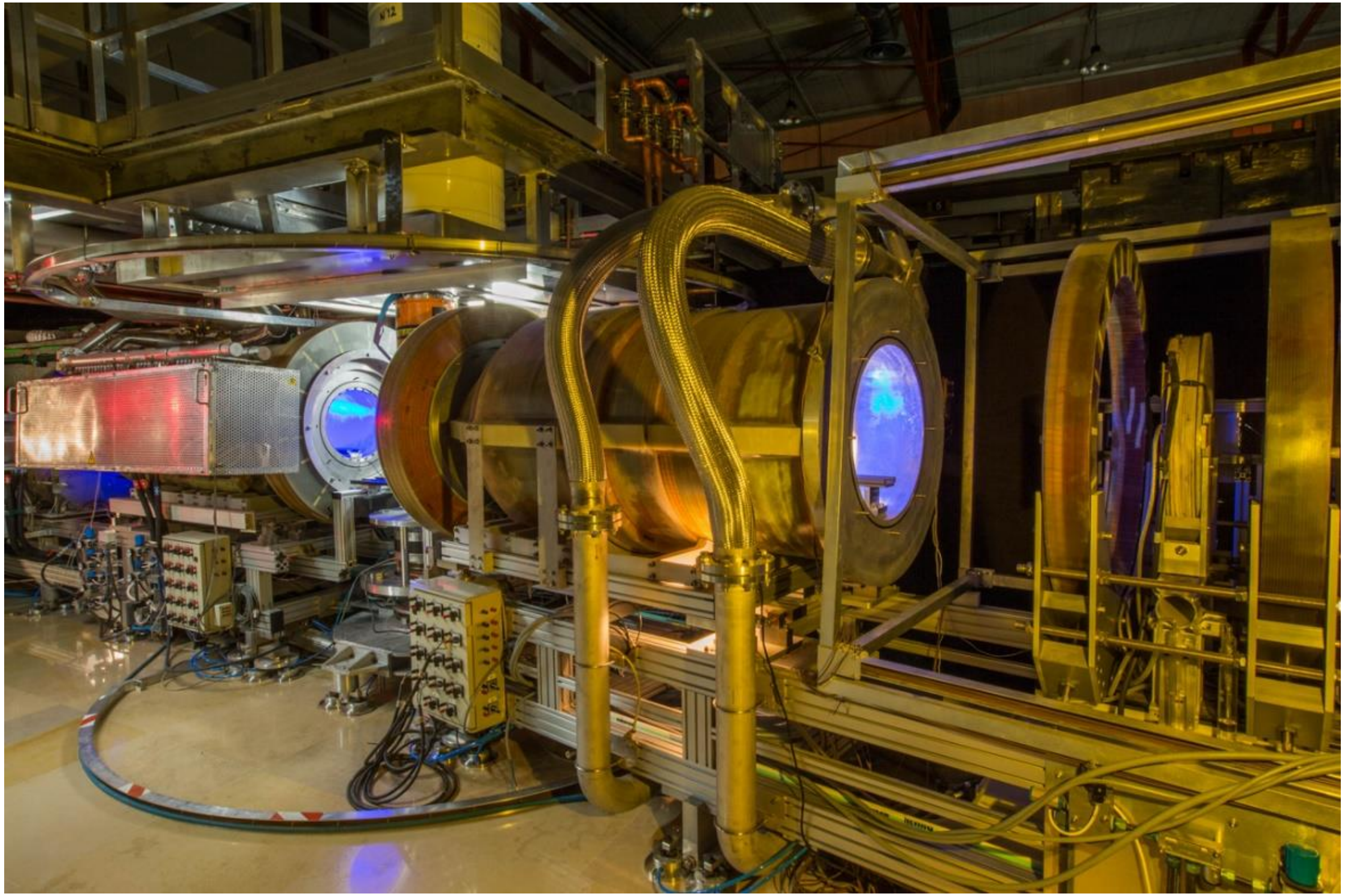
Example – oxide ion conductors





Generic instrument

Energy selection - precession of neutron magnetic moments in a magnetic field (depends on t.o.f. in B)



Magnetism

Structure and dynamics – double differential cross-section

As for interactions with nuclei but

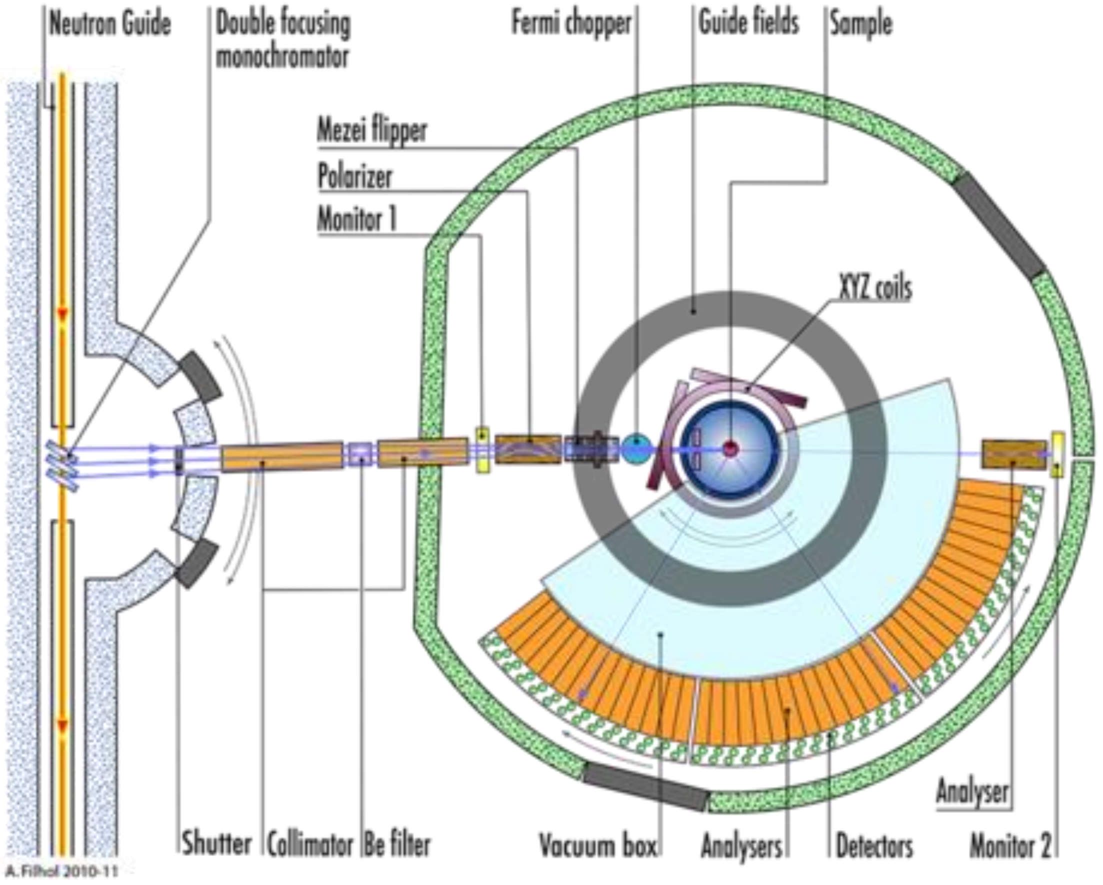
- Neutron spin probes local magnetic fields due to electron spin and orbital contribution
- Atomic form factor – scattering from an atom is angular dependent due to electron cloud
- No incoherence effects
- N.B. σ and *V* in these equations

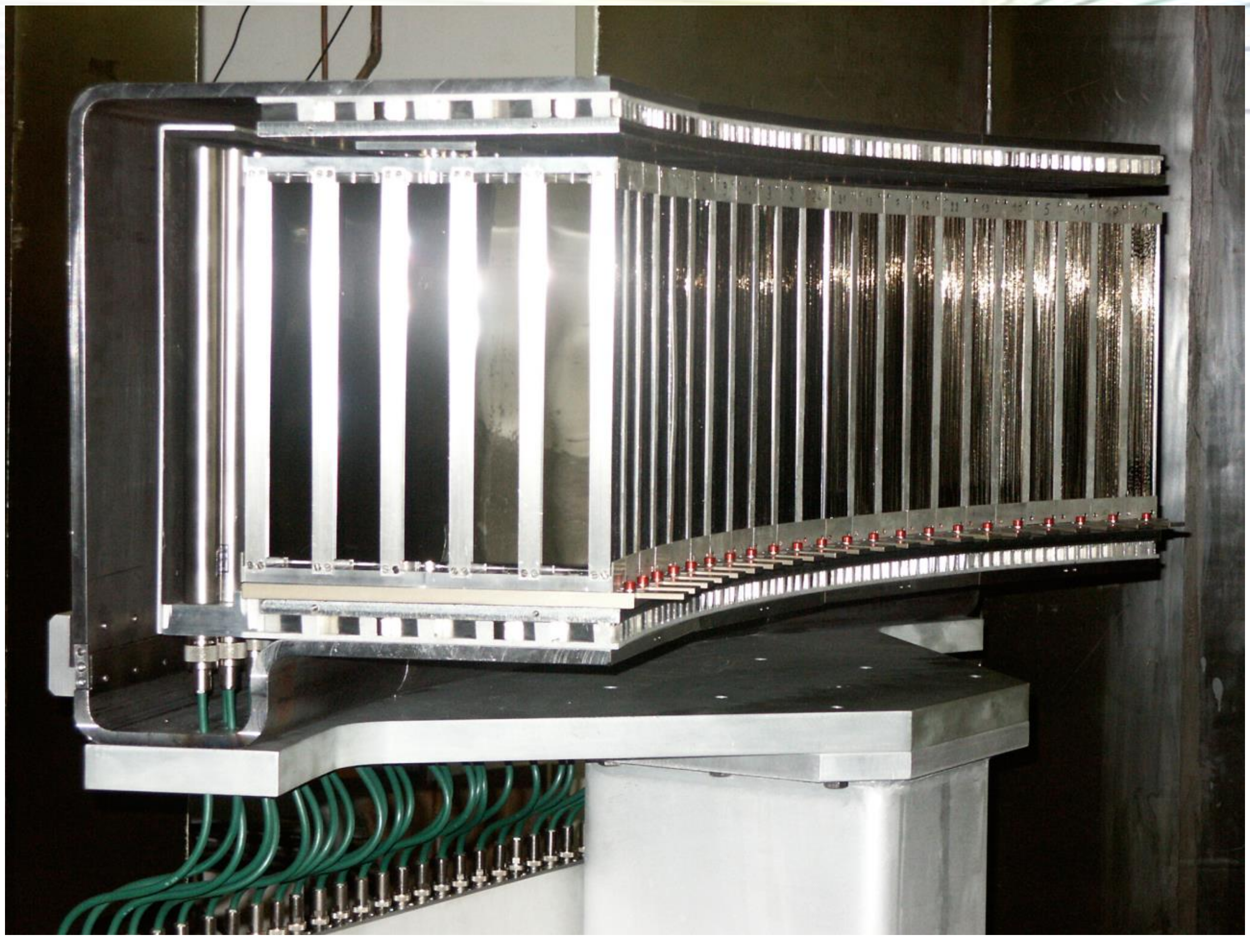
$$V_m = -\mu_n \cdot B = -\frac{\mu_0}{4\pi}\gamma\mu_N 2\mu_B \left\{ curl\left(\frac{s \times R}{R^2}\right) + \frac{1}{\hbar}\frac{p \times R}{R^2} \right\}$$

$$\left(\frac{d^2\sigma}{dE_f\, d\Omega}\right)_{\sigma_i\lambda_i \to \sigma_f\lambda_f} = \frac{k_f}{k_i}\left(\frac{m_n}{2\pi\hbar^2}\right)^2 \left|\left\langle k_f\sigma_f\lambda_f \middle| V_m \middle| k_i\sigma_i\lambda_i \right\rangle\right|^2 \delta\left(E_i - E_f + E_{\lambda_i} - E_{\lambda_f}\right)$$

Magnetism

Polarised neutrons – separate nuclear and magnetic signals & more precise information on magnetic structures





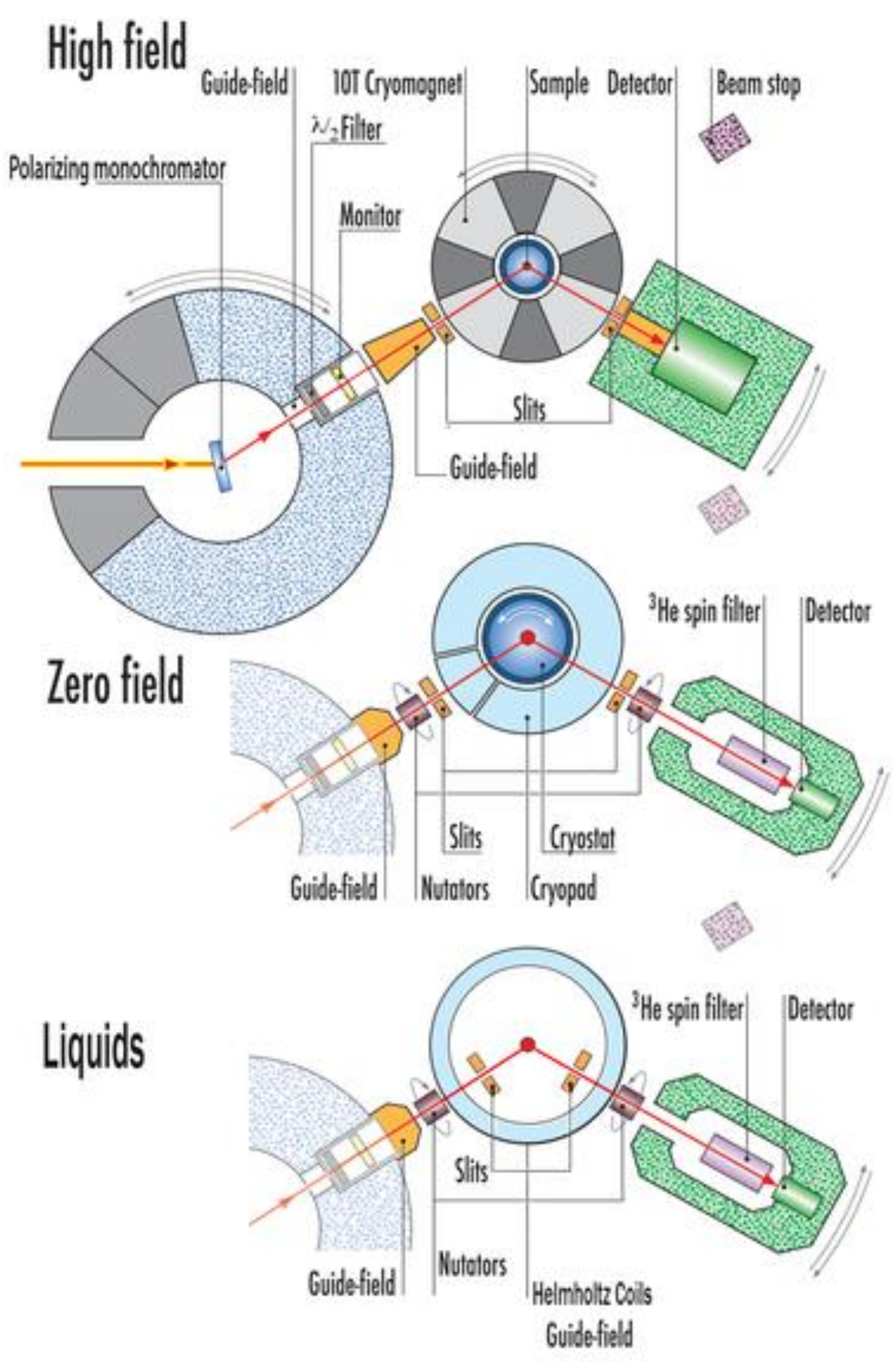
- Typically measure 4 polarised scattering channels: u→u, d→d, u→d, d→u

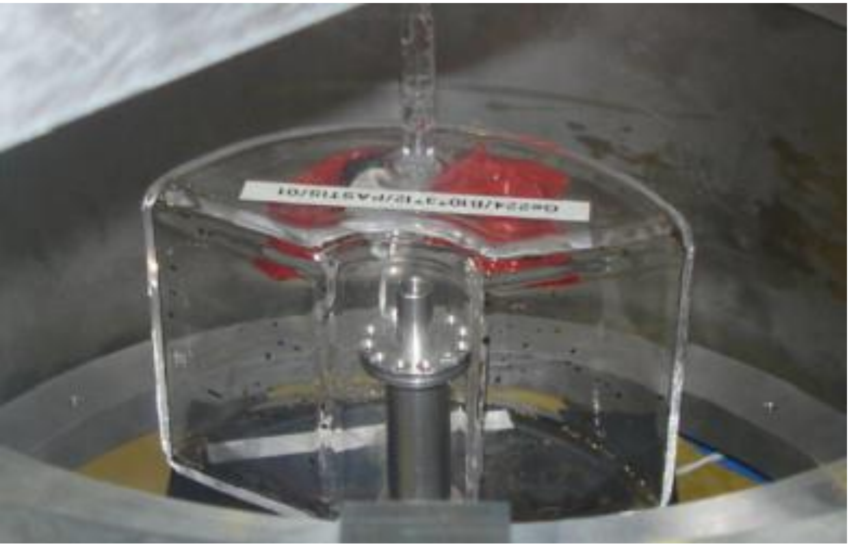
NEUTRONS FOR SOCIETY

Magnetism

Polarised neutrons – separate nuclear and magnetic signals
& more precise information on magnetic structures

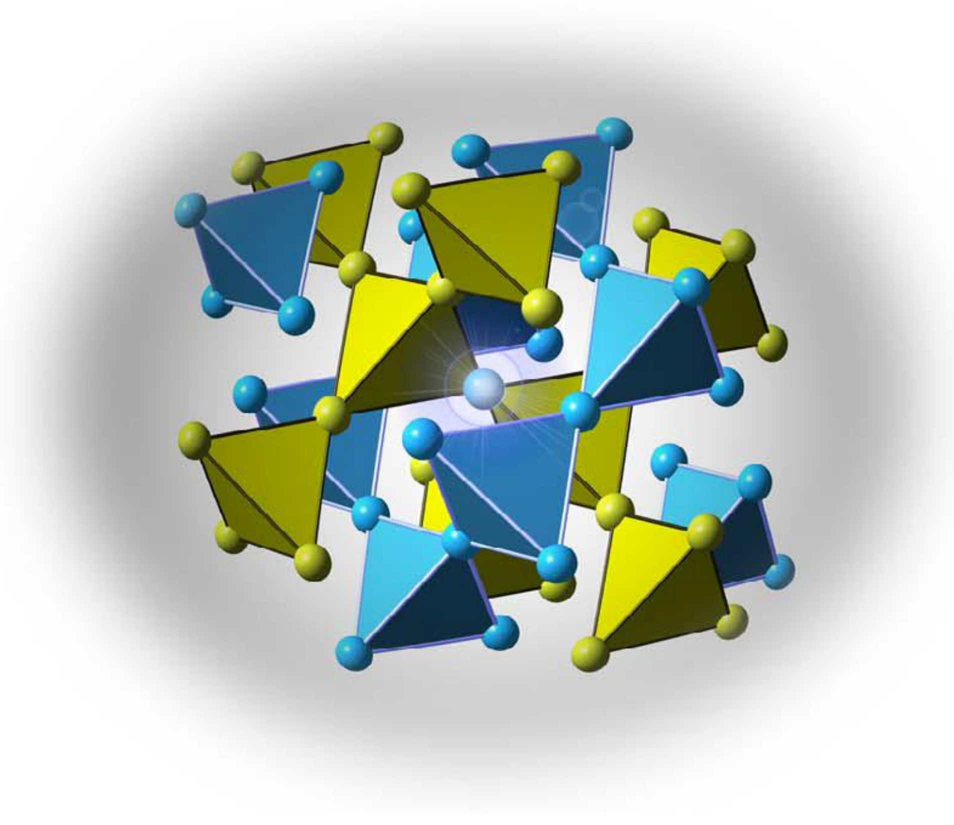
- Polarised (optically pumped) 3He selectively absorbs one neutron spin state – more versatile polariser
- Cryopad allows full control of incident and scattered neutron polarisation – spherical polarimetry

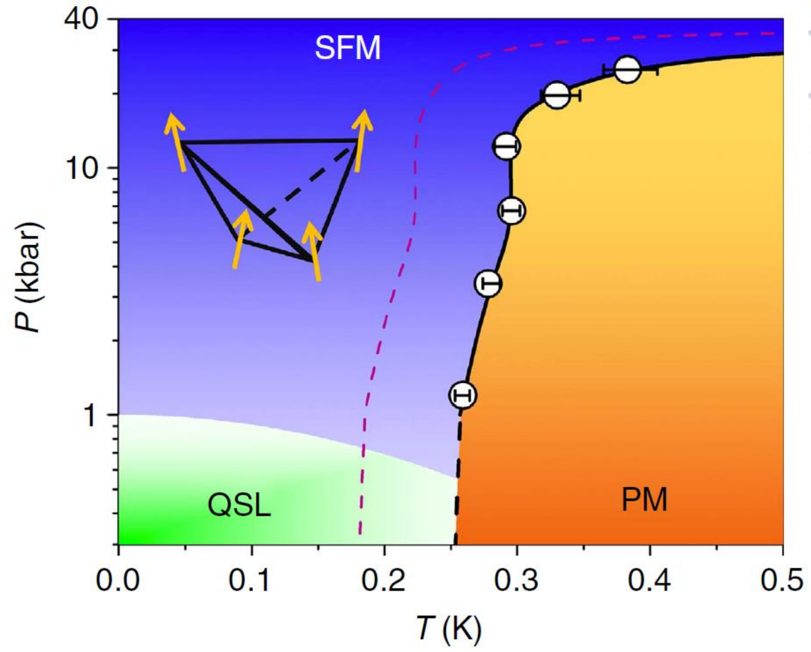


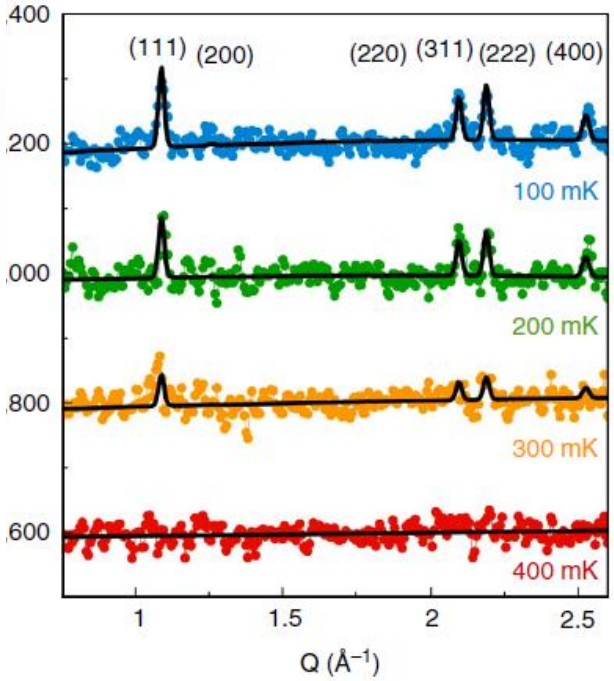


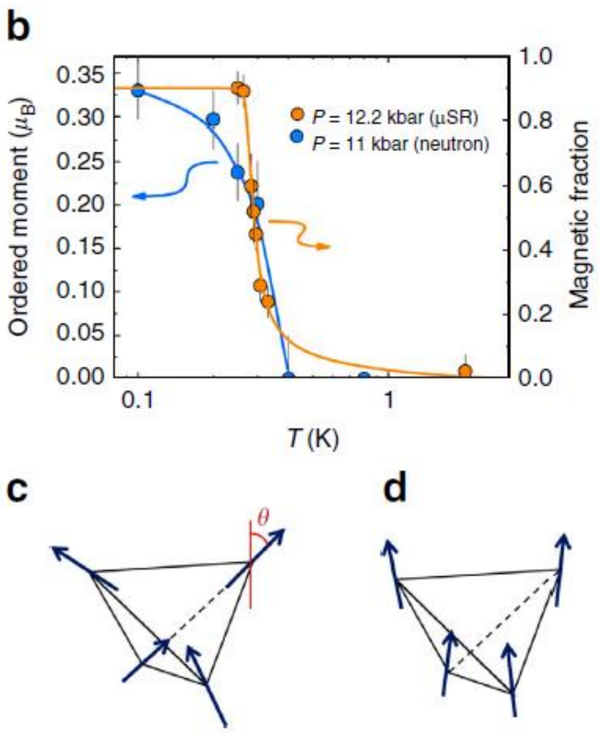
Magnetism

Example – Ground state selection under pressure in the quantum pyrochlore magnet $Yb_2Ti_2O_7$





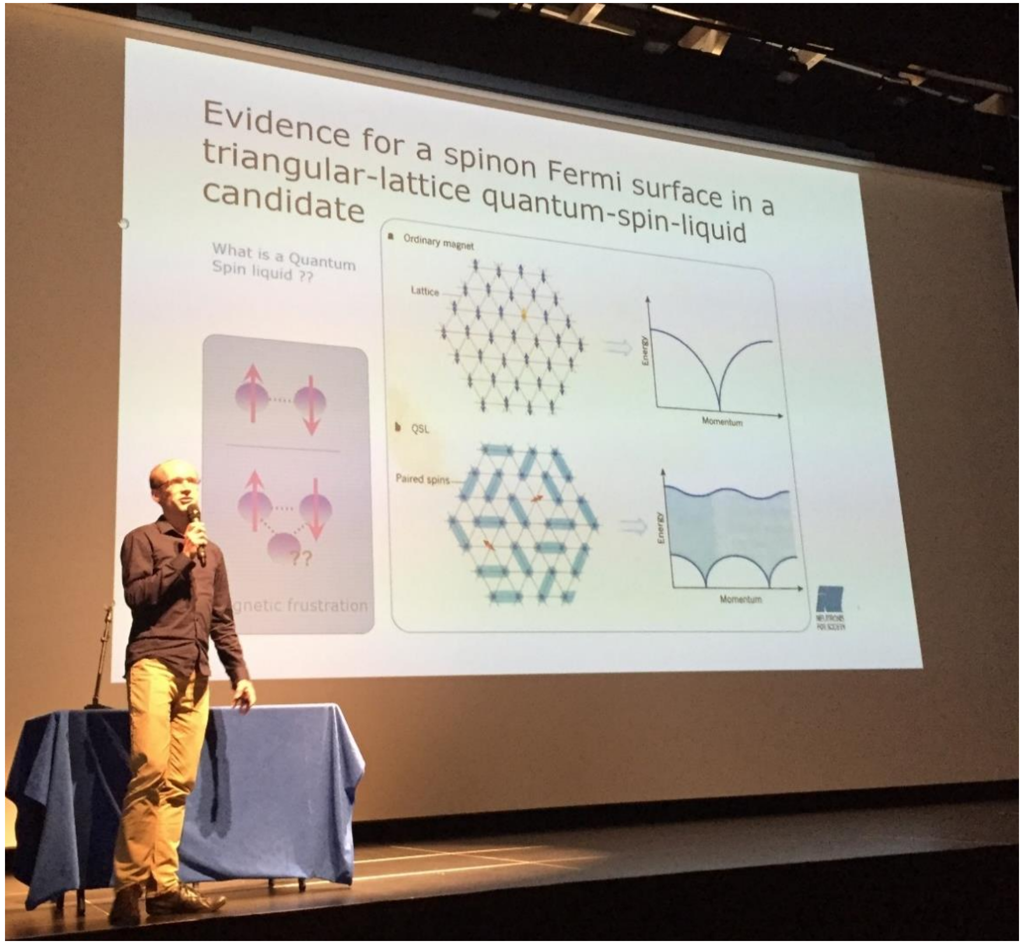


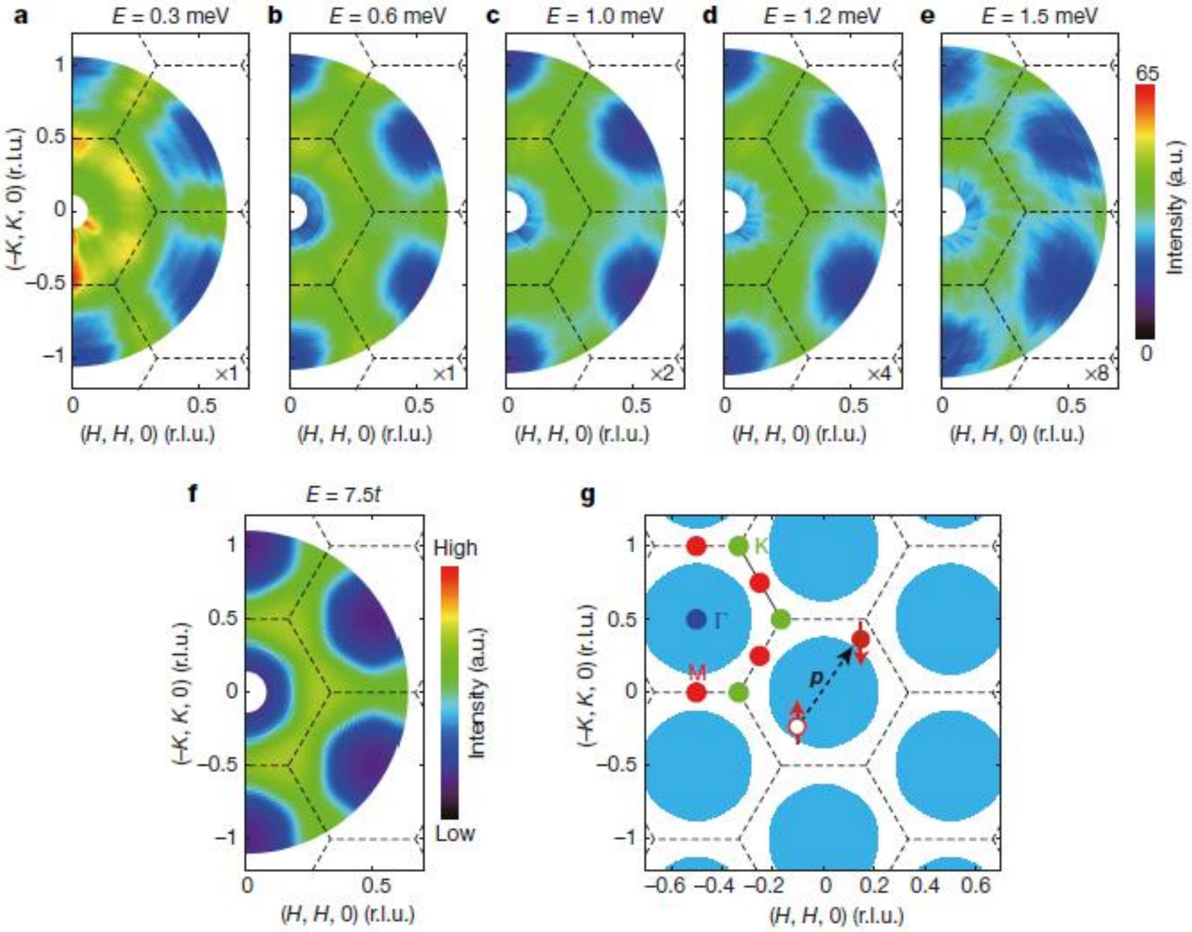


NEUTRONS FOR SOCIETY

Magnetism

Example – How do electrons/spins organise in a triangular lattice? Spins pair into quantum-mechanical bonds and fluctuate…





NEUTRONS FOR SOCIETY

Summary – key messages

The neutron

- Is Highly penetrating
- Interacts with nuclei – favourable for light atoms (H, Li, O,…)
- Incoherent scattering is ideal for proton dynamics
- Isotopes provide selectivity – contrast matching
- Interacts with unpaired electrons – magnetism
- Probes 15 orders of magnitude in length & 10 in time

Neutron sources have relatively low intensity and are only available in large scale facilities – ILL, ISIS, PSI, FRM2 in Europe, SNS & NIST in US

Additional reading

Search the web! Plus…

- *Introduction to the Theory of Thermal Neutron Scattering*
- G.L. Squires Reprint edition (1997) Dover publications ISBN 04869447

- *Experimental Neutron Scattering*
- B.T.M. Willis & C.J. Carlile (2009) Oxford University Press ISBN 978-0-19-851970-6

- *Neutron Applications in Earth, Energy and Environmental Sciences*
- L. Liang, R. Rinaldi & H. Schober Eds Springer (2009) ISBN 978-0-387-09416-8

- *Methods in Molecular Biophysiscs*
- I.N. Serdyuk, N. R. Zaccai & J. Zaccai Cambridge University Press (2007) ISBN 978-0-521-81524-6

- *Thermal Neutron Scattering*
- P.A. Egelstaff ed. Academic Press (1965)

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