The neutron: properties and interactions

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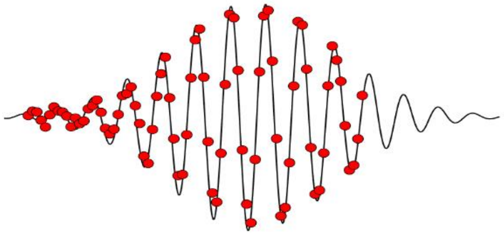
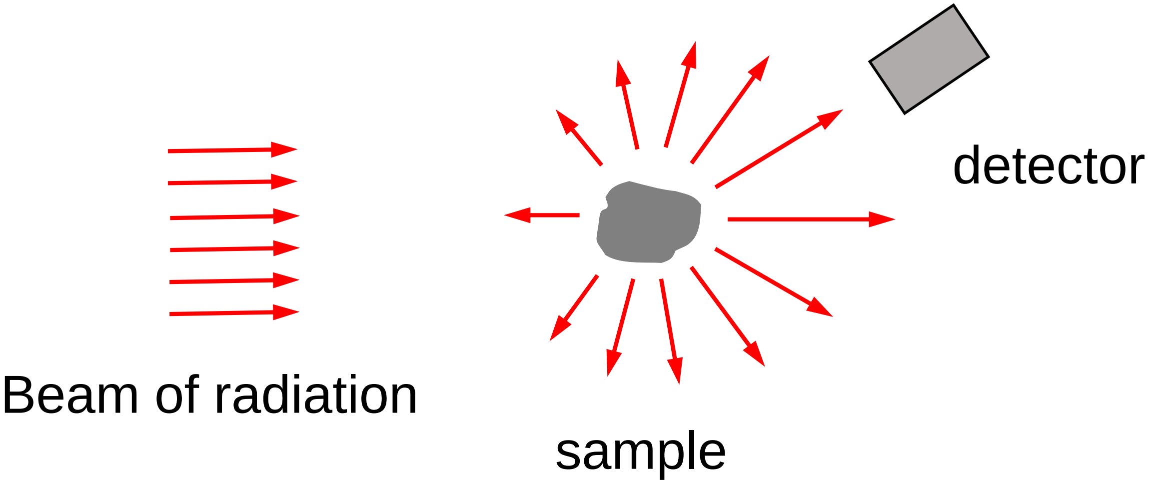
Oxford University

- What is a neutron?
- How does it interact with matter?
- Prepare the ground for understanding the principles of neutron scattering



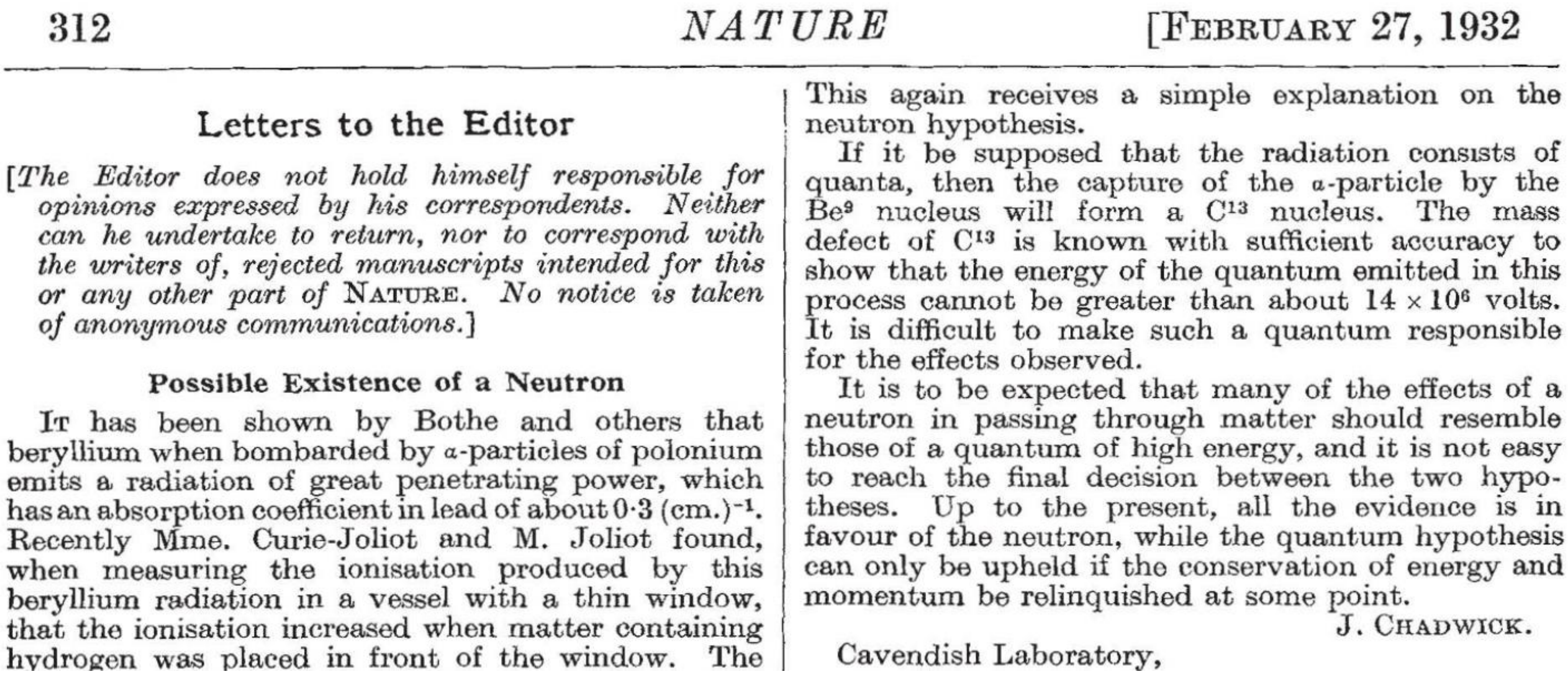
Scattering ‘nuts and bolts’



- Source of radiation: photons, neutrons, electrons, atoms, …
- Measure distribution of radiation scattered from a sample
- Form of interaction determines what you can measure
- Radiation must be coherent to measure correlations

Discovery of the neutron

1932 (Chadwick)



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Letters to the Editor

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Possible Existence of a Neutron

It has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The

This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^{9} nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^{6} volts. It is difficult to make such a quantum responsible for the effects observed.

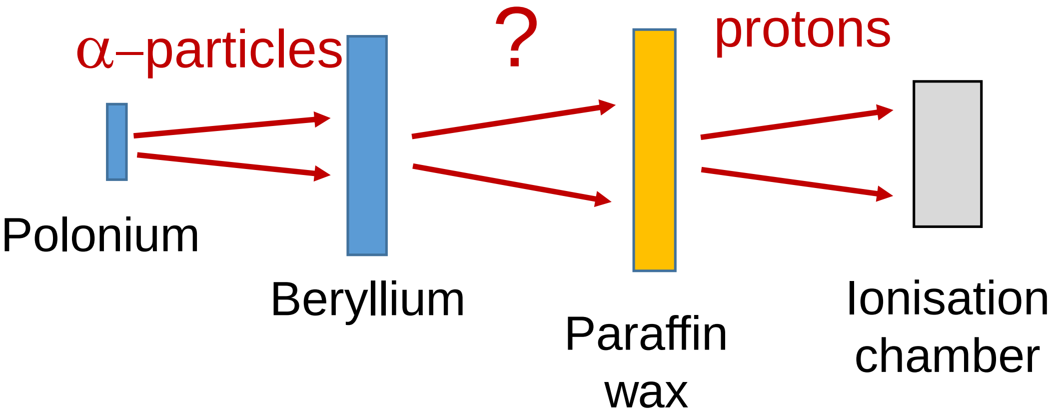
It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. Chadwick.

Cavendish Laboratory,

Discovery of the neutron

I. Curie and F. Joliot, 1932



α–particles

?

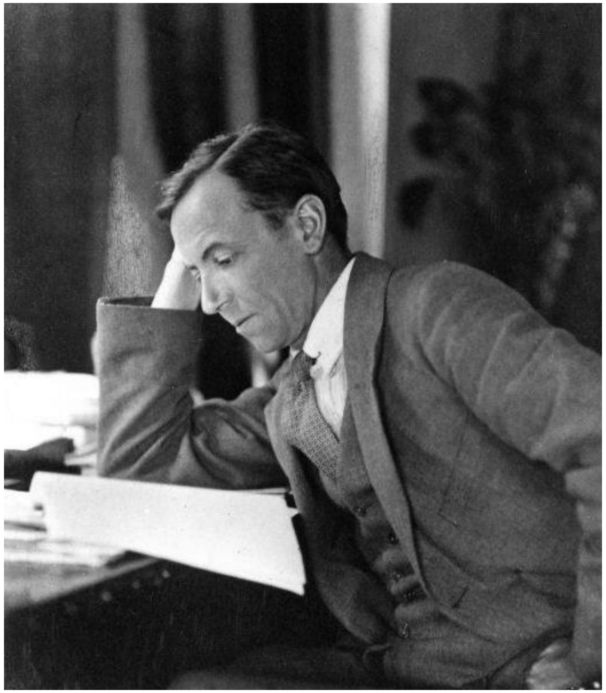
protons

Polonium

Beryllium

Paraffin wax

Ionisation chamber



James Chadwick (1891-1974)
Nobel Prize in Physics (1935)

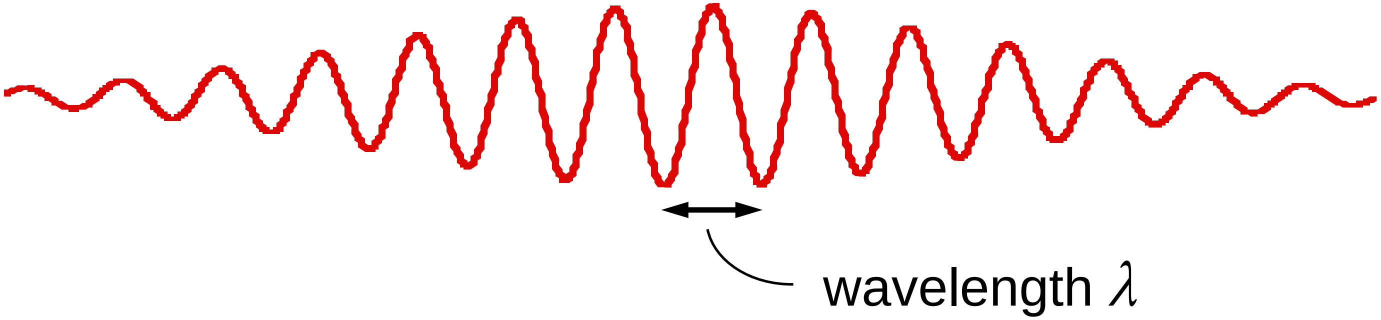
Chadwick, 1932

? = neutrons

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

Neutrons are particles and waves!

- matter wave:



- Kinematics (de Broglie):

momentum: $p = h/\lambda$ ($h =$ Planck's constant)

$\mathbf{p} = \hbar\mathbf{k}$ ($\mathbf{k} =$ wavevector, $k = 2\pi/\lambda$)

($\hbar = h/2\pi$)

kinetic energy: $E = \frac{1}{2} m_\mathrm{n} v^2 = p^2/2m_\mathrm{n}$

$\longrightarrow E = h^2/(2m_\mathrm{n}\lambda^2) = \hbar^2 k^2/2m_\mathrm{n}$

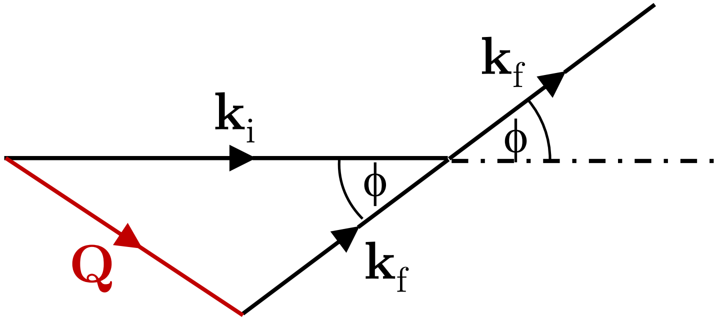
Scattering kinematics

- momentum transfer

$$\hbar\mathbf{Q} = \hbar\mathbf{k}_\mathrm{i} - \hbar\mathbf{k}_\mathrm{f}$$

- energy transfer

$$\begin{aligned}\hbar\omega &= E_\mathrm{i} - E_\mathrm{f} \\ &= \hbar^2(k_\mathrm{i}^2 - k_\mathrm{f}^2)/2m_\mathrm{n}\end{aligned}$$



scattering triangle

- a scattering event is characterised by ($\mathbf{Q}$, ω)

Elastic scattering (diffraction): $\hbar\omega = 0$

Inelastic scattering (spectroscopy): $\hbar\omega \neq 0$

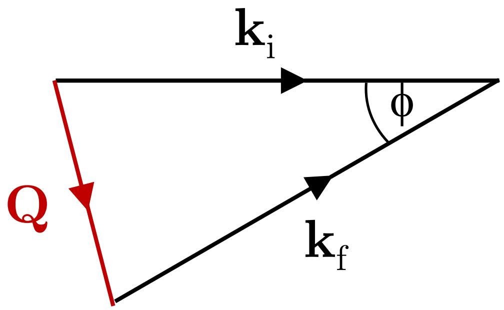
Elastic scattering (diffraction): $\hbar\omega = 0$

- Scattering vector

$$\mathbf{Q} = \mathbf{k}_\mathrm{i} - \mathbf{k}_\mathrm{f}$$

BUT sometimes written

$$\mathbf{Q} = \mathbf{k}_\mathrm{f} - \mathbf{k}_\mathrm{i}$$



isosceles scattering triangle

Beware of crystallographers!

Particle properties of the neutron

- Mass = 1.675×10^{-27} kg (= $1.001 m_\mathrm{p}$)
- Charge = 0
- Mean lifetime ≈ 15 min
- Spin = ½
- Magnetic moment = $1.91\ \mu_\mathrm{N}$ ($\sim 0.001 \mu_\mathrm{B}$)

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Particle properties of the neutron

- Mass = 1.675 x 10^{-27} kg (= $1.001m_\mathrm{p}$)

kinetic energy: $E = ½ m_\mathrm{n} v^2$

$= p^2/2m_\mathrm{n}$ $(p =$ momentum)

de Broglie: $p = h/\lambda$ $(h =$ Planck's constant)

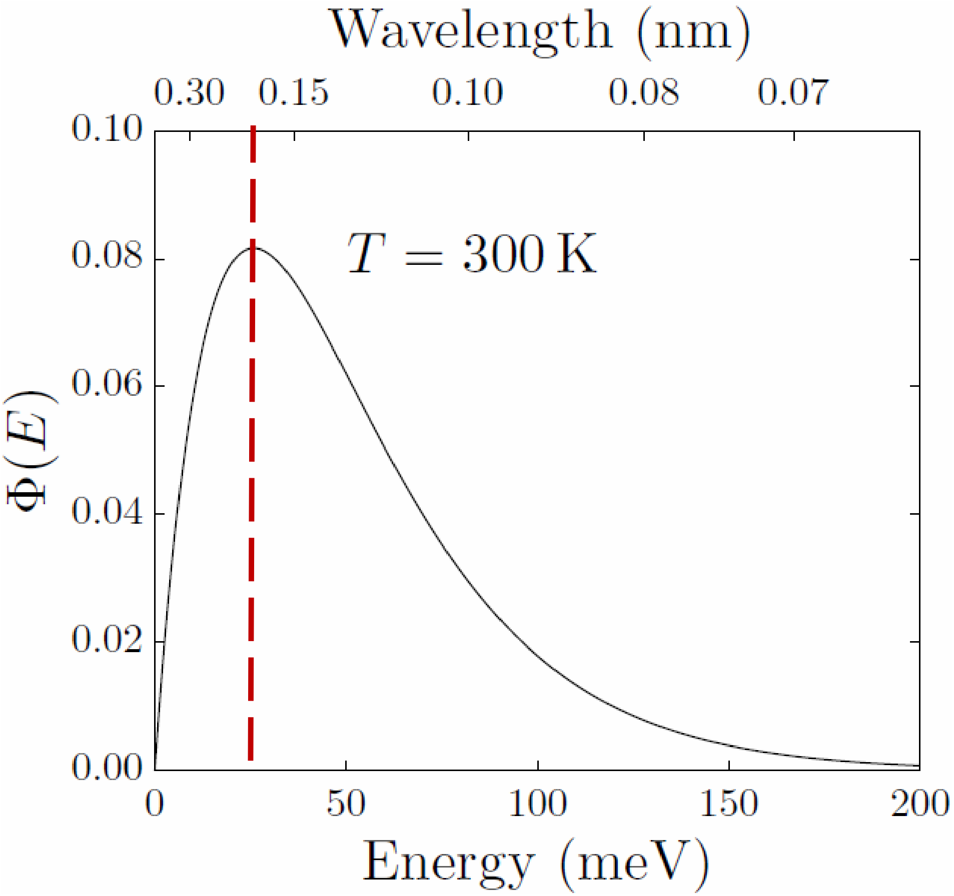
$$\longrightarrow E = h^2/(2m_\mathrm{n}\lambda^2)$$

hence $E = 25\,\mathrm{meV} \longrightarrow v = 2{,}200\,\mathrm{ms}^{-1}$ and $\lambda = 0.18\,\mathrm{nm}$

$E \sim$ energy of thermal excitations in condensed matter

$\lambda \sim$ inter-atomic distances in condensed matter

Thermal neutrons



Maxwell distribution
of the kinetic energies
of particles
in thermal equilibrium

neutrons are well matched to probe the atomic-scale structure and dynamics of substances at normal operating temperatures

Comparison with x-rays

X-rays are electromagnetic radiation (photons)

Einstein: $E = hf$ ($f =$ frequency)

$= hc/\lambda$ ($c = f\lambda =$ speed of light

$= 3.0$ x $10^8\ \mathrm{ms}^{-1}$)

hence $E = 6.9\,\mathrm{keV} \longrightarrow \lambda = 0.18\,\mathrm{nm}$ (x-rays)

$E = 25\,\mathrm{meV} \longrightarrow \lambda = 0.18\ \mathrm{nm}$ (neutrons)

Neutrons better suited to low energy dynamics

Particle properties of the neutron

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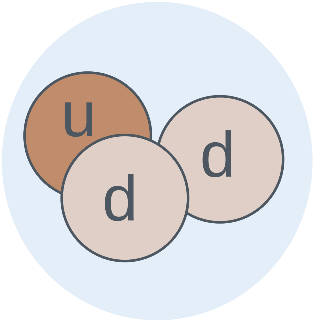
Particle properties of the neutron

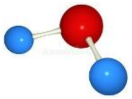
Standard model:
neutron composed of 3 quarks



u: $+\frac{2}{3}e$
d: $-\frac{1}{3}e$

Charge = 0

Electric dipole moment: $d < 4.6 \times 10^{-47}$ C m
(water molecule: $d = 6.1 \times 10^{-30}$ C m)



Neutrons do not feel electrostatic forces

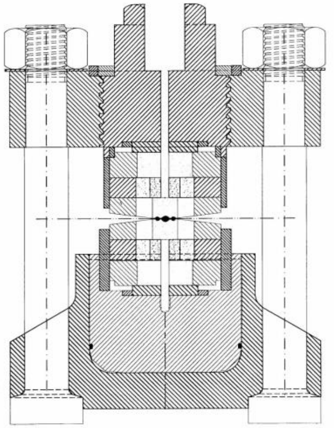
⟶ *neutrons are highly penetrating*

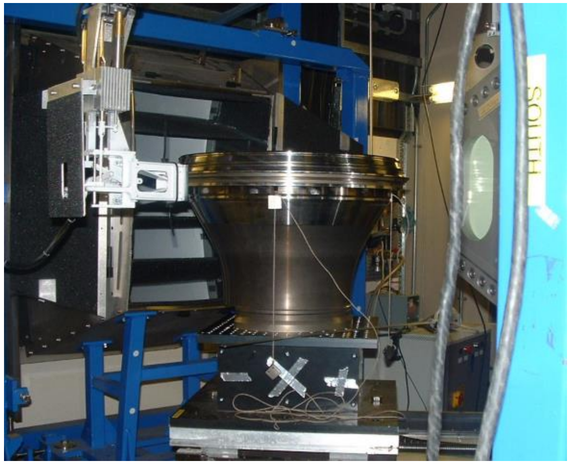
Neutron penetration depth ~ 1 cm

- bulk probe

⟶ surface effects can usually be neglected
(exception is neutron reflectometry)

- non-destructive
- can study samples in complex sample environments,
e.g. cryostats, magnets, pressure cells, …





Particle properties of the neutron

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Neutrons last long enough to perform experiments

Particle properties of the neutron

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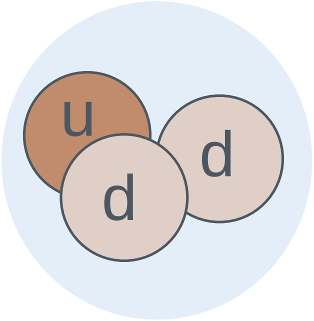
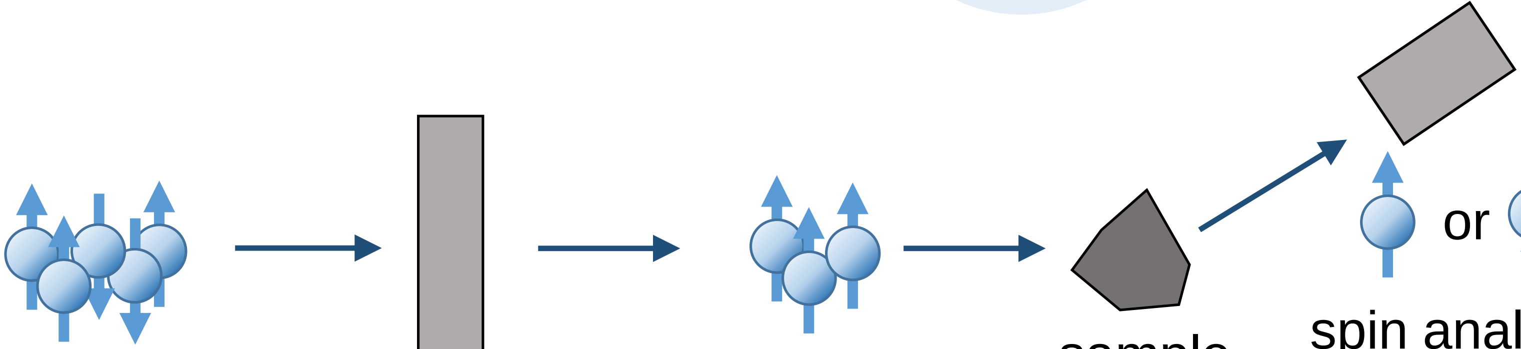
Neutrons can be spin-polarized

Polarized neutrons

Quarks are spin-1/2 particles



→ neutron has spin = 1/2



unpolarized neutrons

Spin polarizer

polarized neutrons

sample

spin analyser & detector

or

measure polarization-dependent scattering intensities

→ neutron polarization analysis

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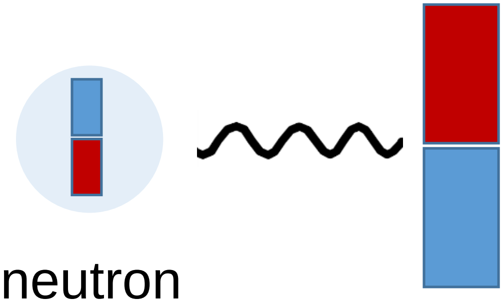
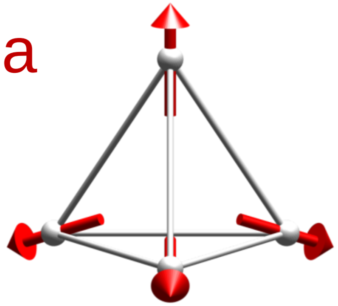
→ Magnetic neutron scattering

Magnetic scattering



Can study a wide range of magnetic phenomena
e.g. magnetic structures



Neutron interactions with matter

Neutrons interact with

1. Atomic nuclei (strong nuclear force — short-range)
2. Magnetic fields from unpaired electrons

In both cases, the interaction is very weak

Strengths:

1. Neutrons probe the bulk (~1 cm)
2. Neutrons are non-destructive
3. Intensity can be calibrated
4. Theory is quantitative

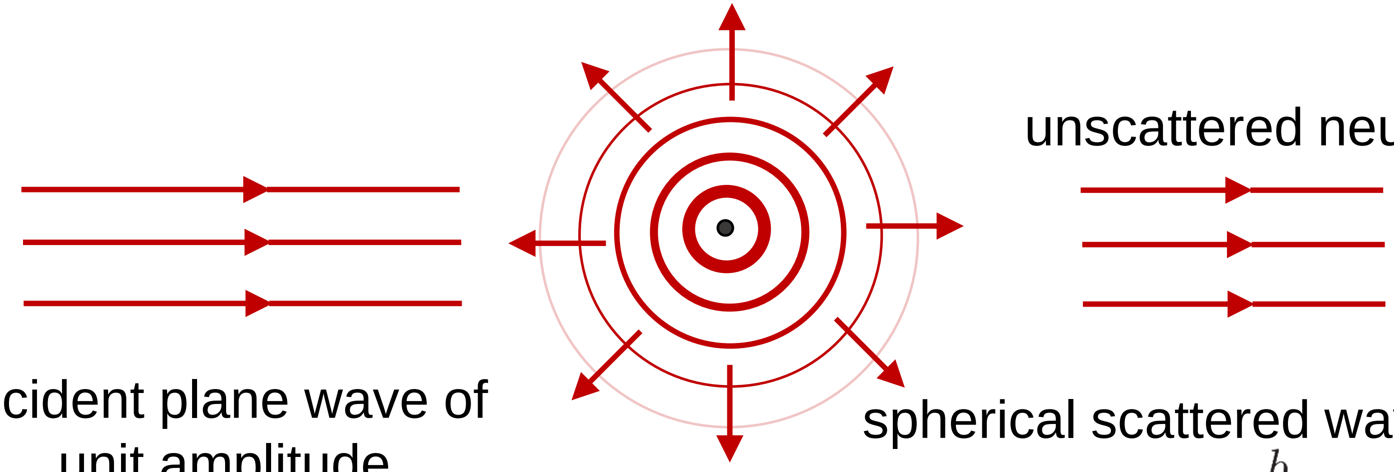
Weakness:

Sample size is important:

single crystals: ~1 mm^3 (diffraction)
~1 cm^3 (spectroscopy)

powders/fluids: ~1 g (diffraction)
~10 g (spectroscopy)

Scattering from bound nuclei



unscattered neutrons

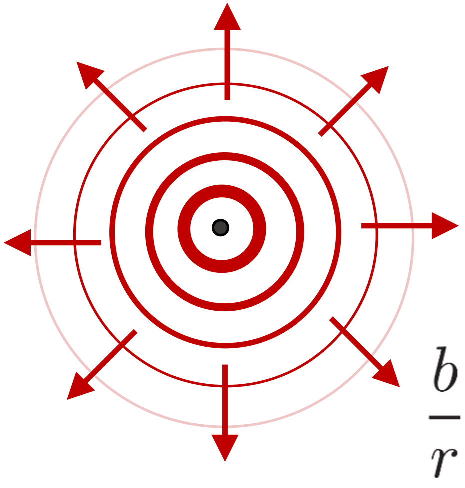
incident plane wave of
unit amplitude

nucleus

spherical scattered wave
of amplitude $\frac{b}{r}$

Image source: US Department of Health and Human Services

Nuclear scattering length



Nucleus is very small $\sim 10^{-15}\ \mathrm{m}$

Formal theory uses a pseudopotential:

$$V_{\mathrm{N}}(\mathbf{r}) = \frac{2\pi\hbar^2}{m_{\mathrm{n}}}\, b\, \delta(\mathbf{r})$$

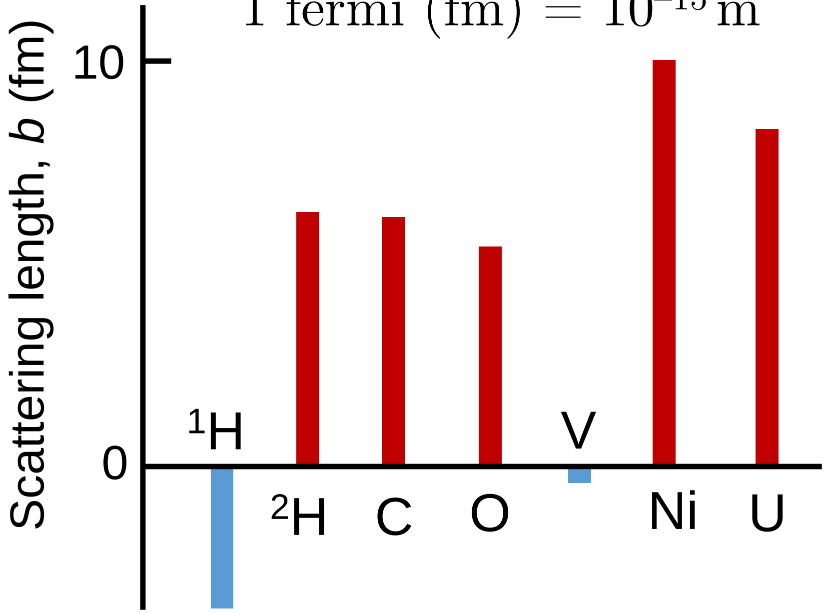
$b =$ nuclear scattering length

b measures both the amplitude of scattered wave and the strength of the nuclear potential

Nuclear scattering length

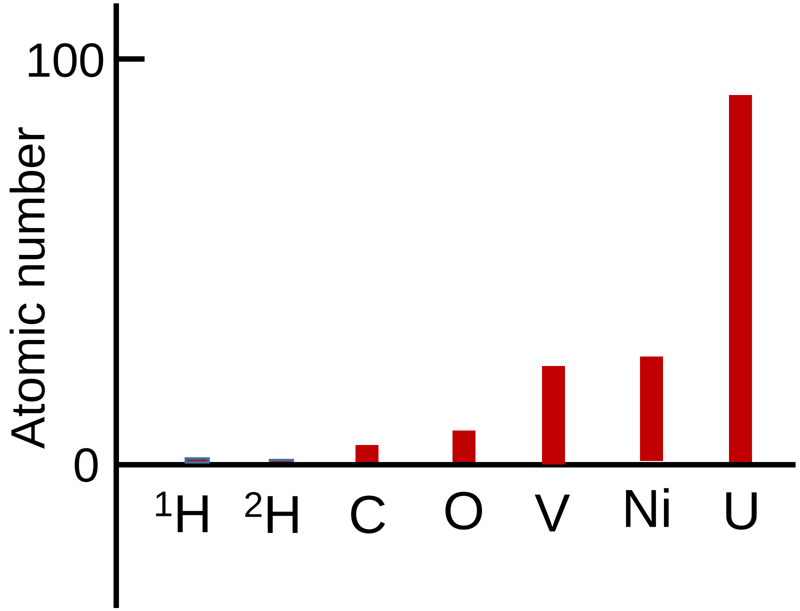
b varies irregularly with atomic number

b also depends on isotope and on nuclear spin orientation



$1\ \mathrm{fermi}\ (\mathrm{fm}) = 10^{-15}\,\mathrm{m}$

contrast with X-ray
scattering amplitude



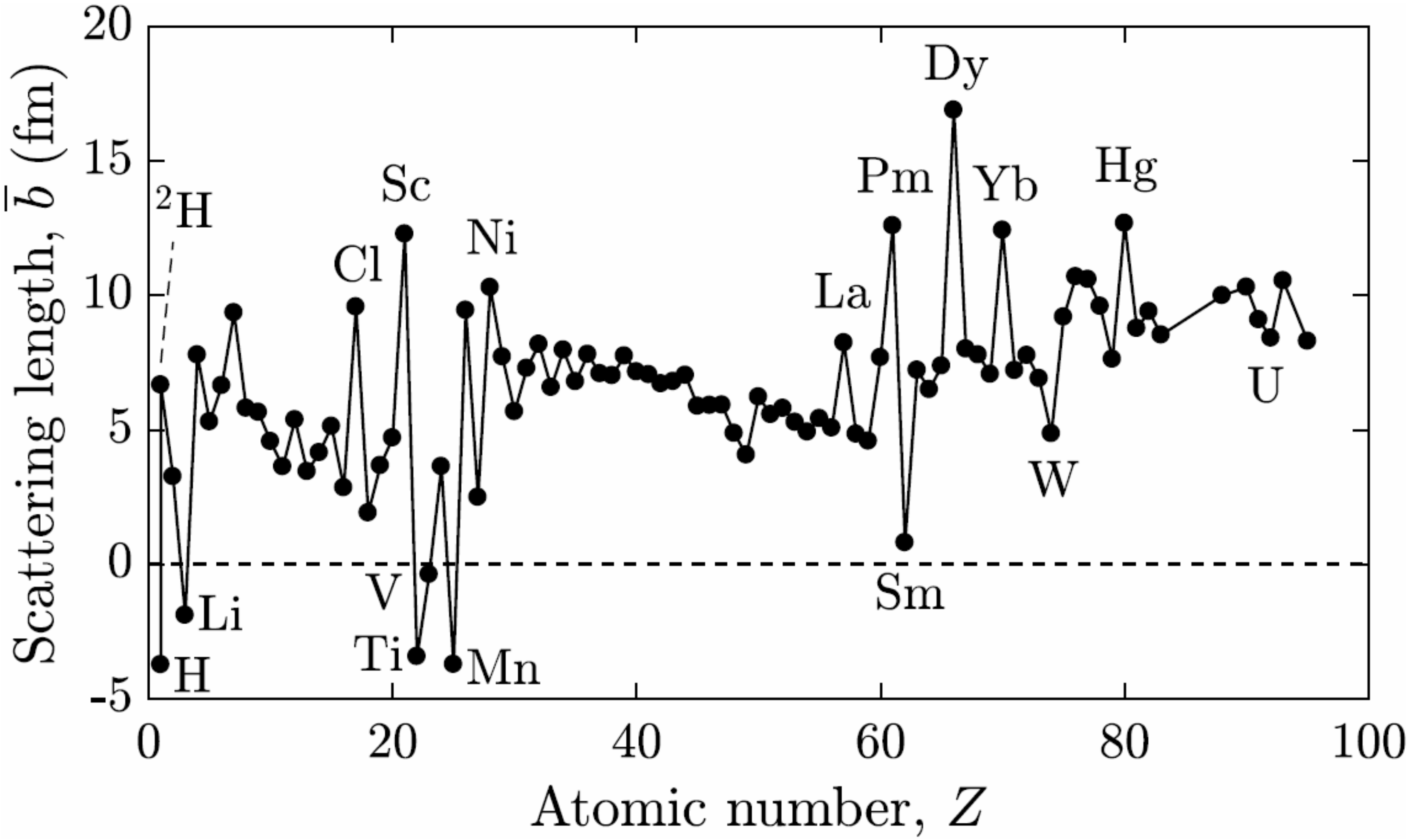


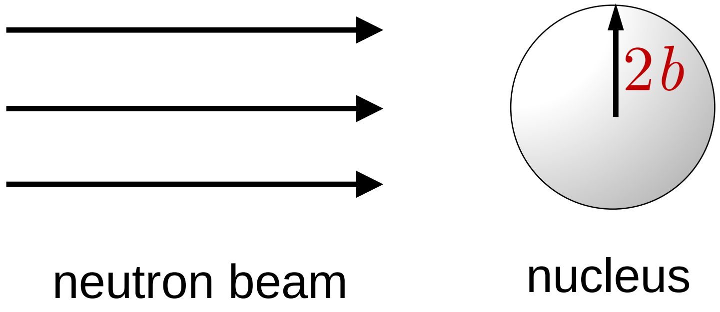
Image credit: Boothroyd (2020)

Cross-sections

scattering amplitude ~ b [length]

scattering intensity ~ b^2 [area]

$2b =$ effective radius of nucleus



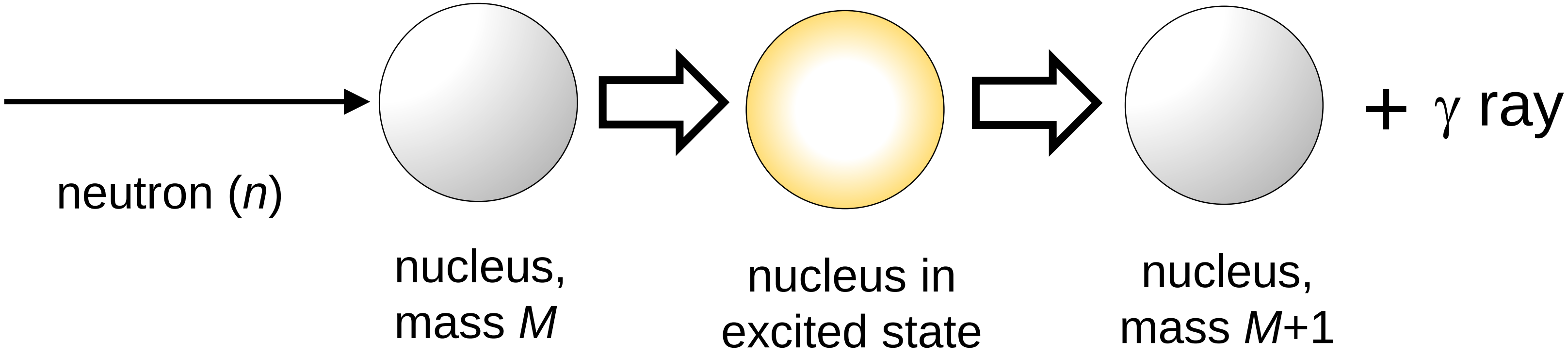
$\sigma_s = 4\pi b^2 =$ effective cross-sectional area of nucleus

Scattering probabilities are expressed as cross-sections

unit: $1\,\mathrm{barn}\ (\mathrm{b}) = 10^{-28}\,\mathrm{m}^2$

Absorption cross-sections

(n,γ) reaction:



neutron (n)

nucleus, mass M

nucleus in excited state

nucleus, mass M+1

+ γ ray

Strongly absorbing nuclei:

^{3}He, ^{10}B, ^{113}Cd, ^{149}Sm, ^{151}Eu, ^{155}Gd, ^{157}Gd

Reaction probability is described by the absorption cross-section σ_a, which is dependent on neutron energy: $\sigma_a(E) \propto 1/\sqrt{E}$

Absorption cross-section of cadmium

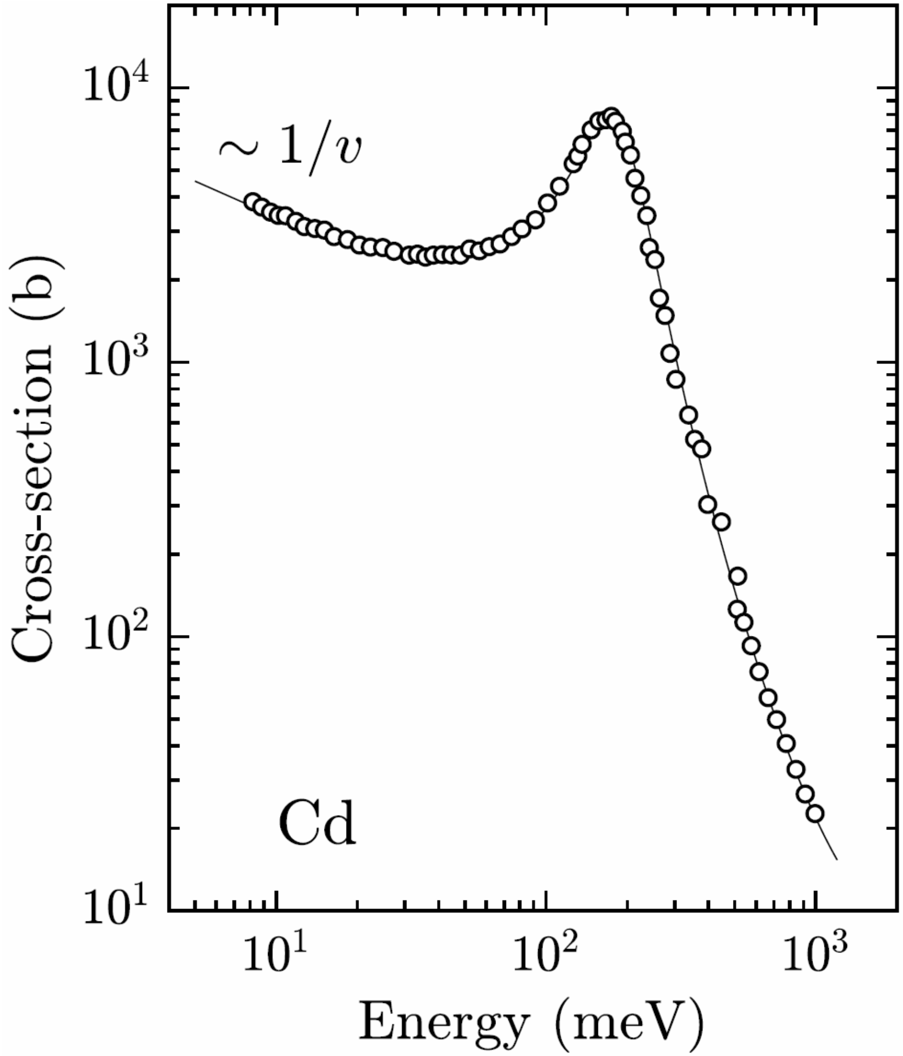
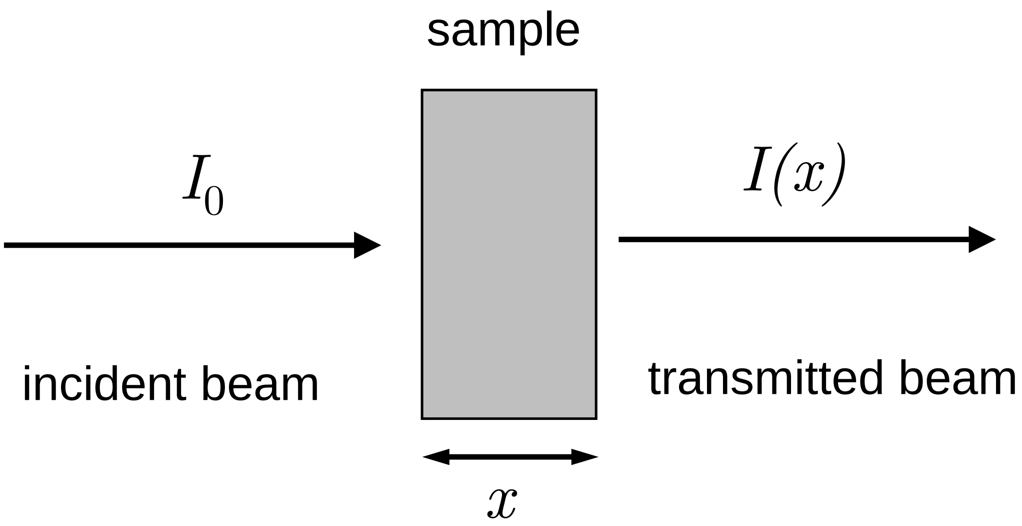


Image credit: Boothroyd (2020)

neutron transmission



sample

I_0

$I(x)$

incident beam

transmitted beam

x

- Beer-Lambert law:

$$I(x) = I_0 \underbrace{\exp(-n\sigma x)}_{\text{transmission}}$$

$n =$ number density

$\sigma = \sigma_{\mathrm{a}} + \sigma_{\mathrm{s}}$

Comparison with x-rays

neutrons	X-rays
● good for low energies	● good for high energies
● bulk probe: mm to cm	● probes nm to µm
● large samples required	● can measure small samples
● non-destructive	● X-rays can affect sample
● good for light elements	● good for heavy elements
● scattering is isotope-dependent	● scattering depends on atomic number
● can obtain cross-sections quantitatively	● difficult to be quantitative
● theory is accurate and understood	● theory still being developed

Final words

It might well be said that, if the neutron did not exist, it would need to be invented!

(B. N. Brockhouse, 1983)