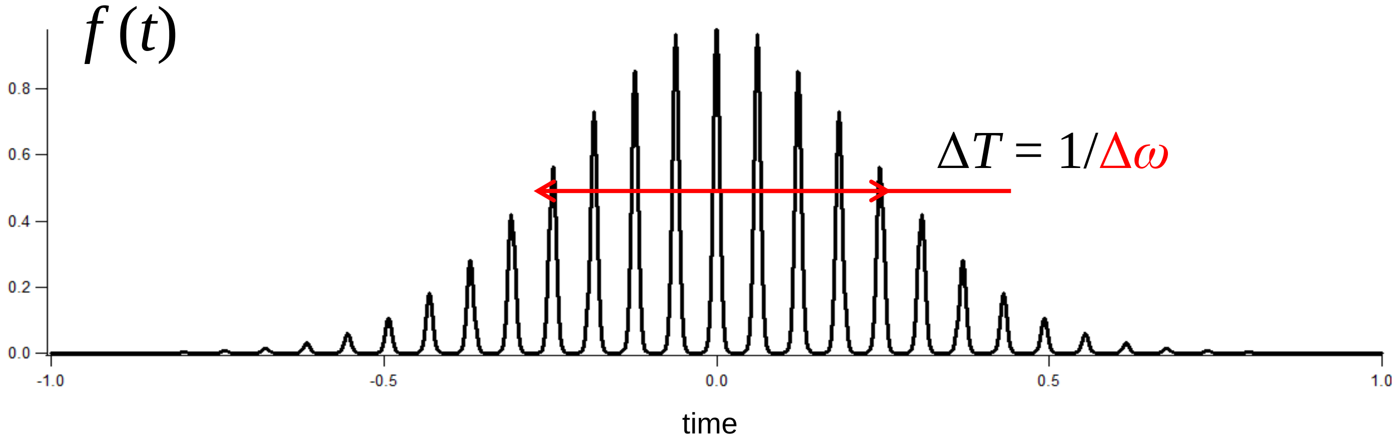
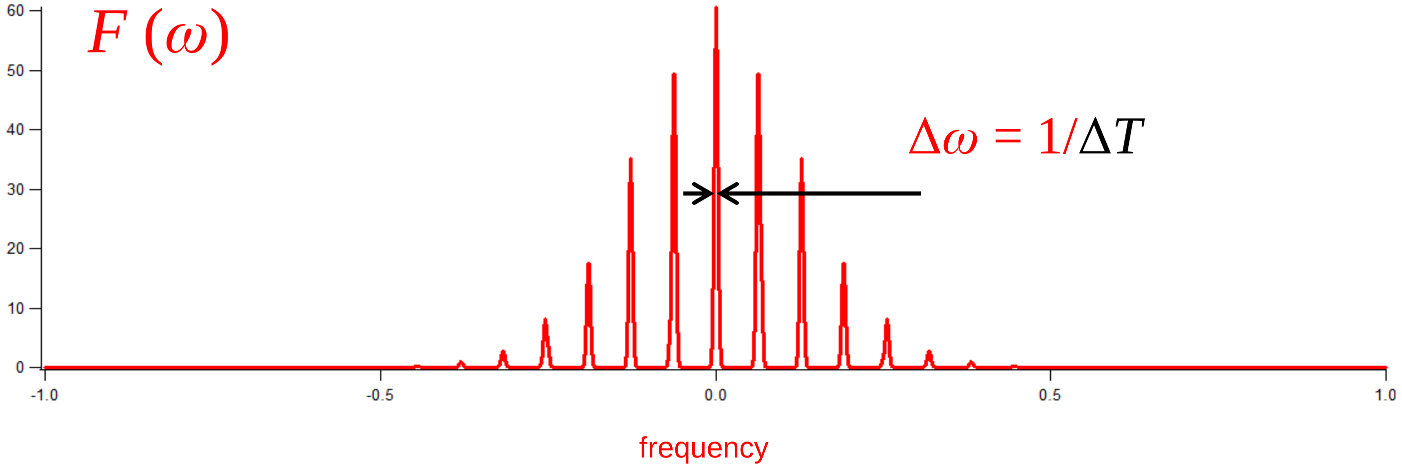
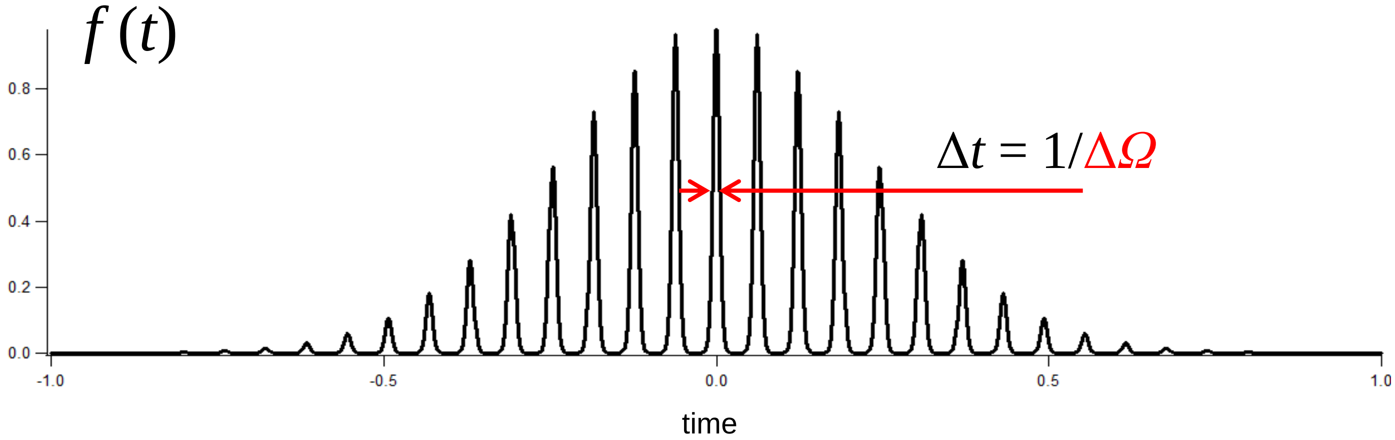
FFT



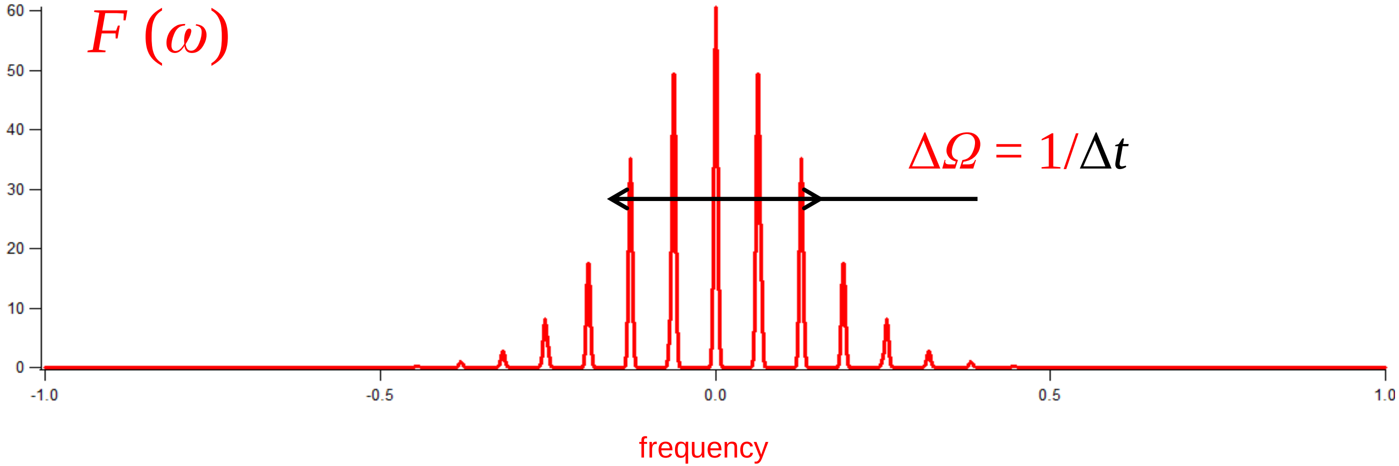
$f\,(t)$
$\Delta T = 1/\Delta\omega$
0.8
0.6
0.4
0.2
0.0
-1.0
-0.5
0.0
0.5
1.0
time



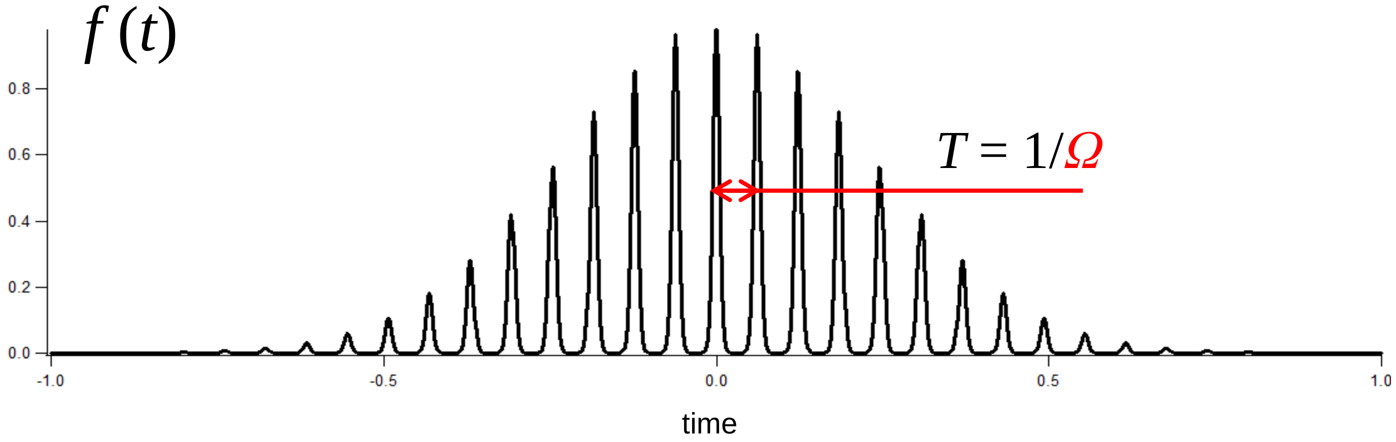
$F\,(\omega)$
$\Delta\omega = 1/\Delta T$
60
50
40
30
20
10
0
-1.0
-0.5
0.0
0.5
1.0
frequency

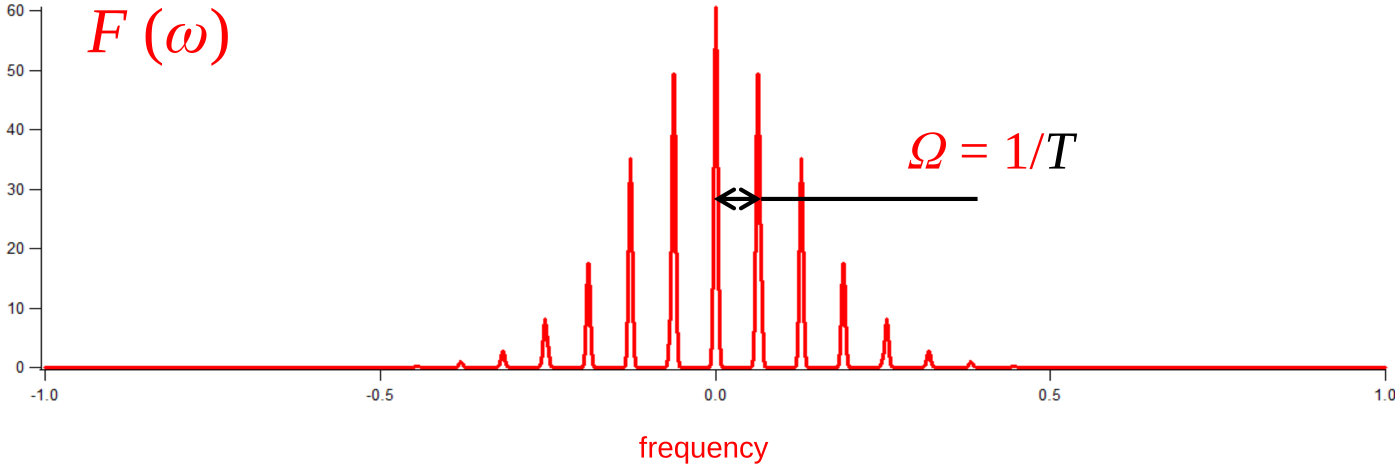


$\Delta t = 1/\Delta\Omega$

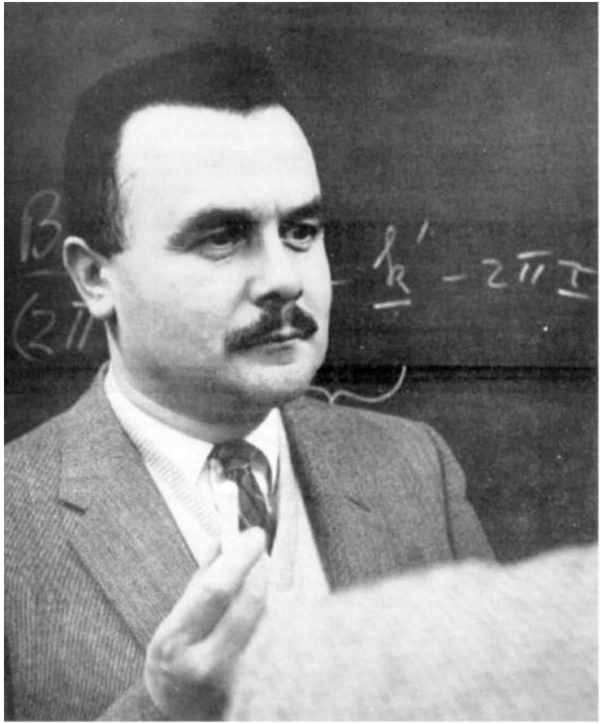


$\Delta\Omega = 1/\Delta t$


$f(t)$
$T = 1/\Omega$
0.8
0.6
0.4
0.2
0.0
-1.0
-0.5
0.0
0.5
1.0
time


$F(\omega)$
$\Omega = 1/T$
60
50
40
30
20
10
0
-1.0
-0.5
0.0
0.5
1.0
frequency

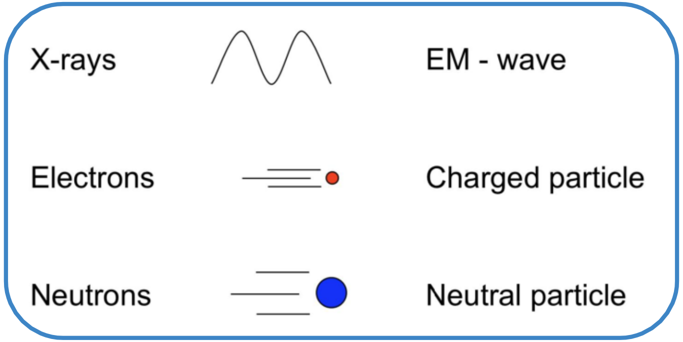
Inelastic neutron scattering



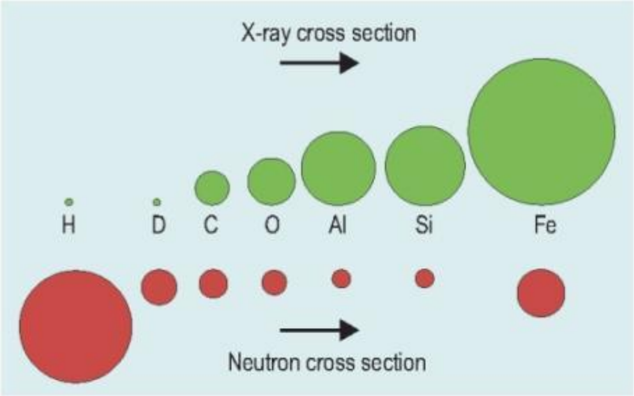
“If the neutron did not exist, it would need to be invented.”

Bertram Brockhouse
1994 Nobel Laureate in Physics

Peter Gehring (NIST)
https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf



X-rays	EM - wave
Electrons	Charged particle
Neutrons	Neutral particle



Advantages

Wavelengths easily varied to match atomic spacings

Zero charge → not strongly attenuated by furnaces, etc.

Magnetic dipole moment → can study magnetic structures

Nuclear interaction → can see low-Z elements easily like H → good for the study of biomolecules and polymers.

Nuclear interaction is simple → scattering is easy to model

Low energies → Non-destructive probe

Disadvantages

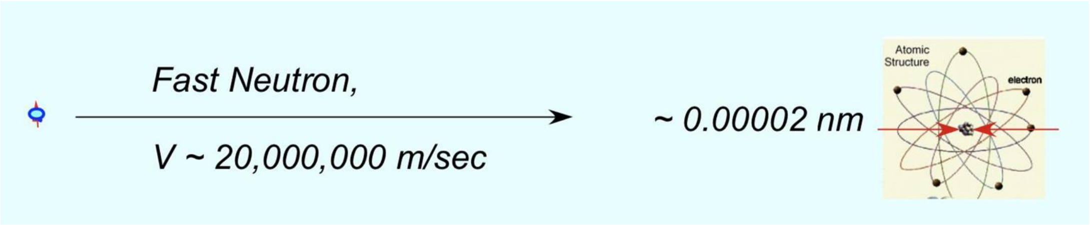
Neutrons are expensive to produce → access is not as easy

Interact weakly with matter → often require large samples

Available fluxes are low compared to those for x-rays

Let’s consider neutrons …

Peter Gehring (NIST)
https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf

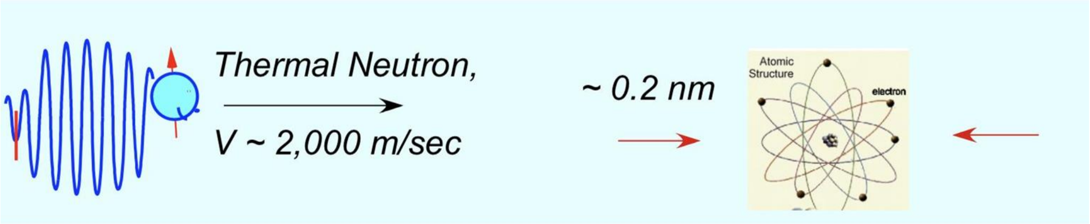


$m_n = 1.675 \times 10^{-27}$ kg

$Q = 0$

$S = ½\ h$

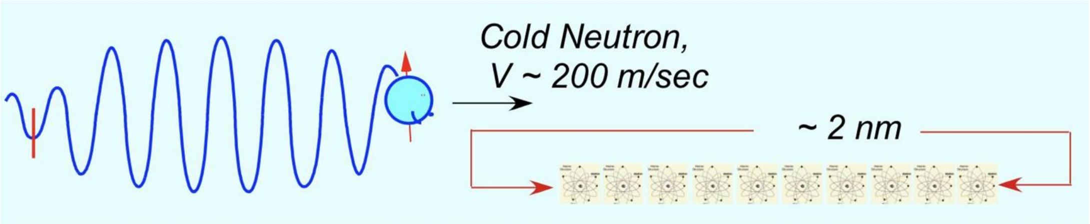
$\mu_n = -1.913\ \mu_N$



$\lambda = 1$ Å

$v = 4000$ m/s

$E = 82$ meV



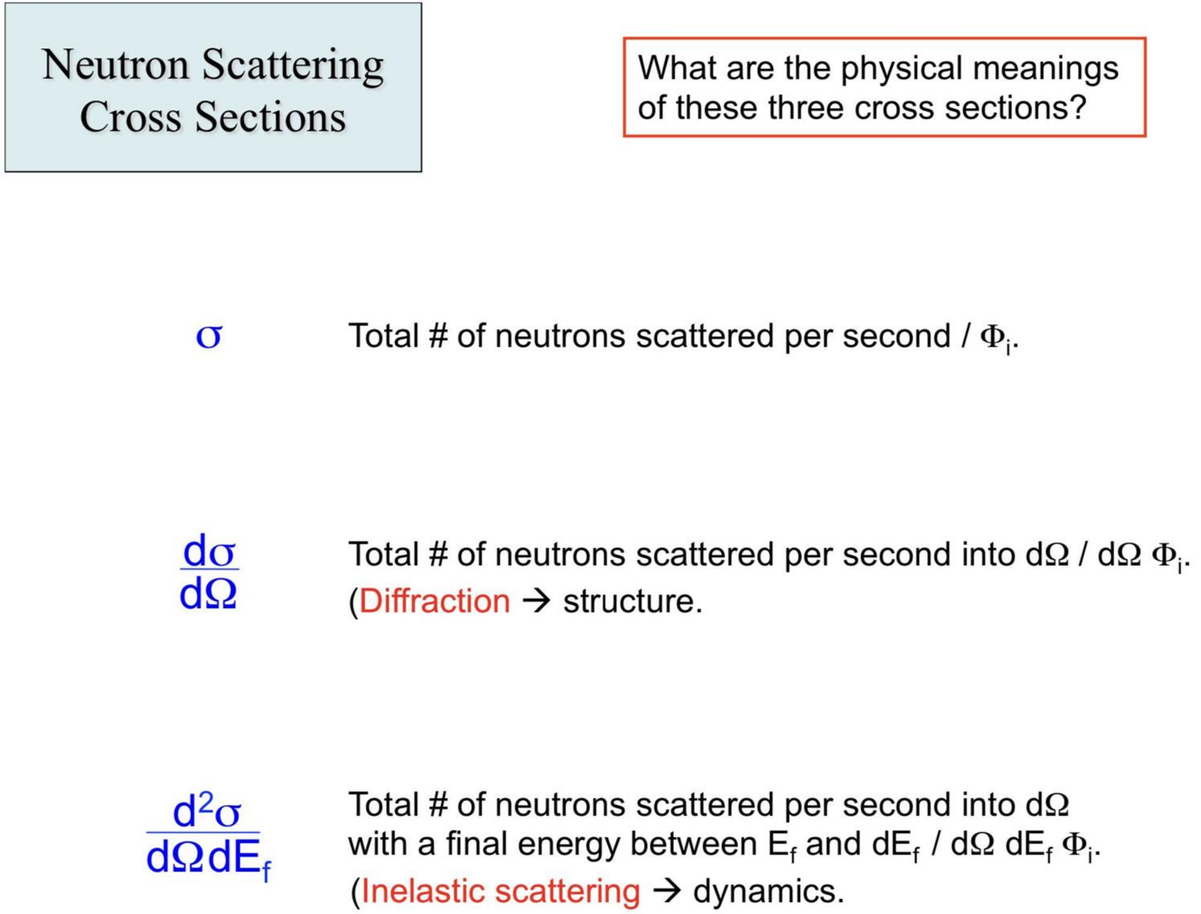
$\lambda = 9$ Å

$v = 440$ m/s

$E = 1$ meV

Peter Gehring (NIST)

https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf



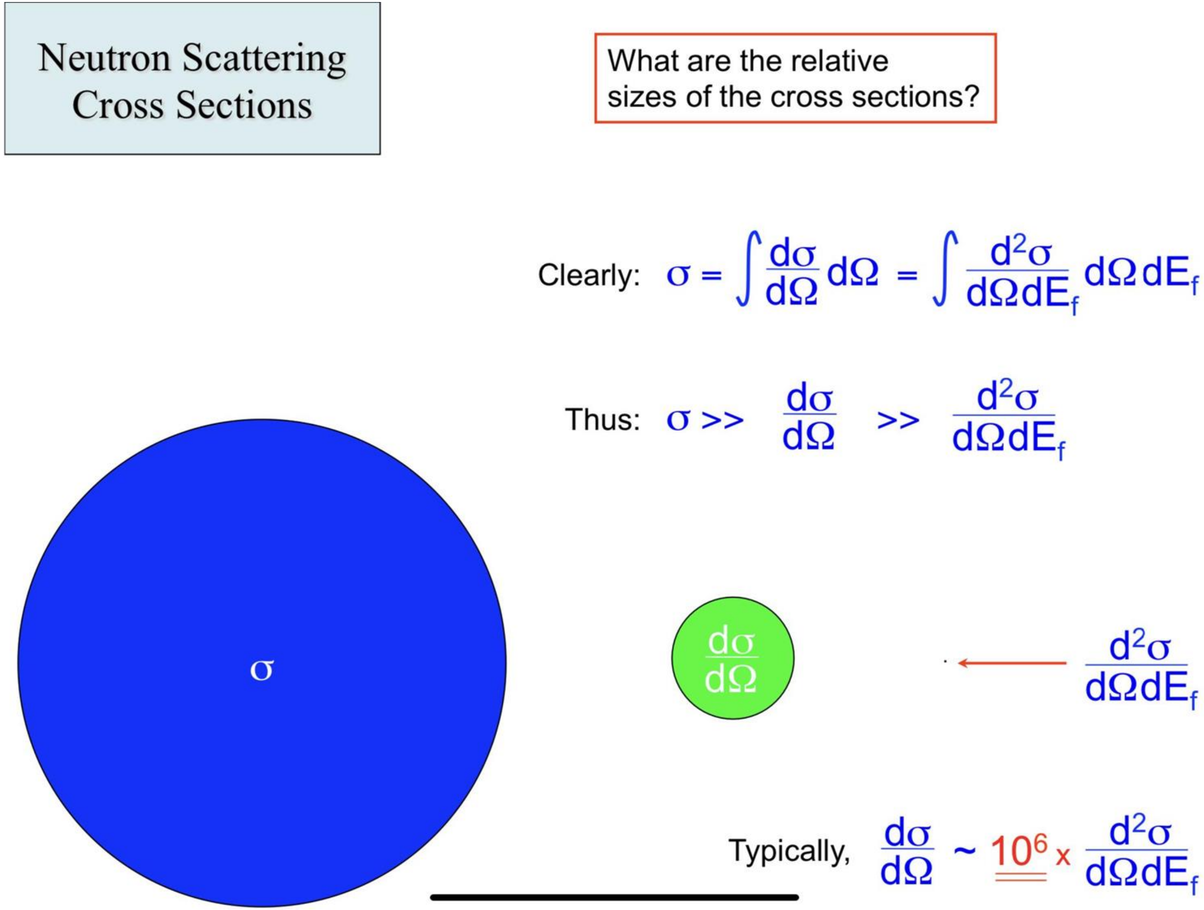
Neutron Scattering Cross Sections

What are the physical meanings of these three cross sections?

σ	Total # of neutrons scattered per second / Φ_i.
$\frac{d\sigma}{d\Omega}$	Total # of neutrons scattered per second into $d\Omega$ / $d\Omega\ \Phi_i$. (Diffraction → structure.
$\frac{d^2\sigma}{d\Omega dE_f}$	Total # of neutrons scattered per second into $d\Omega$ with a final energy between E_f and dE_f / $d\Omega\ dE_f\ \Phi_i$. (Inelastic scattering → dynamics.

Peter Gehring (NIST)

https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf



Neutron Scattering Cross Sections

What are the relative sizes of the cross sections?

Clearly: $\sigma = \int \frac{d\sigma}{d\Omega} d\Omega = \int \frac{d^2\sigma}{d\Omega dE_f} d\Omega dE_f$

Thus: $\sigma >> \frac{d\sigma}{d\Omega} >> \frac{d^2\sigma}{d\Omega dE_f}$

Typically, $\frac{d\sigma}{d\Omega} \sim \underline{\underline{10^6}} \times \frac{d^2\sigma}{d\Omega dE_f}$

Peter Gehring (NIST)

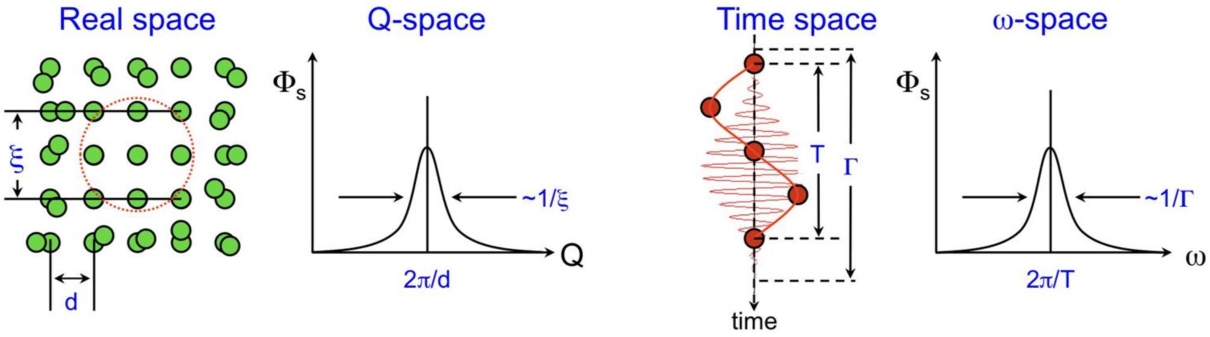
https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf

Pair Correlation Functions

KEY IDEA – Neutron interactions are weak → Scattering only probes two-particle correlations in space and time, but does so simultaneously!

The scattered neutron flux $\Phi_s(\vec{Q},\hbar\omega)$ is proportional to the space ($\vec{r}$) and time (t) Fourier transform of the probability $G(\vec{r},t)$ of finding an atom at ($\vec{r}$,t) given that there is another atom at r = 0 at time t = 0.

$$\Phi_s \propto \frac{\partial^2\sigma}{\partial\Omega\partial\omega} \propto \iint e^{i(\vec{Q}\cdot\vec{r}-\omega t)}G(\vec{r},t)d^3\vec{r}dt$$



Peter Gehring (NIST)

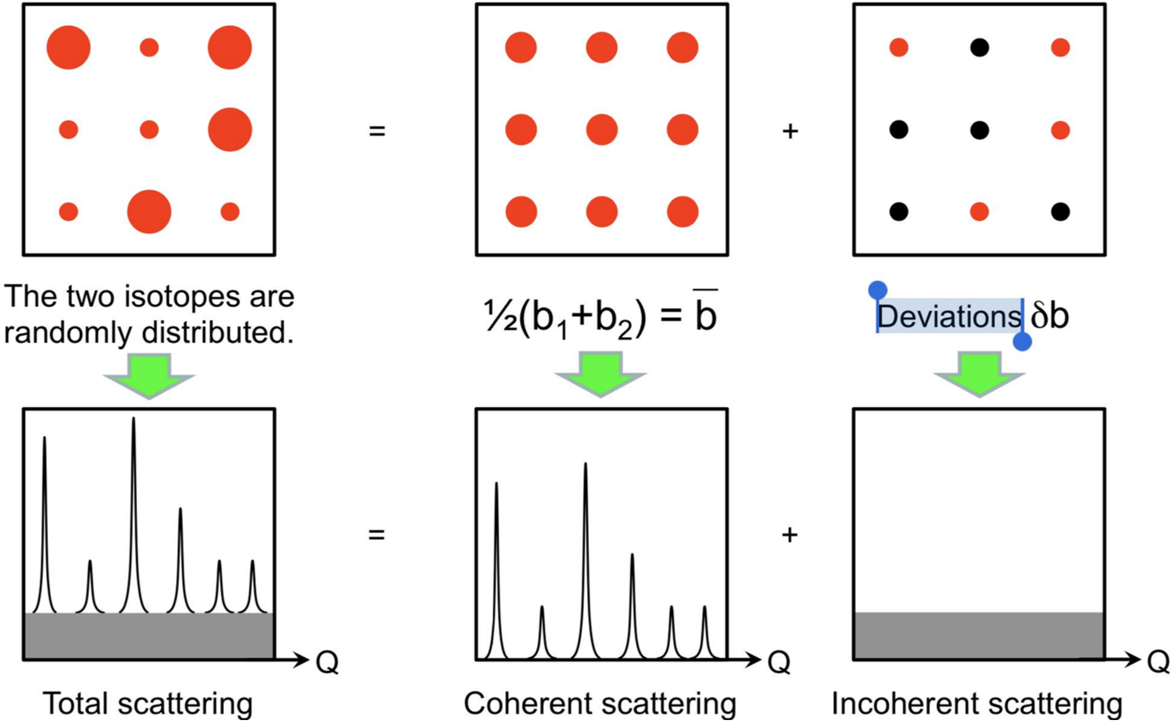
https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf

Neutron Coherent and Incoherent Scattering

Consider a system composed of two different scattering lengths, b_1 and b_2.

b_1 = ●

b_2 = ●



The two isotopes are randomly distributed.

$\frac{1}{2}(b_1+b_2) = \overline{b}$

Deviations δb

Total scattering

Coherent scattering

Incoherent scattering

Peter Gehring (NIST)

https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf

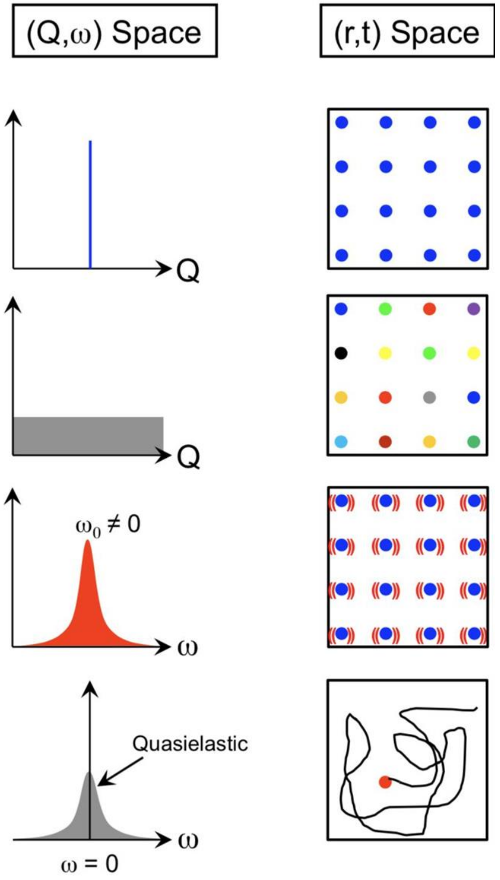
Summary of Cross Sections

$$\left.\frac{d\sigma}{d\Omega}\right|_{coh} = \frac{\sigma_{coh}}{4\pi} S(Q)$$

$$\left.\frac{d\sigma}{d\Omega}\right|_{inc} = \frac{\sigma_{inc}}{4\pi}$$

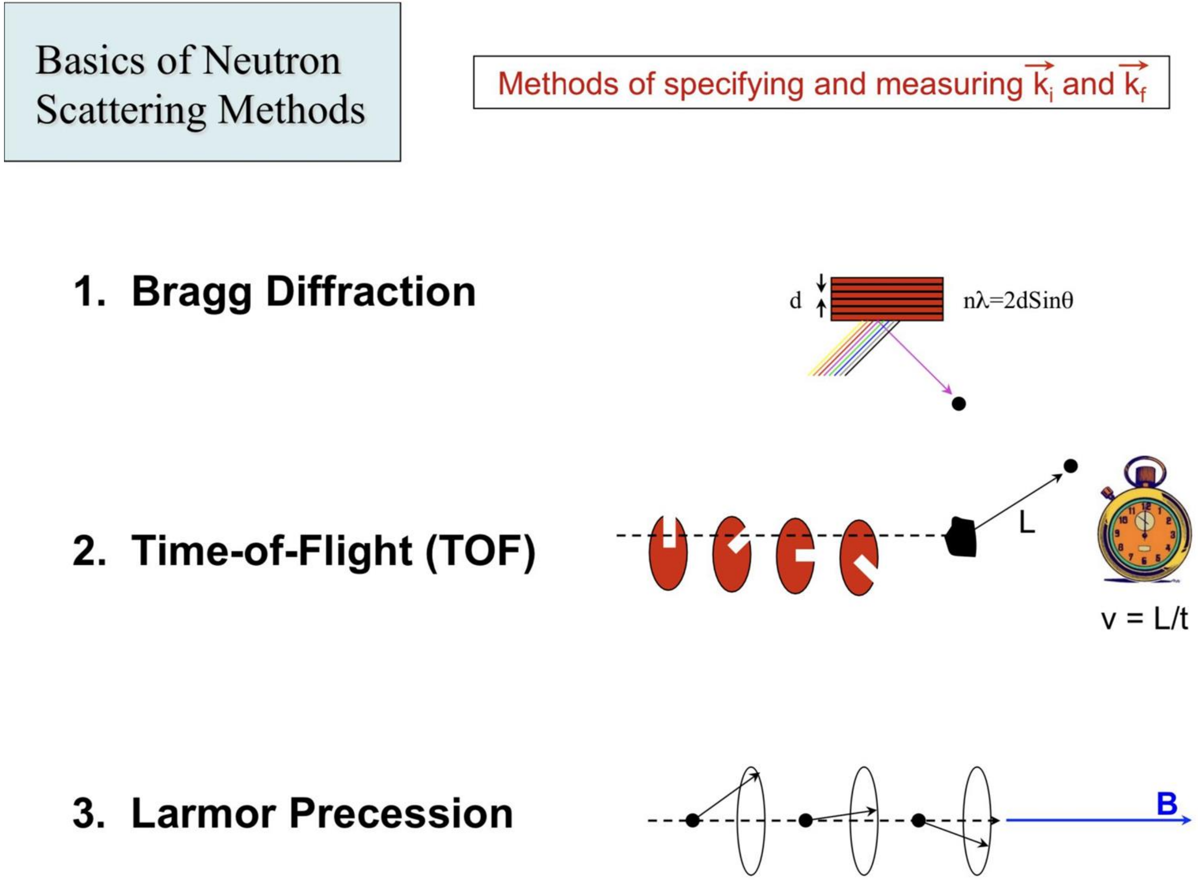
$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right|_{coh} = \frac{k_f}{k_i} \frac{\sigma_{coh}}{4\pi} S_{coh}(Q,\omega)$$

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right|_{inc} = \frac{k_f}{k_i} \frac{\sigma_{inc}}{4\pi} S_{inc}(Q,\omega)$$



Peter Gehring (NIST)

https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf



Basics of Neutron Scattering Methods

Methods of specifying and measuring $\overrightarrow{k_i}$ and $\overrightarrow{k_f}$

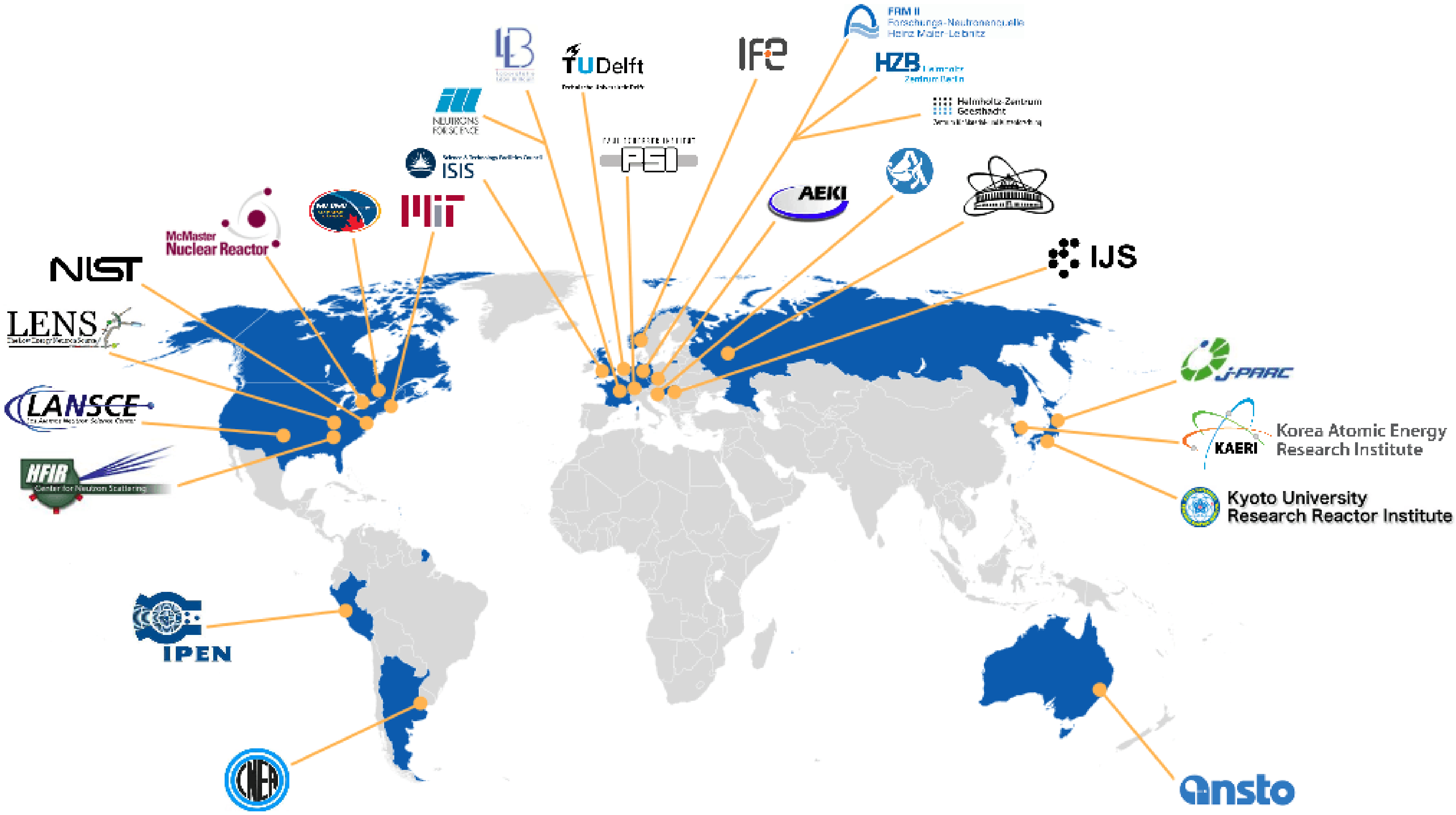
1. **Bragg Diffraction**

2. **Time-of-Flight (TOF)**

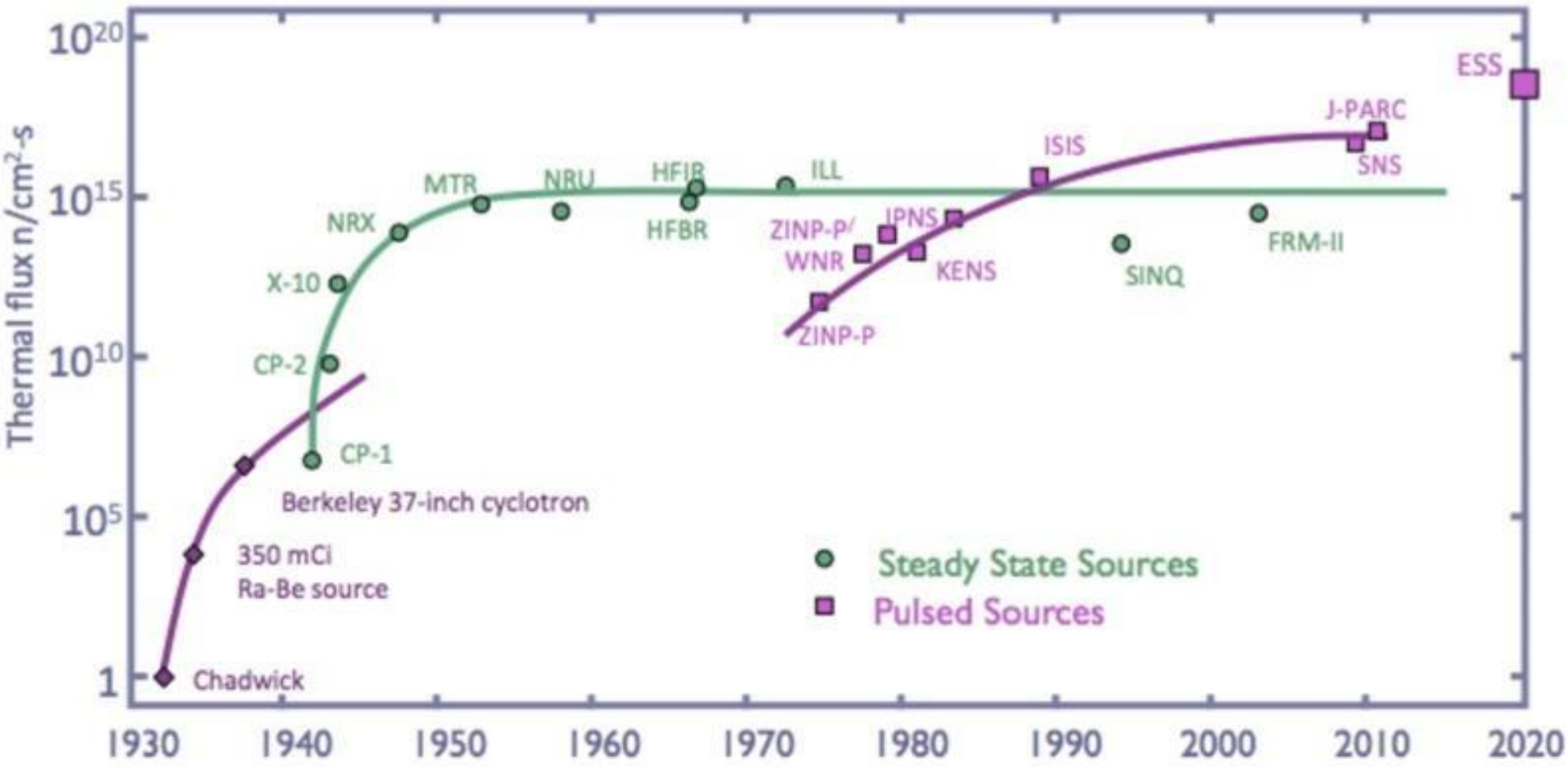
3. **Larmor Precession**

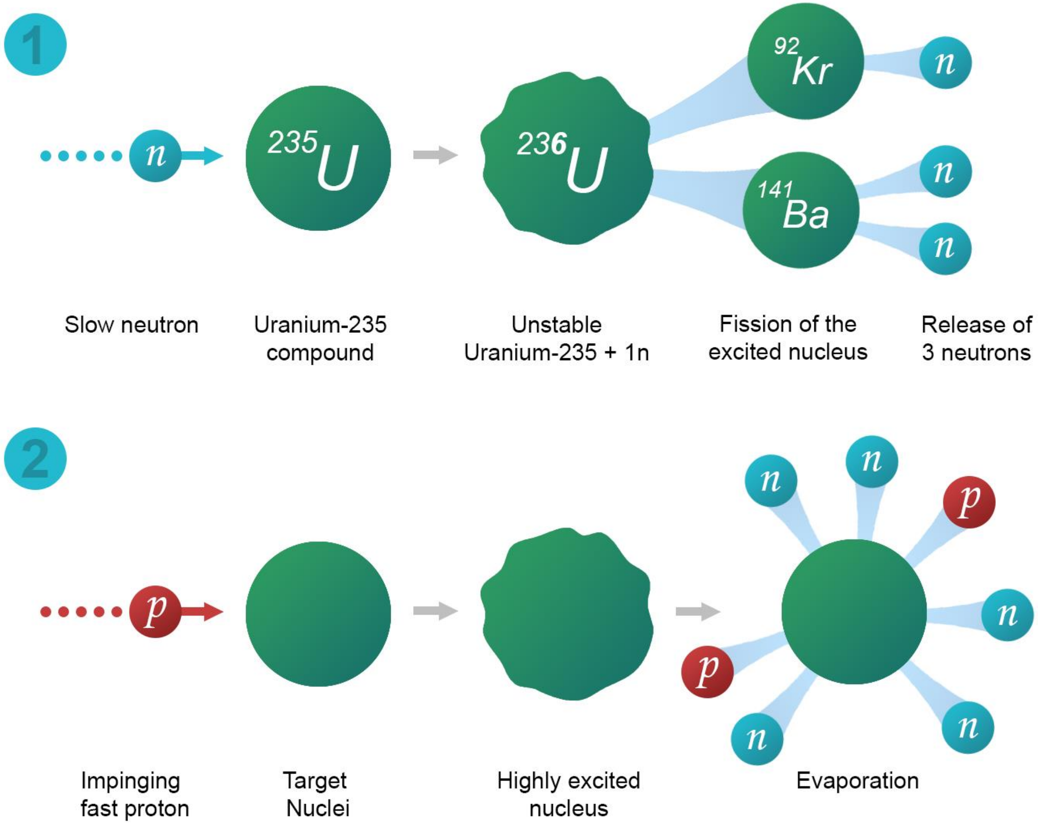
Peter Gehring (NIST)

https://www.ncnr.nist.gov/summerschool/ss12/pdf/SS2012_Gehring_InelasticScattering.pdf


FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz
TUDelft
IFE
HZB Helmholtz Zentrum Berlin
Helmholtz-Zentrum Geesthacht
ILL
NEUTRONS FOR SCIENCE
ISIS
PSI
AEKI
McMaster Nuclear Reactor
MIT
NIST
IJS
LENS
LANSCE
J-PARC
KAERI
Korea Atomic Energy Research Institute
HFIR
Center for Neutron Scattering
Kyoto University Research Reactor Institute
IPEN
CNEA
ansto

Evolution of neutron sources





- **Fission**: A high continuous flux of neutrons is produced in the core of a conventional fission reactor.

- **Spallation**: A pulsed production of neutrons is obtained by bombarding a target of heavy elements with high-energy particles, typically accelerated protons.

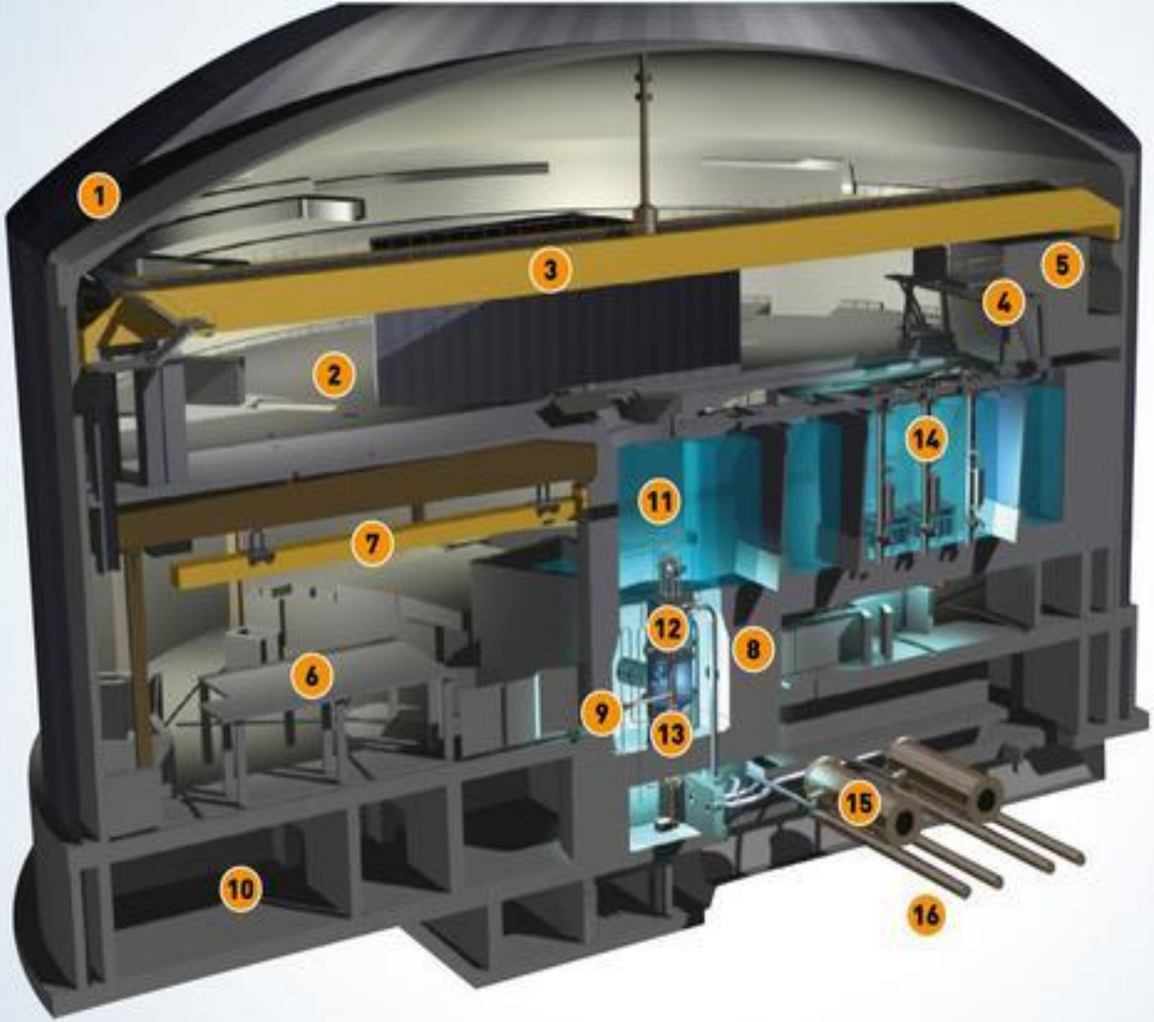
https://pan-learning.org/wiki/index.php/Neutron_scattering_facilities

NEUTRONS FOR SCIENCE®

Institut Laue-Langevin

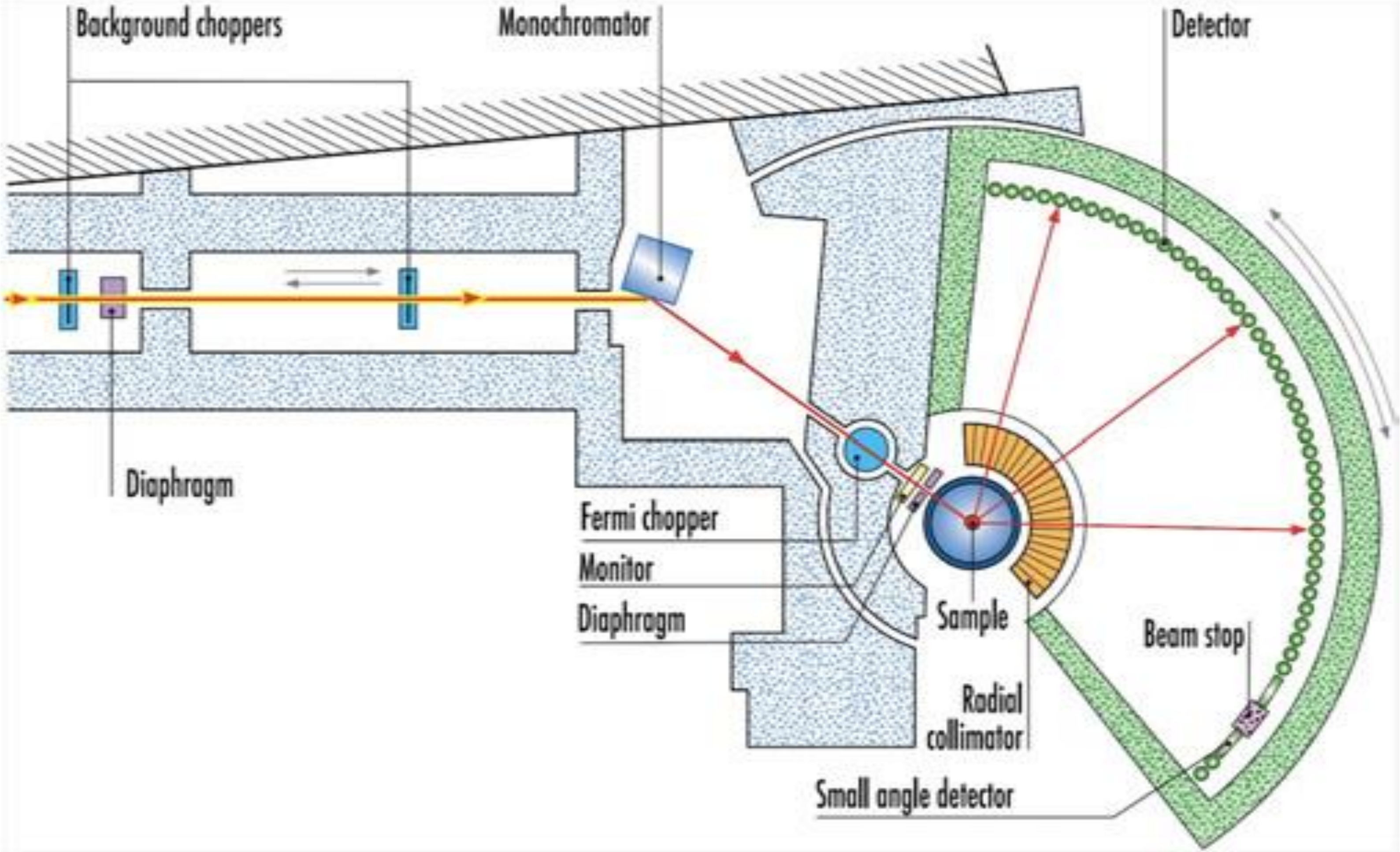
Institut Laue-Langevin https://youtu.be/xrQgURmcAlc

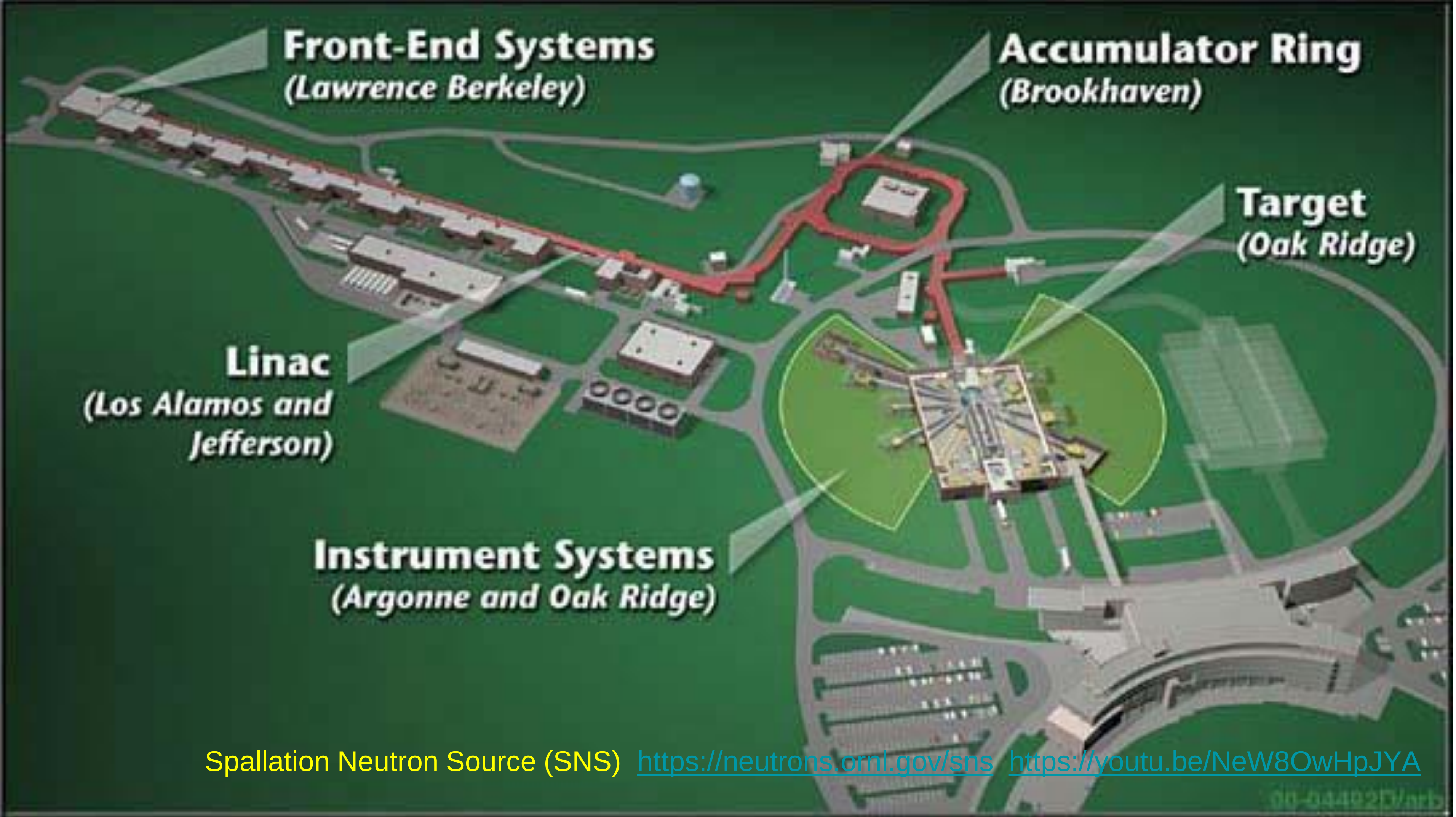
Institut Laue-Langevin https://youtu.be/xrQgURmcAIc



DOUBLE-WALLED REACTOR BUILDING	1
LEVEL D - REACTOR HALL	2
CRANE FOR REACTOR OERATIONS LEVEL D	3
GANTRY FOR HANDLING OF FUEL ELEMENTS	4
HOT CELL	5
LEVEL C - EXPERIMENTAL HALL	6
CRANE FOR EXPERIMENTAL OPERATIONS	7
BIOLOGICAL SHIELDING (CONCRETE)	8
COLLIMATED NEUTRON EXIT POINT	9
LEVEL B - REACTOR AUXILLARY EQUIPMENT	10
REACTOR POOL (LIGHT WATER)	11
HEAVY WATER (MODERATOR & FUEL ELEMENT COOLING)	12
FUEL ELEMENT	13
SPENT FUEL ELEMENTS STORAGE	14
HEAT EXHANGERS (PRIMARY/SECONDARY)	15
SECONDARY COOLING CIRCUIT 'DRAC RIVER)	16

Institut Laue-Langevin https://youtu.be/xrQgURmcAIc


Background choppers
Monochromator
Detector
Diaphragm
Fermi chopper
Monitor
Diaphragm
Sample
Beam stop
Radial collimator
Small angle detector



Spallation Neutron Source (SNS) https://neutrons.ornl.gov/sns https://youtu.be/NeW8OwHpJYA

Oak Ridge, Tennessee
LOCATION

2006
START OF OPERATIONS

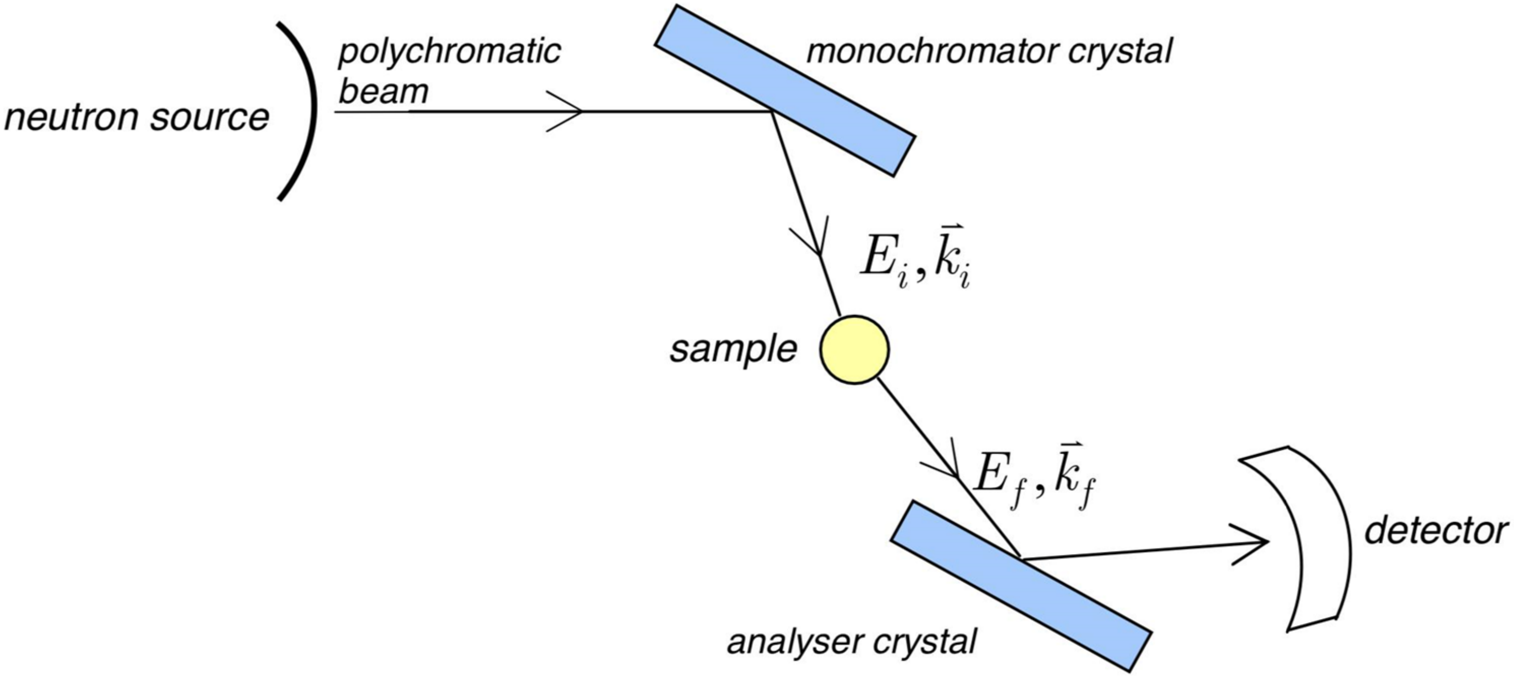
759 (FY 2019)
NUMBER OF USERS

Spallation Neutron Source (SNS)

EUROPEAN SPALLATION SOURCE

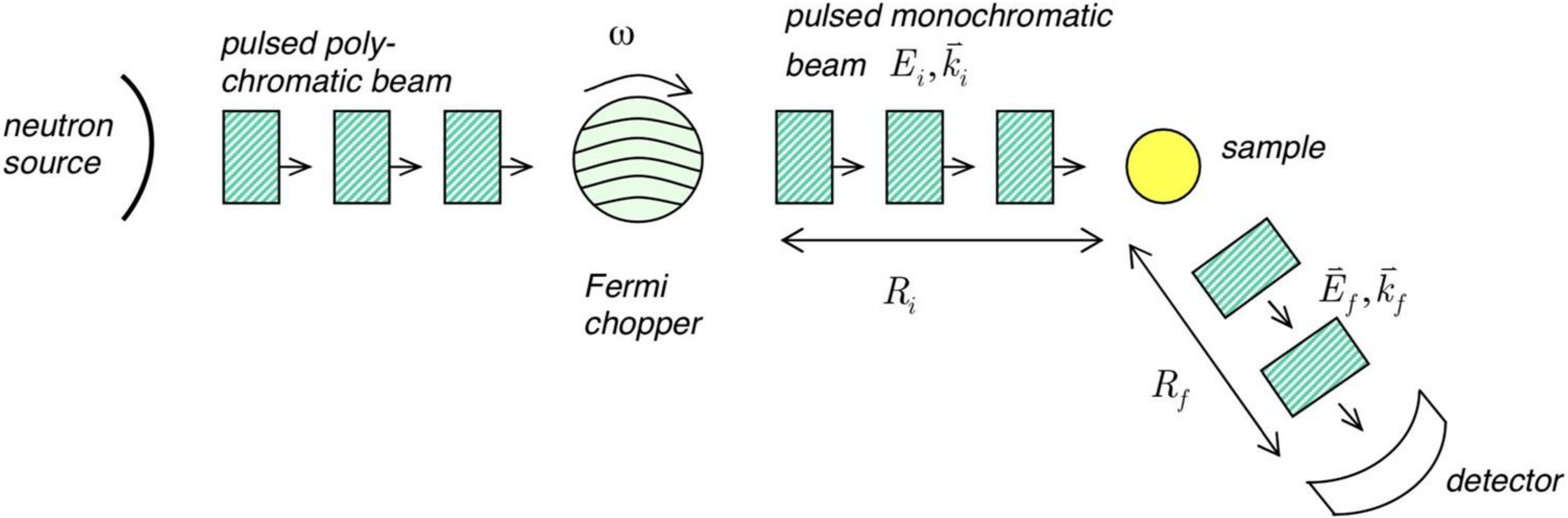
https://europeanspallationsource.se/webcams

1 — Triple-axis spectrometer (commonly used at steady-state neutron sources)



https://www.fkf.mpg.de/5520565/13_Inelastic_Neutron_Scattering.pdf

2 — Time-of-flight spectrometer (commonly used at pulsed neutron sources)



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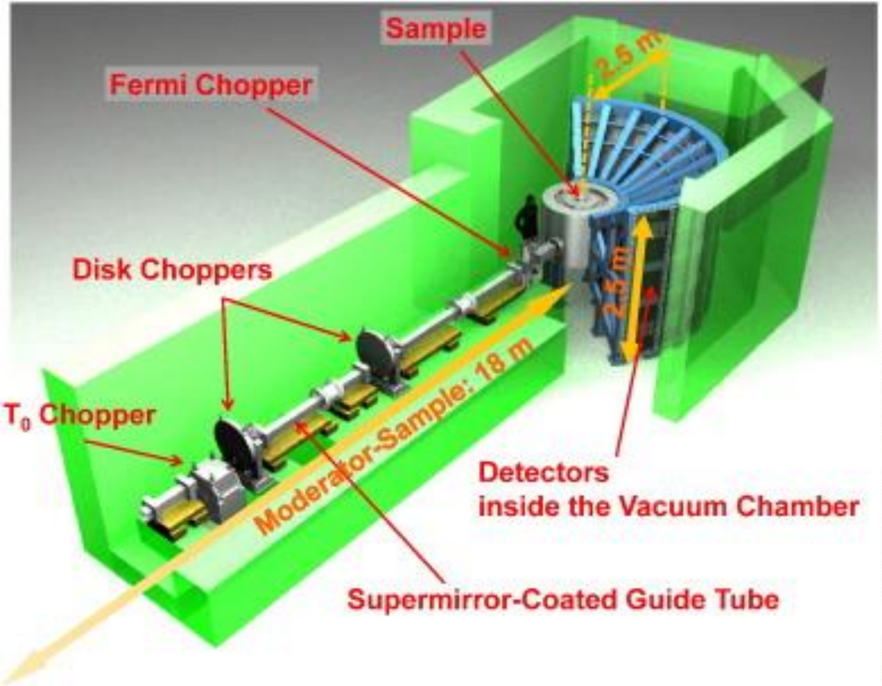
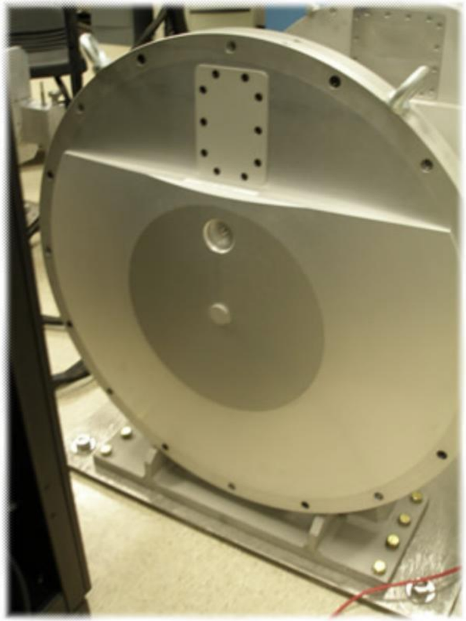
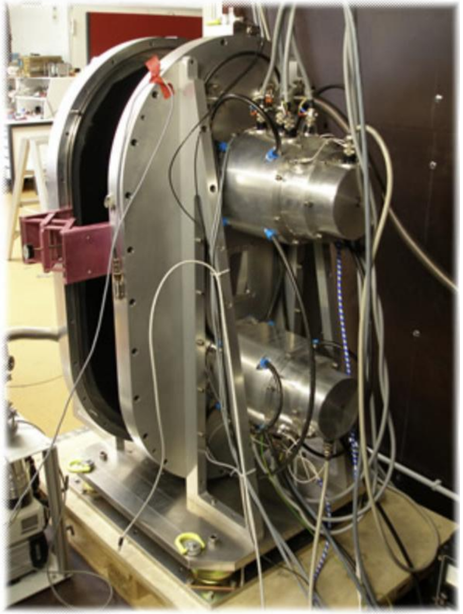
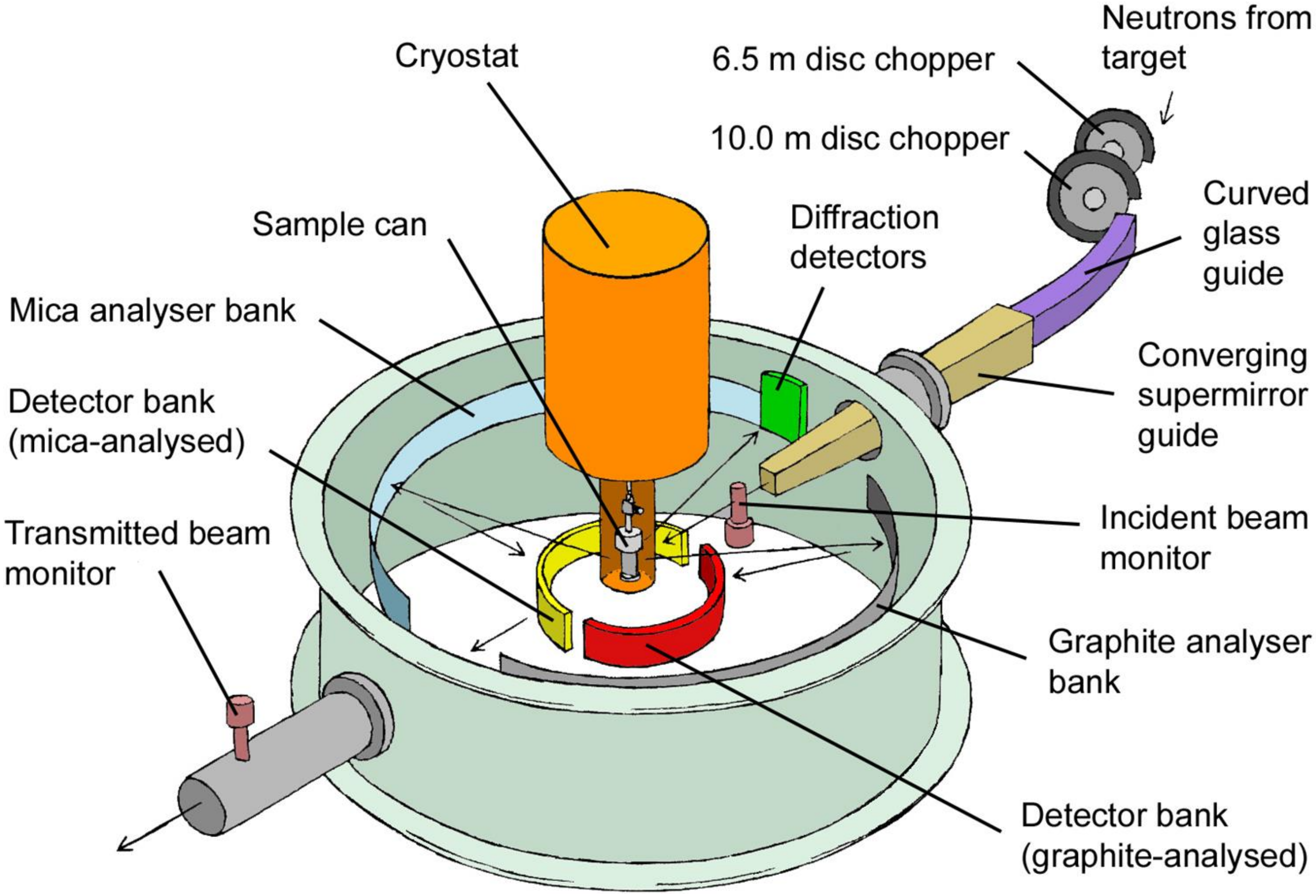
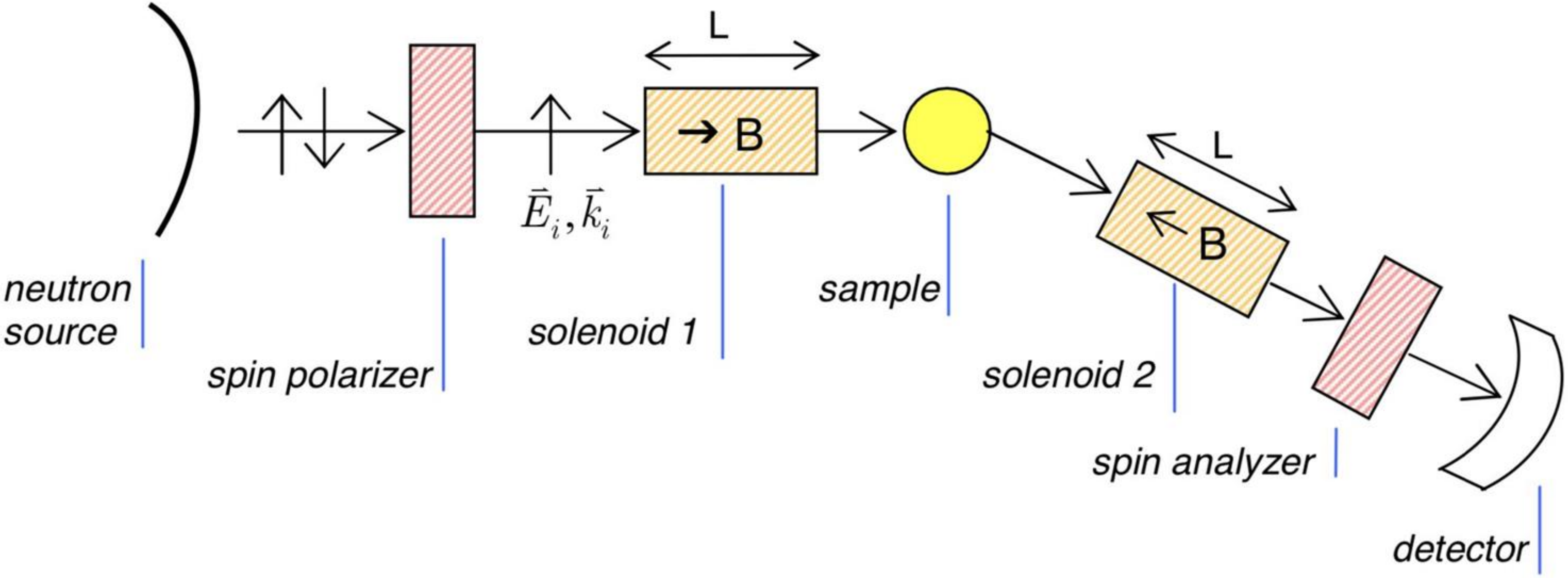



Frame overlap chopper


High-speed double disk chopper

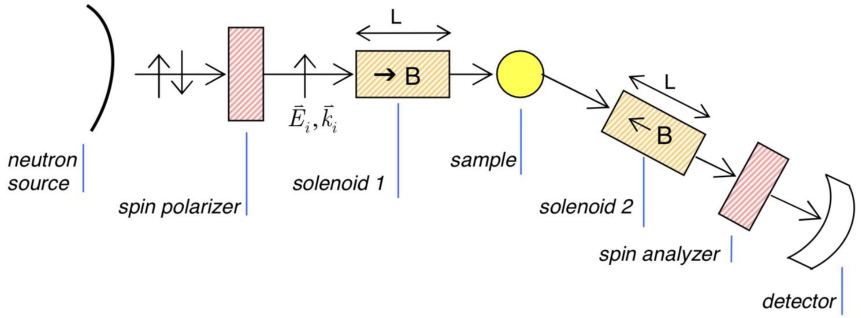

Neutrons from target
6.5 m disc chopper
10.0 m disc chopper
Cryostat
Curved glass guide
Sample can
Diffraction detectors
Mica analyser bank
Converging supermirror guide
Detector bank (mica-analysed)
Incident beam monitor
Transmitted beam monitor
Graphite analyser bank
Detector bank (graphite-analysed)

3 — Spin-echo spectrometer



https://www.fkf.mpg.de/5520565/13_Inelastic_Neutron_Scattering.pdf

3 — Spin-echo spectrometer



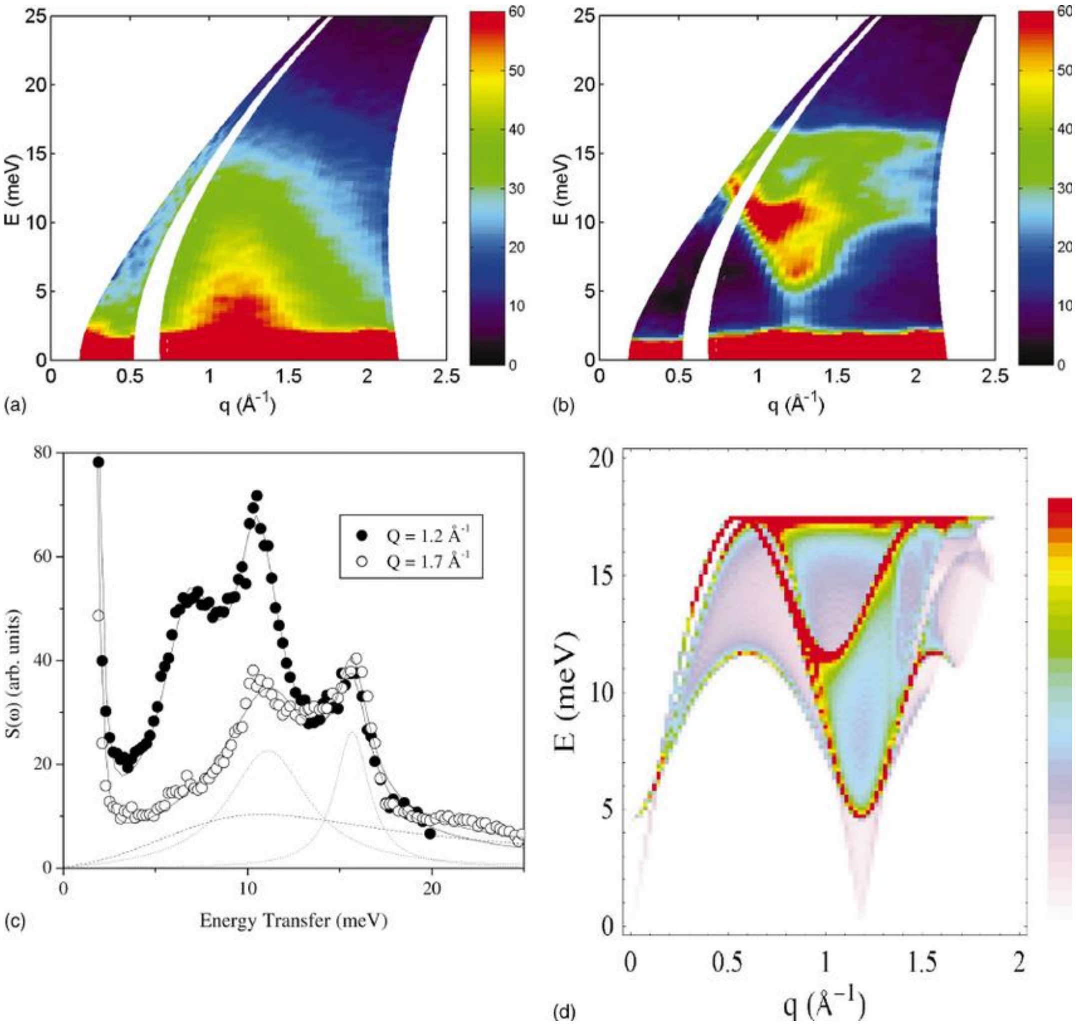
$$\omega_L = \frac{\gamma \mu_N B}{\hbar} \qquad \phi_i = \frac{\omega_L L}{v_i}$$

$$\Delta\Phi = \Phi_i - \Phi_f = \omega_L L\left(\frac{1}{v_i}-\frac{1}{v_f}\right) = \omega_L L\left(\frac{1}{v_i}-\frac{1}{v_i+\Delta v}\right) \approx \frac{\omega_L L}{v_i^{2}}\Delta v \ \text{ for } \ \Delta v \ll v_i$$

$$\hbar\omega = \frac{m_n}{2}\left(v_f^{2} - v_i^{2}\right) \approx m_n v_i \Delta v \Rightarrow \Delta\Phi \approx \frac{\hbar\omega_L L}{m_n v_i^{3}}\omega \equiv \omega\tau_{SE}$$

τ_{SE} = spin echo time

https://www.fkf.mpg.de/5520565/13_Inelastic_Neutron_Scattering.pdf



Magnetic ordering and spin-liquid state of YMnO3 - Park *PRB* 2003