PAUL SCHERRER INSTITUT

PSI

CCMX
Competence Centre for
Materials Science and Technology

IAEA
International Atomic Energy Agency

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Neutron interaction with matter

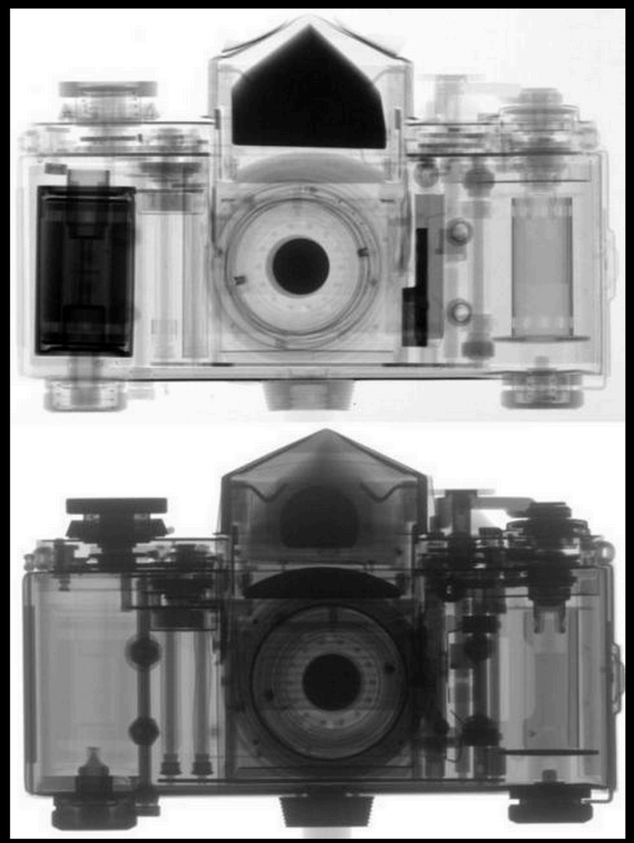
http://goo.gl/eC1P9V

Outline

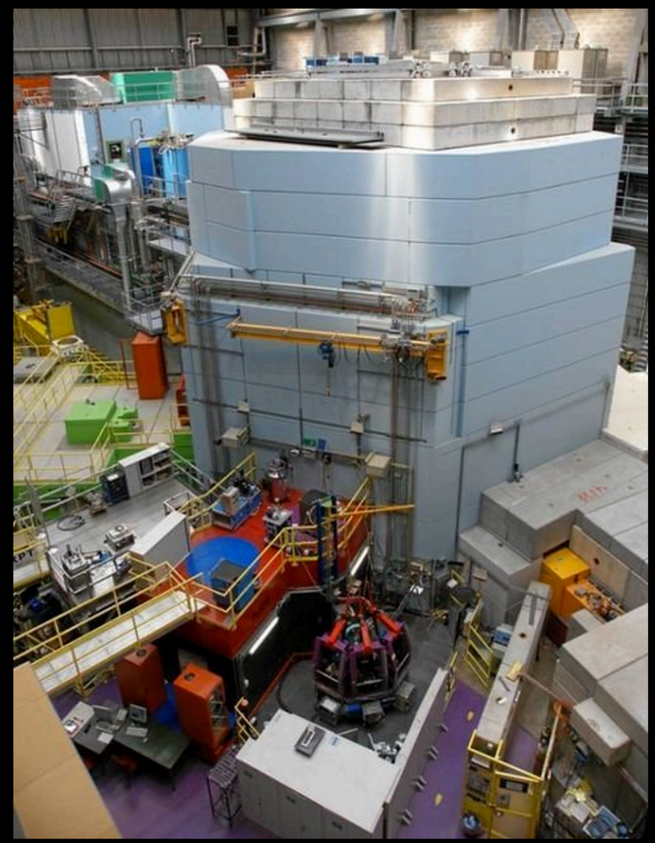
- Introduction
- What are cross-sections?
- Types of absorption and scattering
- Macroscopic cross-sections
- Neutron attenuation
- Energy dependence of cross-sections
- Interactions and their impact on images

WHY DO WE CARE?

Science



Safety

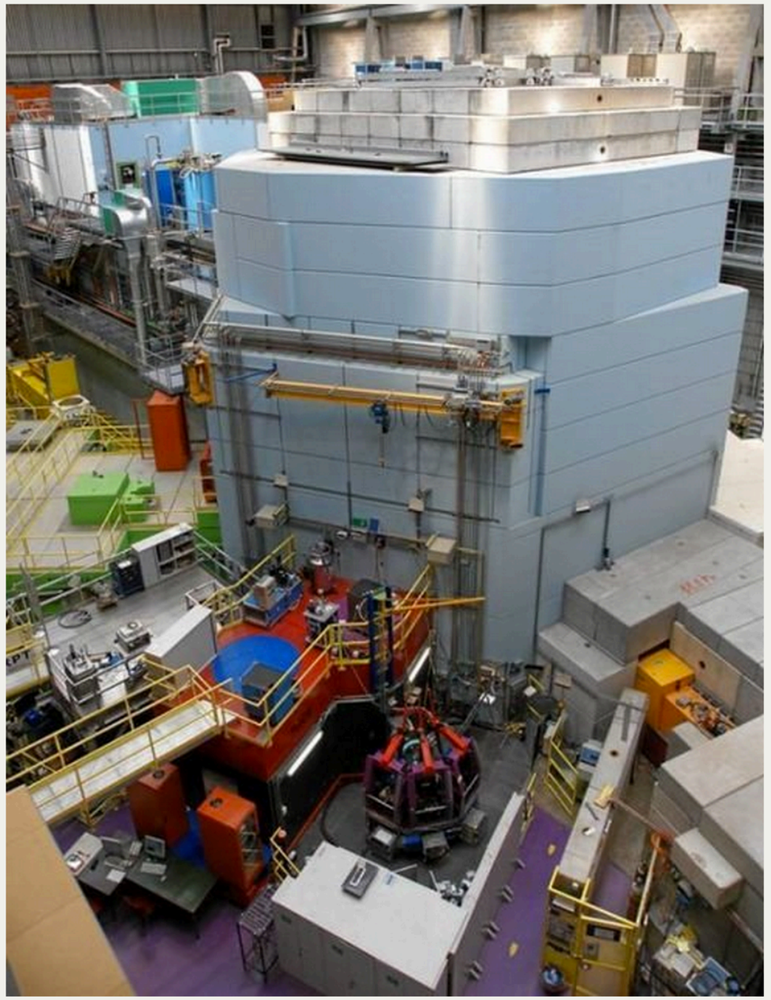


Shielding

Materials, that prevent radiation to leave restricted areas.

Often used:

- Heavy concrete
- Bor plastic



Sample interaction

Different types of interactions can give us a variety of information.

- Absorption
- Scattering

Neutron wavelength - energy correlation

de Broglie equation relates energy to wavelength of massive particles

$$\lambda = \frac{h}{p}$$

Kinetic energy equation combines particle mass and velocity

$$E = \frac{1}{2}mv^2$$

$$\lambda = \frac{h}{\sqrt{2Em}}$$

Cross-sections

$$\sigma = \frac{\#_{interaction}}{flux} = \frac{\#}{\frac{\#}{[m^2]}} = [m^2]$$

$$\sigma = \sigma_s + \sigma_a$$

barn: $10^{-28} m^2$

$$\sigma = \sigma_s + \sigma_a$$

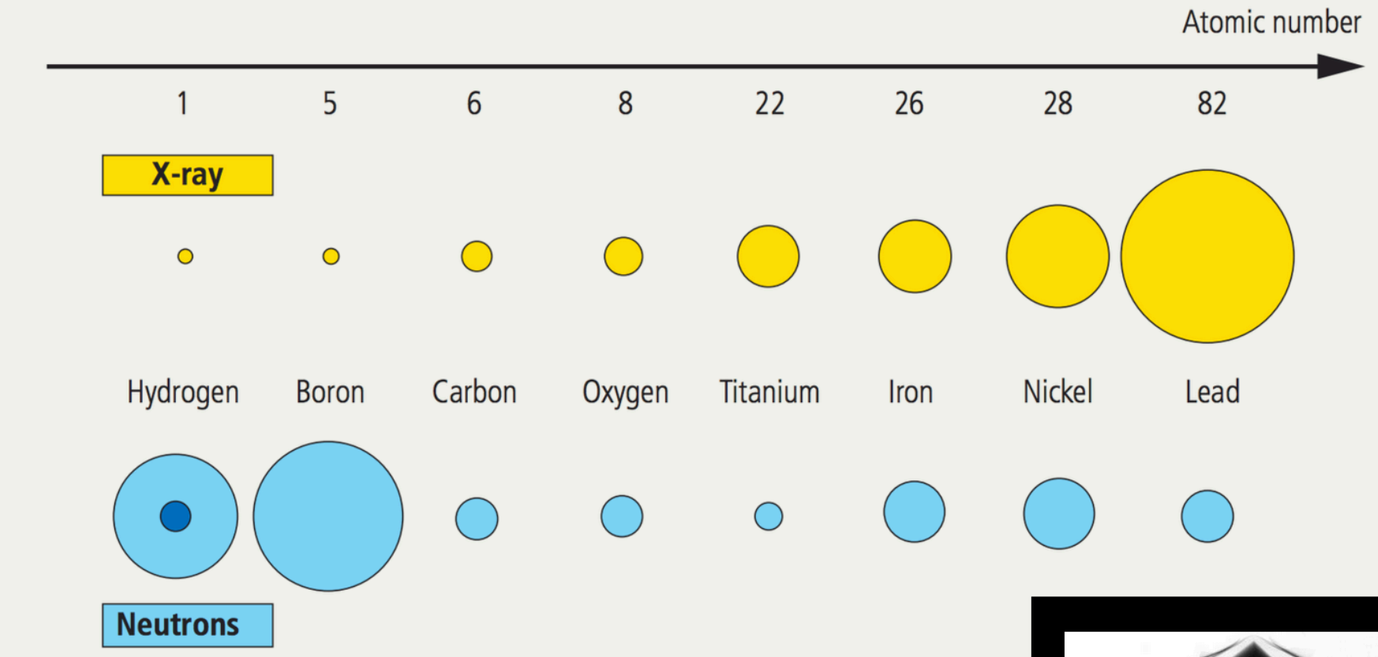
Scattering

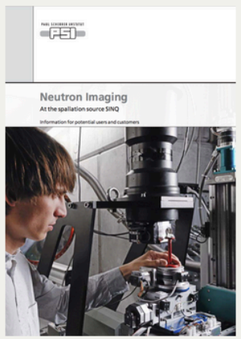
σ_s

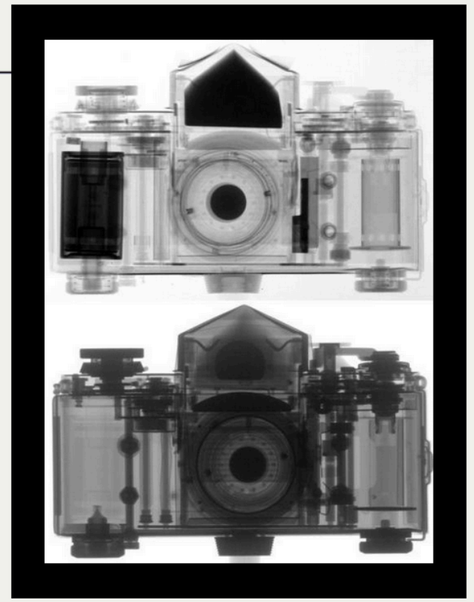
Absorption

σ_a

Elastic	Inelastic	Electromagnetic	Charged
Coherent	Incoherent	Neutral	Fission

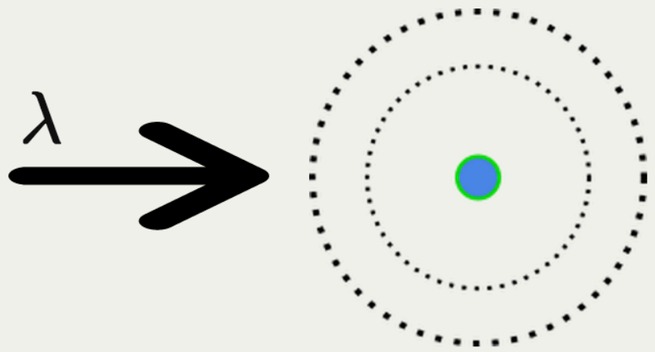

Atomic number
1
5
6
8
22
26
28
82
X-ray
Hydrogen
Boron
Carbon
Oxygen
Titanium
Iron
Nickel
Lead
Neutrons


Neutron Imaging
At the spallation source SINQ
Information for potential users and customers



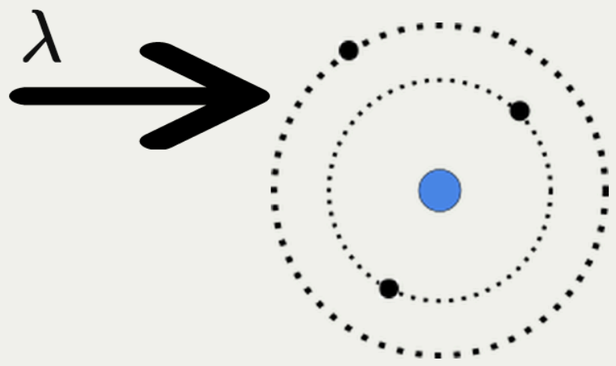
Neutron/X-ray difference

Neutron interaction



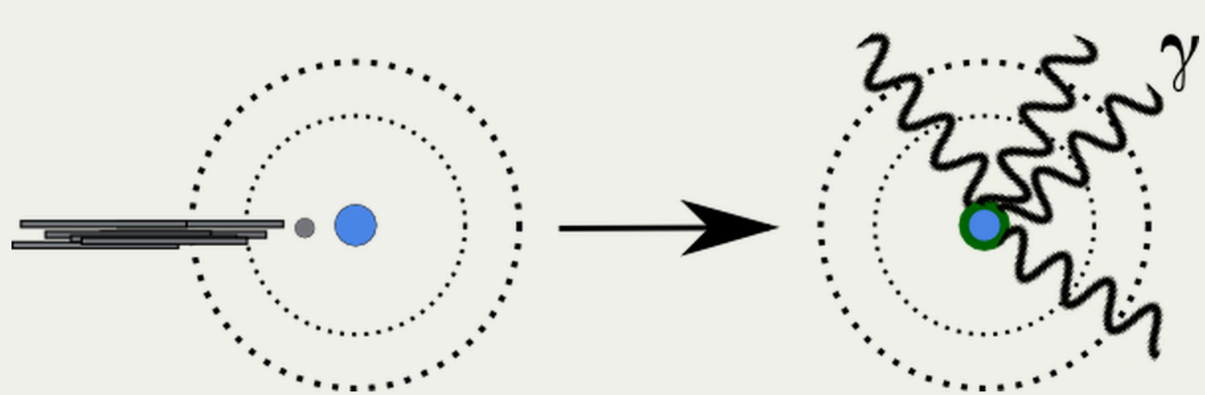
Nucleus interaction

X-ray interaction



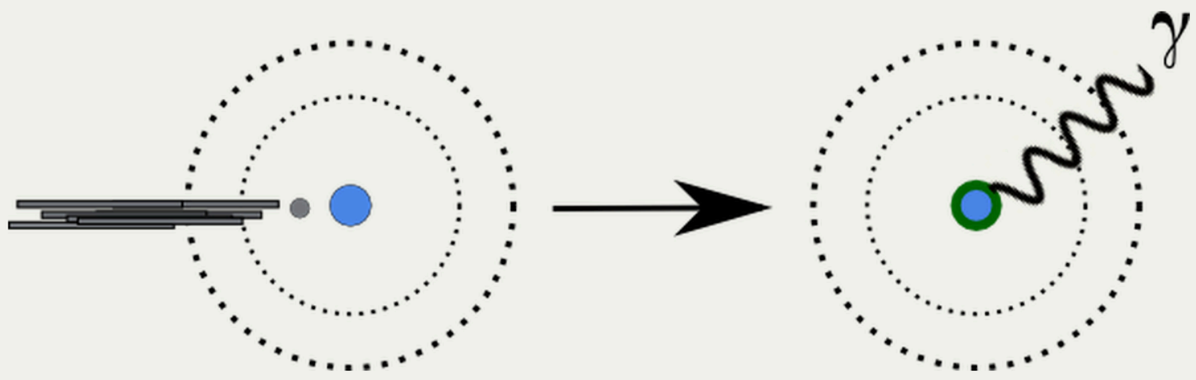
Electron interaction

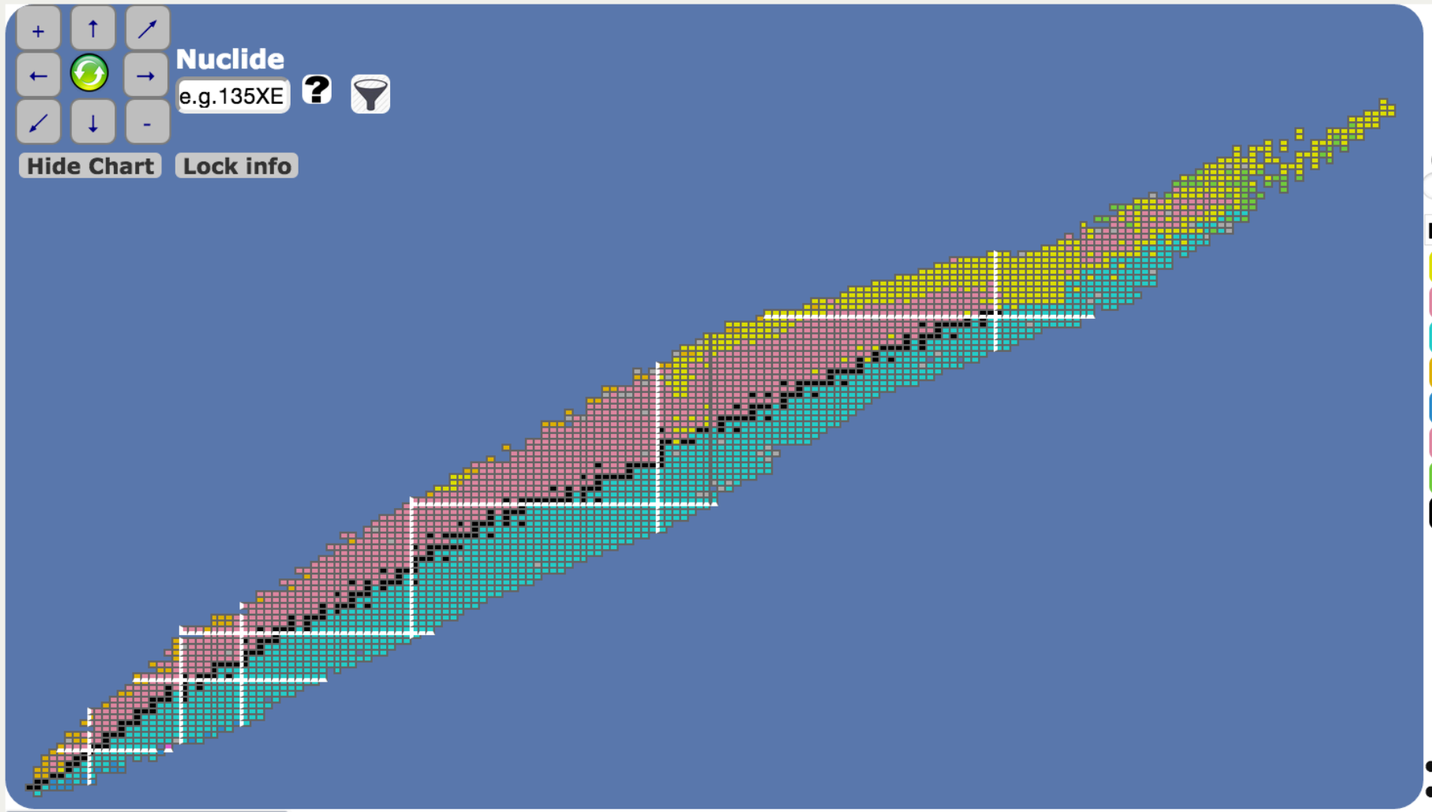
Absorption



Absorption

Electromagnetic	Charged	Neutral	Fission
(n,γ)	(n,p)	(n,2n)	(n,f)
	(n,α)	(n,3n)	
	(n,d)	(n,4n)	
	etc...	etc...	





Live Chart of Nuclides

nuclear structure and decay data ms: *616

email: nds contact point guid

Color zones by ?
value quantile

Main Decay Mode ...

- alpha
- EC+ beta+
- beta-
- p
- n
- EC
- SF
- Stable

Search & Filter on Ground states, Bands, Gammas,

Isotope Browser the ap

Mass chains β and ec decays pl

Neutron Cross Se Resonance Integra

Updated Nuclides since April 2014

- **Click** on a nuclide to fill
- **Double click** to bring it

- **Mouse:** to move the chart **drag.** Use the **wheel** to zoo
- **Numeric keypad:** zoom with **3 and 7**. Use **8, 6, 2, 4,**

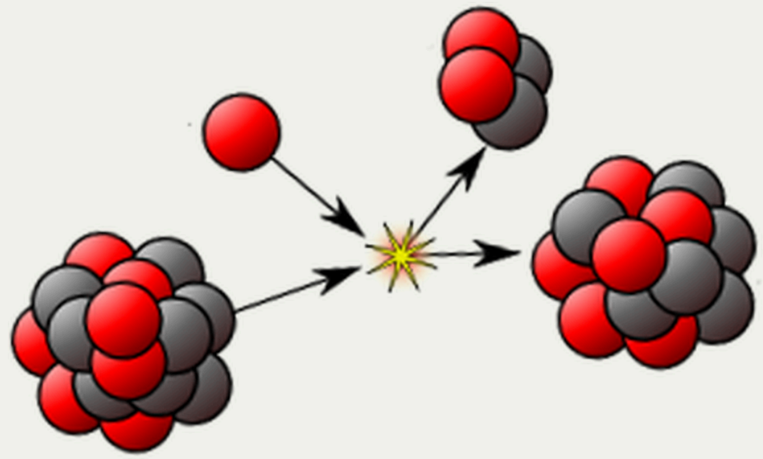
Ground State - Isomers | Levels | Gammas | Bands | Decay Radiation | Nuclear Moments | Ther. Neutrons Capture | Fission Yields | Schema plot

IAEA - Nuclear Data Section
Vienna International Centre, PO Box 100
A-1400 Vienna, Austria
Telephone: (+431) 2600-0

email:**nds.contact-point**

https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Fission (n,f)



Nuclear power source:

$$U^{235} + n \longrightarrow U^{236} \longrightarrow Kr^{92} + Ba^{141} + 3n$$

Neutral (n,2n)

$$H^2 + n \longrightarrow H^1 + 2n$$

Neutron gets kicked out of nucleus.

Can be more than two neutron -> (n,3n), (n,4n),...

Charged

Emitted particles

(n,p)

(n,α)

(n,d)

etc...

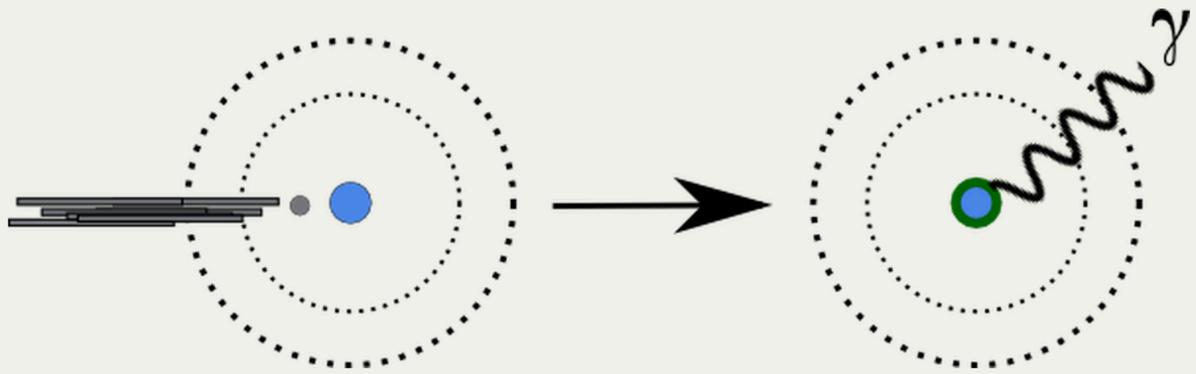
Example

$$N^{14} + n \longrightarrow C^{14} + p$$

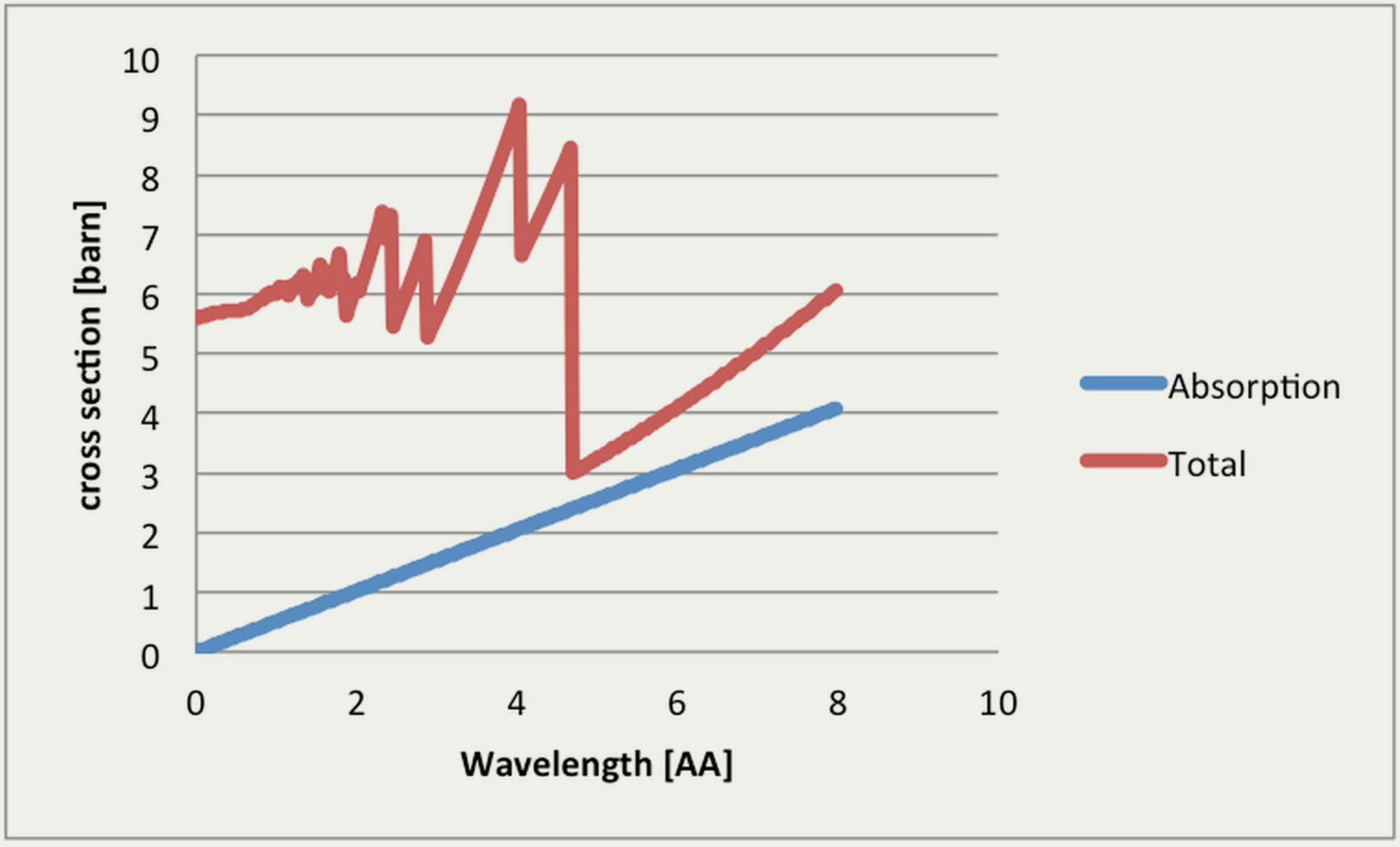
Equilibrium C14 amounts on earth

Usually needs very high energies, with one **exception!**

Electromagnetic (n,γ)

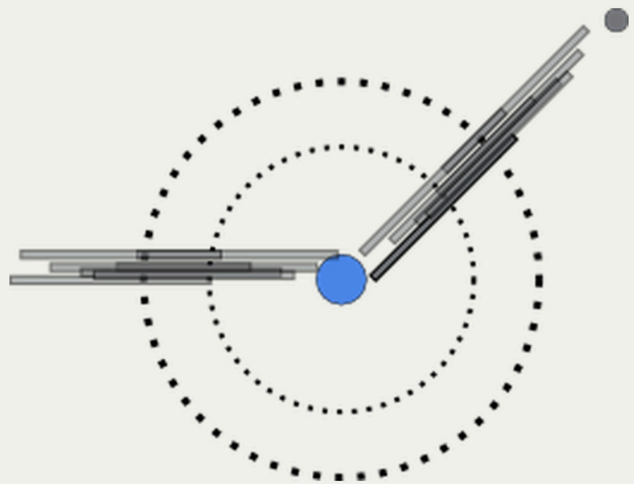


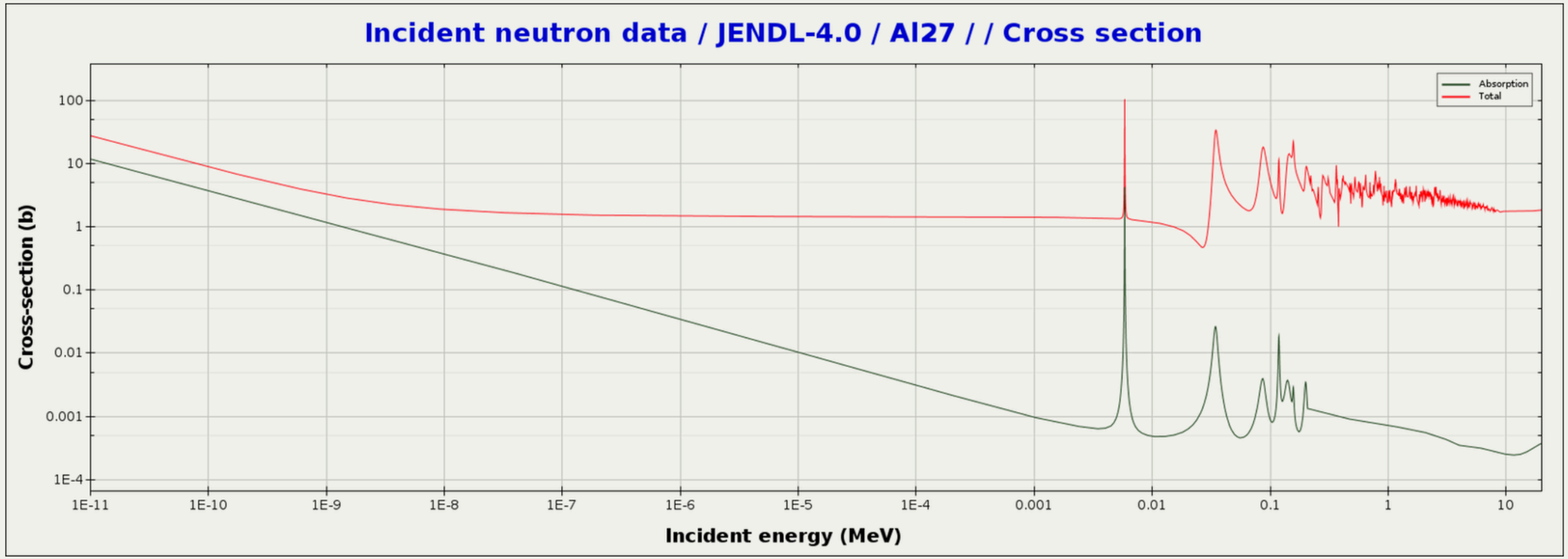
Can lead to image artifacts

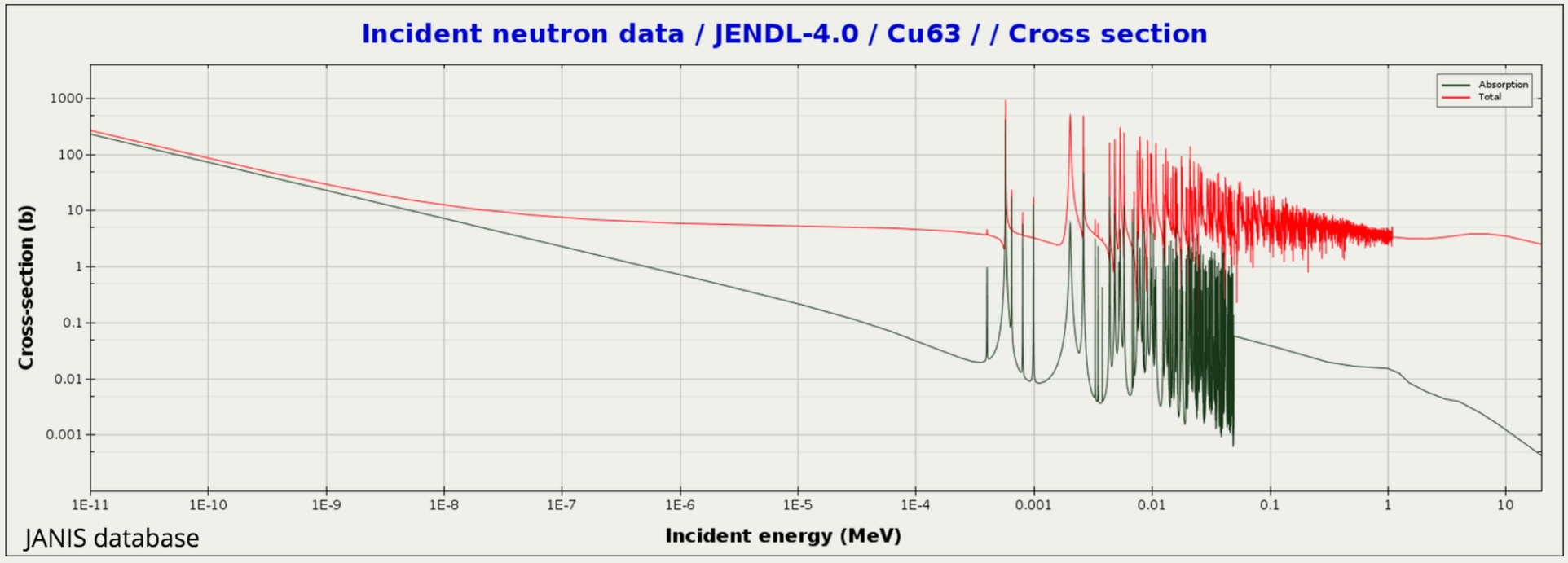

10
9
8
7
6
5
4
3
2
1
0
cross section [barn]
0
2
4
6
8
10
Wavelength [AA]
Absorption
Total

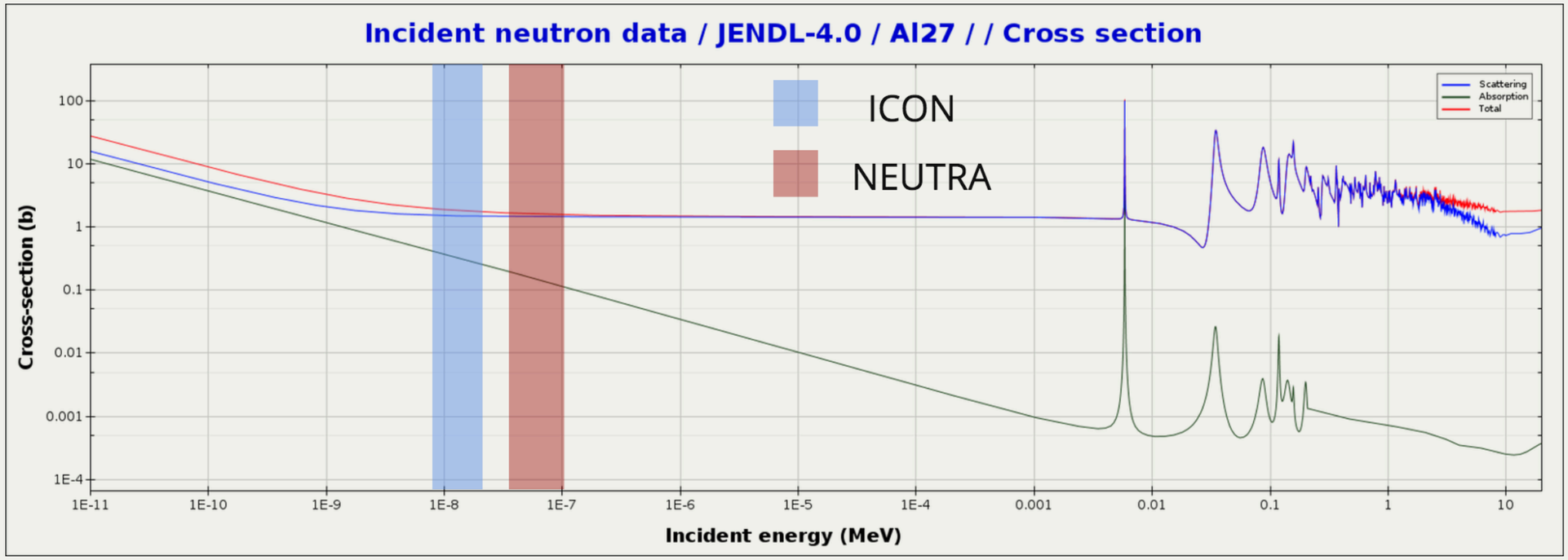
Aluminium

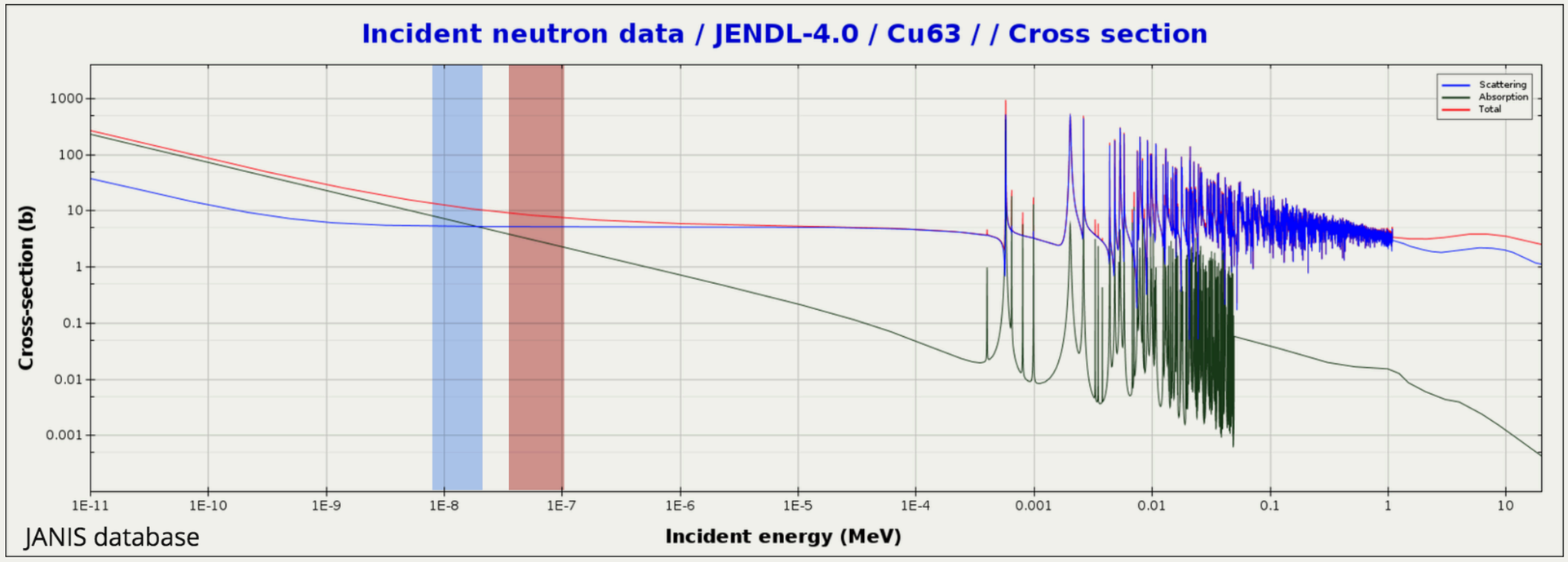
Scattering




Incident neutron data / JENDL-4.0 / Al27 / / Cross section
Absorption
Total
Cross-section (b)
100
10
1
0.1
0.01
0.001
1E-4
1E-11
1E-10
1E-9
1E-8
1E-7
1E-6
1E-5
1E-4
0.001
0.01
0.1
1
10
Incident energy (MeV)


Incident neutron data / JENDL-4.0 / Cu63 / / Cross section
Absorption
Total
Cross-section (b)
1000
100
10
1
0.1
0.01
0.001
1E-11
1E-10
1E-9
1E-8
1E-7
1E-6
1E-5
1E-4
0.001
0.01
0.1
1
10
Incident energy (MeV)
JANIS database


Incident neutron data / JENDL-4.0 / Al27 / / Cross section
ICON
NEUTRA
Scattering
Absorption
Total
Cross-section (b)
100
10
1
0.1
0.01
0.001
1E-4
1E-11
1E-10
1E-9
1E-8
1E-7
1E-6
1E-5
1E-4
0.001
0.01
0.1
1
10
Incident energy (MeV)


Incident neutron data / JENDL-4.0 / Cu63 / / Cross section
Scattering
Absorption
Total
Cross-section (b)
1000
100
10
1
0.1
0.01
0.001
1E-11
1E-10
1E-9
1E-8
1E-7
1E-6
1E-5
1E-4
0.001
0.01
0.1
1
10
Incident energy (MeV)
JANIS database

Scattering

Elastic

(n,n)

Inelastic

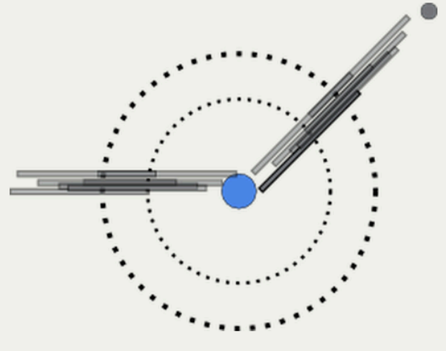
(n,n')

Coherent

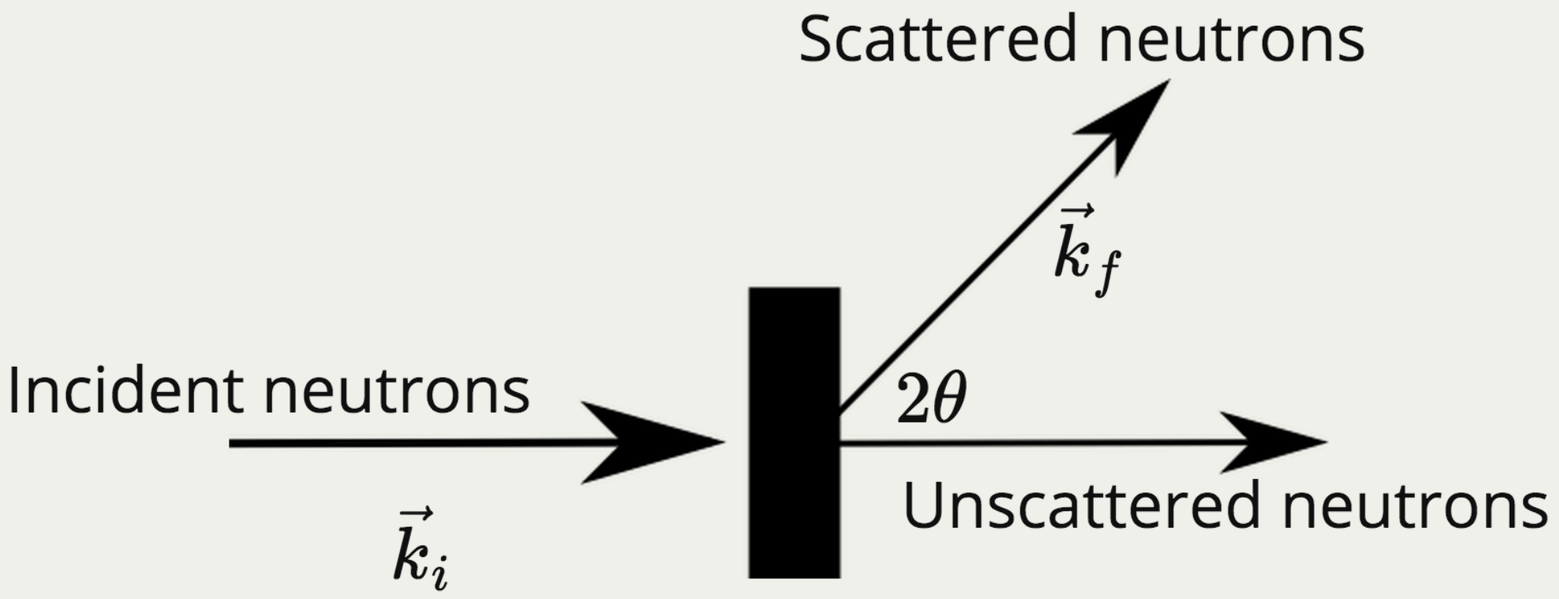
Q-dependent

Incoherent

Uniform in all directions



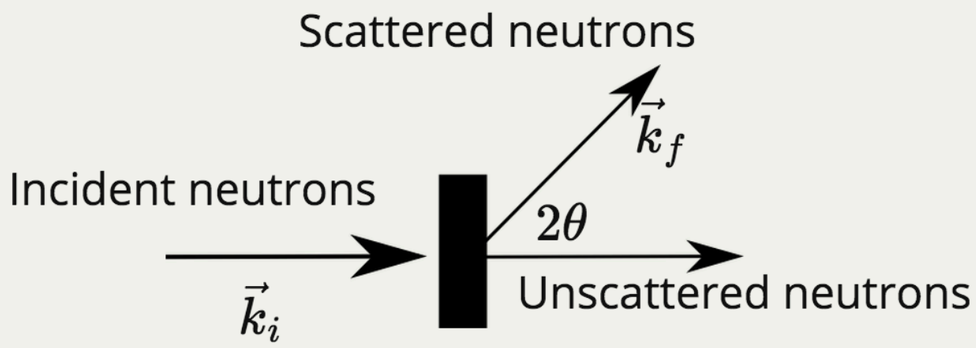
What is the Q-vector?



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

$$|\vec{k}| = \frac{2\pi}{\lambda}$$

Scattering



Inelastic

(n,n')

Elastic

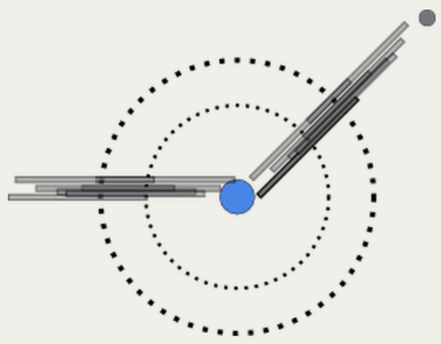
(n,n)

Elastic:

$$|\vec{k_i}| = |\vec{k_f}|$$

Inelastic:

$$|\vec{k_i}| \neq |\vec{k_f}|$$



Coherent and incoherent scattering

Q-dependent coherent scattering

Scattering structures

Nuclear

Magnetic

$$n\lambda = 2dsin(\theta)$$

Bragg's Law

Incoherent scattering

Scattering density

Spin incoherence

Isotopic incoherence

Calculating scattering cross-sections

Scattering length (b)

Is used to calculate cross-section

Spin dependent scattering length

$$b_{coh} = \bar{b} = \sum_r c_r (w_r^+ b_r^+ + w_r^- b_r^-)$$

$$w_r^+ = \frac{I+1}{2I+1} \qquad w_r^- = \frac{I}{2I+1}$$

Coherent scattering cross-section

$$\sigma_{coh} = 4\pi b_{coh}^2 = 4\pi \bar{b}^2$$

Calculating scattering cross-sections

$$b_{coh} = \bar{b} = \sum_r c_r (w_r^+ b_r^+ + w_r^- b_r^-) \qquad \sigma_{coh} = 4\pi b_{coh}^2 = 4\pi \bar{b}^2$$

$$w_r^+ = \frac{I+1}{2I+1} \qquad w_r^- = \frac{I}{2I+1}$$

Example

	spin I	**b+**	**b-**
H	1/2	10.82	-47.4
D	1	9.53	0.98

Calculating scattering cross-sections

Total scattering cross-section

$$\sigma_{tot} = 4\pi \sum_r c_r \{w_r^+ (b_r^+)^2 + w_r^- (b_r^-)^2\} = 4\pi \bar{b^2}$$

Averaging separate cross-sections for each isotope (r) in both spin states.

Coherent scattering cross-section

$$\sigma_{coh} = 4\pi b_{coh}^{\ 2} = 4\pi \bar{b}^2$$

Incoherent scattering

$$\sigma_{incoh} = \sigma_{tot} - \sigma_{coh} = 4\pi(\bar{b^2} - \bar{b}^2)$$

Example molecules

https://www.ncnr.nist.gov/resources/n-lengths/

H20 and D20

Macroscopic cross-sections

Microscopic cross-sections

$$\sigma_{tot} = \sigma_s + \sigma_a$$

Interaction with single particle

In a material

$$\sum_{tot} = \frac{\sigma_{tot}}{V_m}$$

	H_2O	D_2O
	$\Sigma_{coh} = 0.004 \frac{1}{cm}$	$\Sigma_{coh} = 0.513 \frac{1}{cm}$
	$\Sigma_{incoh} = 5.366 \frac{1}{cm}$	$\Sigma_{incoh} = 0.137 \frac{1}{cm}$
	$\Sigma_{abs} = 0.022 \frac{1}{cm}$	$\Sigma_{abs} = 0.000 \frac{1}{cm}$
	$\Sigma_{tot} = 5.392 \frac{1}{cm}$	$\Sigma_{tot} = 0.65 \frac{1}{cm}$

Macroscopic cross-sections

Microscopic cross-sections

$$\sigma_{tot} = \sigma_s + \sigma_a$$

Interaction with single particle

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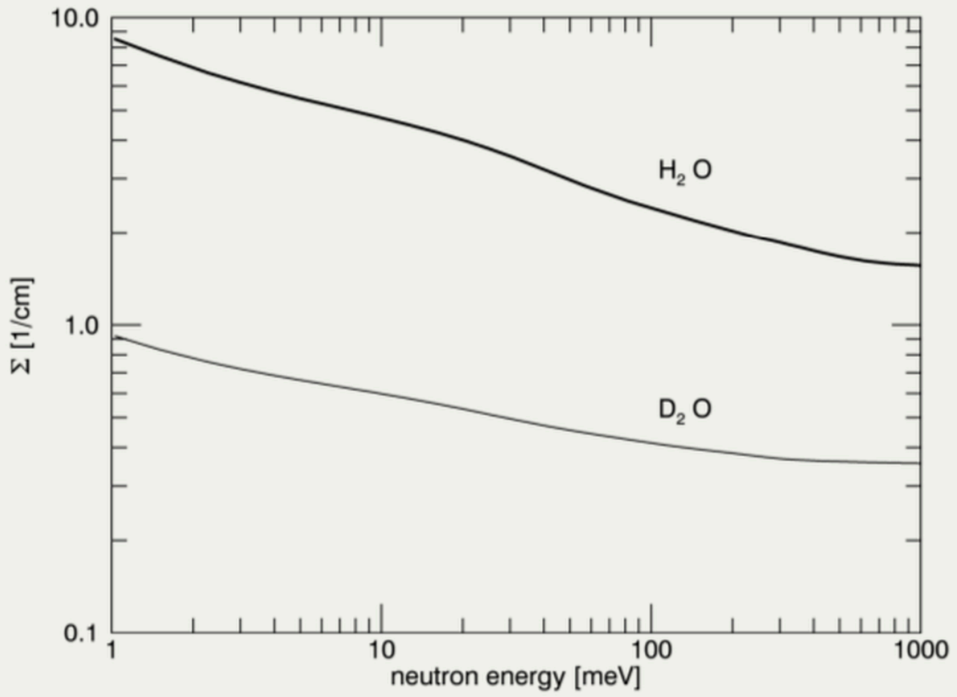
	$\Sigma_{tot} = 5.392 \frac{1}{cm}$	$\Sigma_{tot} = 0.65 \frac{1}{cm}$

Attenuation coefficients

Calculations vs. reality

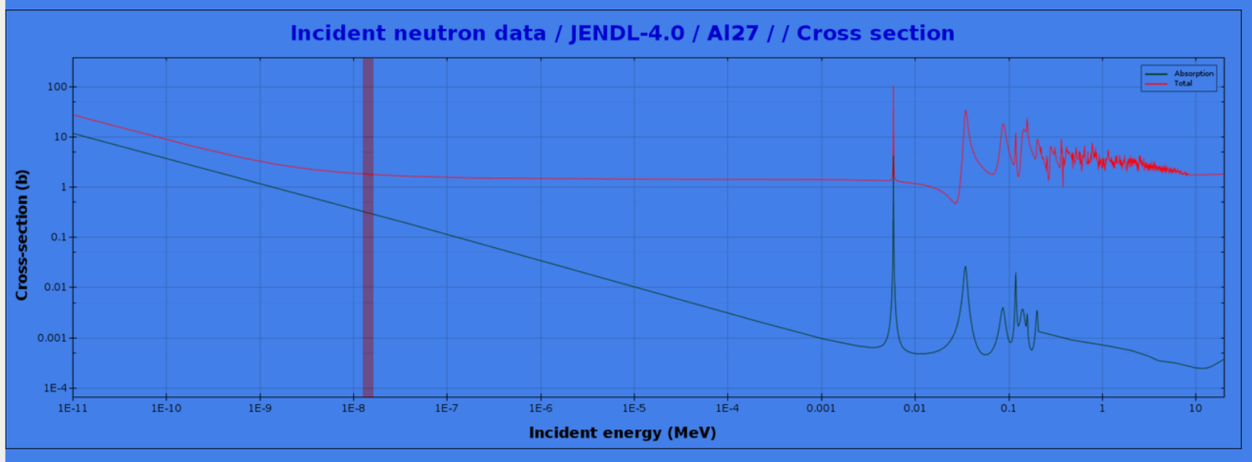
Thermal neutrons	Measured [1/cm]	Calculated [1/cm]
H2O	3.75	5.392
D20	0.51	0.65



Plot of light and heavy water linear attenuation coefficient data based on the MCNP cross section library

Energy dependence of cross-sections

Absorption



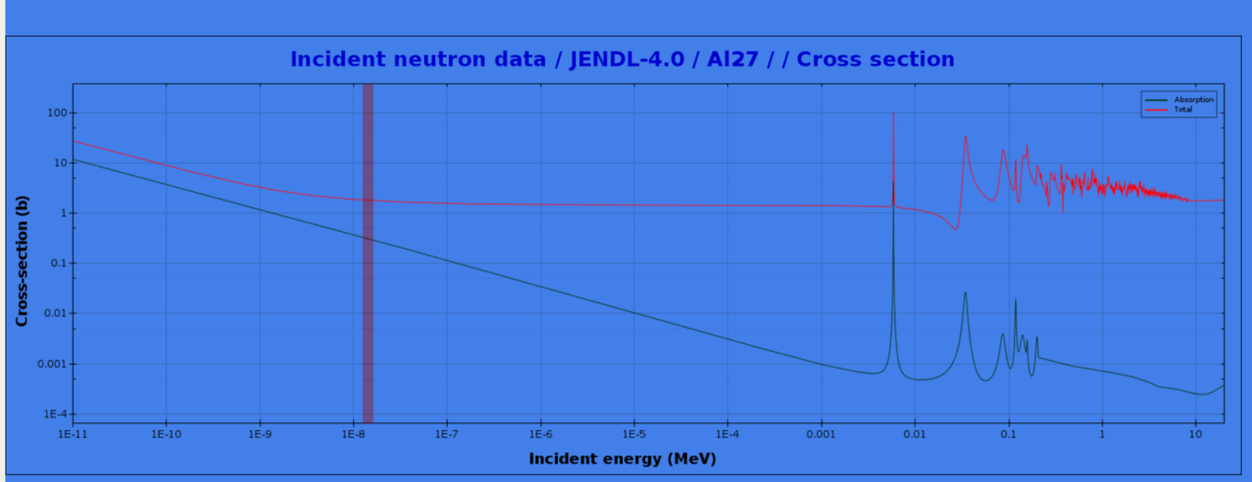
Tabulated value at 1.8 Å:

$$\sigma_{abs} = 0.231b$$

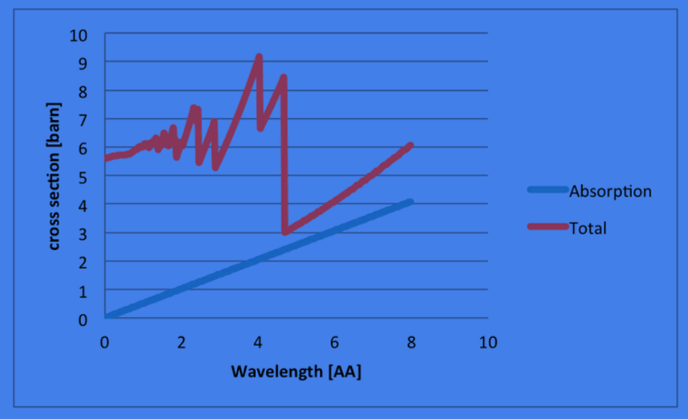
$$\sigma_{abs}(\lambda) = \sigma_{abs}^{tab} \cdot \frac{\lambda}{1.8A}$$

Energy dependence of cross-sections

Scattering



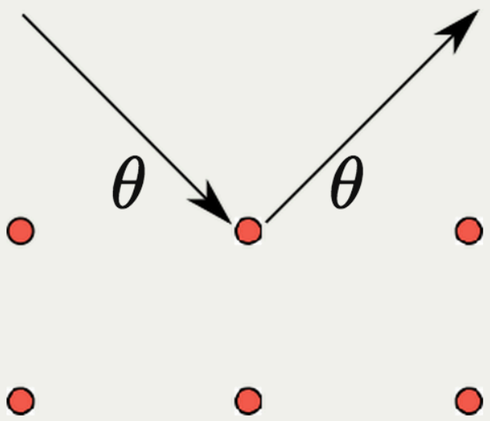
If we had isolated nuclei.



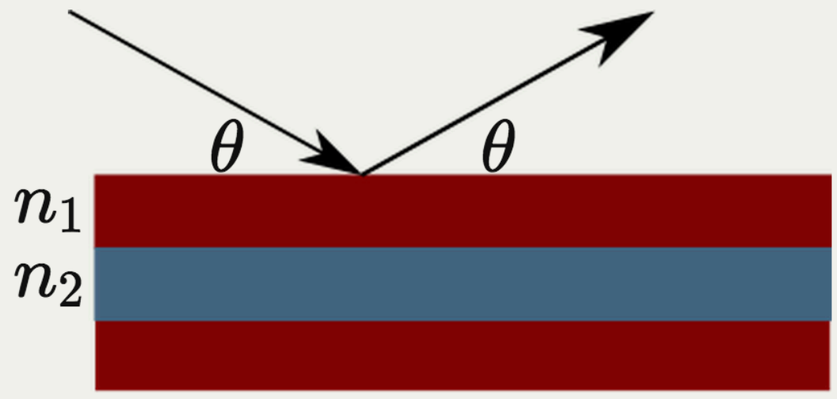
Don't forget Bragg scattering!

Scattering from structures

Crystal

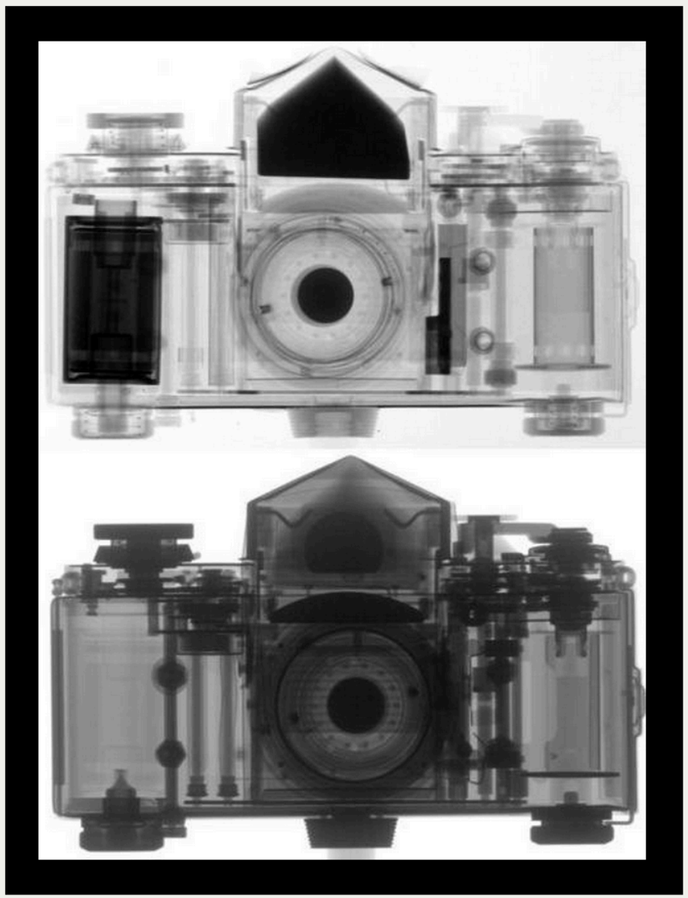


Layers



$$n\lambda = 2dsin(\theta)$$

Interactions and their impact on images

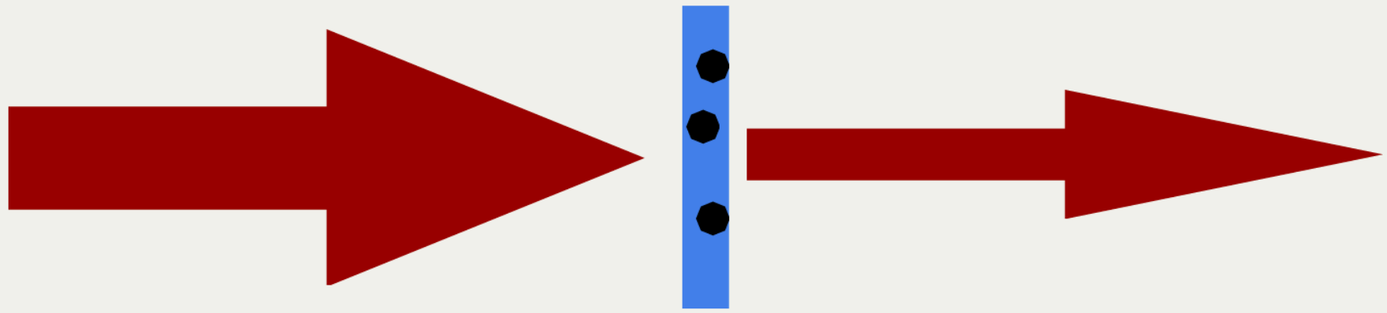


Attenuation coefficient is probed.

Beer-Lambert Law:

$$I = I_0 \cdot e^{-\Sigma t}$$

What does that mean?



2cm

H_2O

$$\Sigma_{tot} = 5.392 \frac{1}{cm}$$

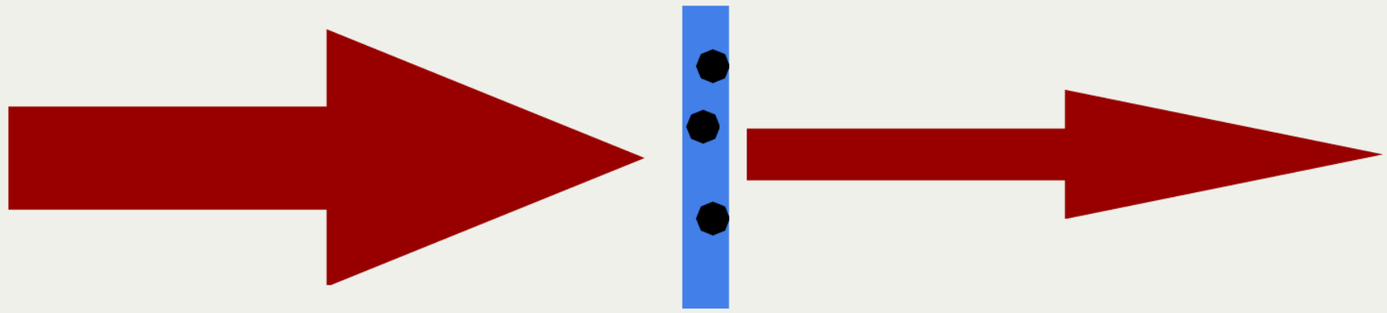
D_2O

$$\Sigma_{tot} = 0.65 \frac{1}{cm}$$

$$I = I_0 \cdot e^{-\Sigma_{tot} \cdot t}$$

$I = 0.0000207 \cdot I_0$	$I = 0.273 \cdot I_0$
0.002% transmission	27.3% transmission

Mean free path



2cm

H_2O

$$\Sigma_{tot} = 5.392 \frac{1}{cm}$$

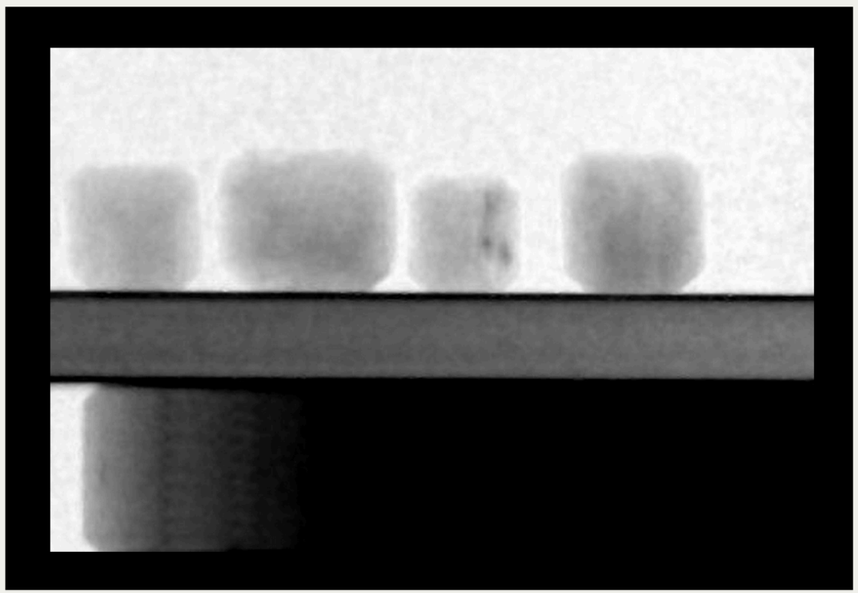
D_2O

$$\Sigma_{tot} = 0.65 \frac{1}{cm}$$

$$P = \frac{1}{\Sigma_{tot}}$$

$P = 0.185cm$	$P = 1.538cm$
ca. 18 interactions	ca. 1.3 interactions

Interactions and their impact on images

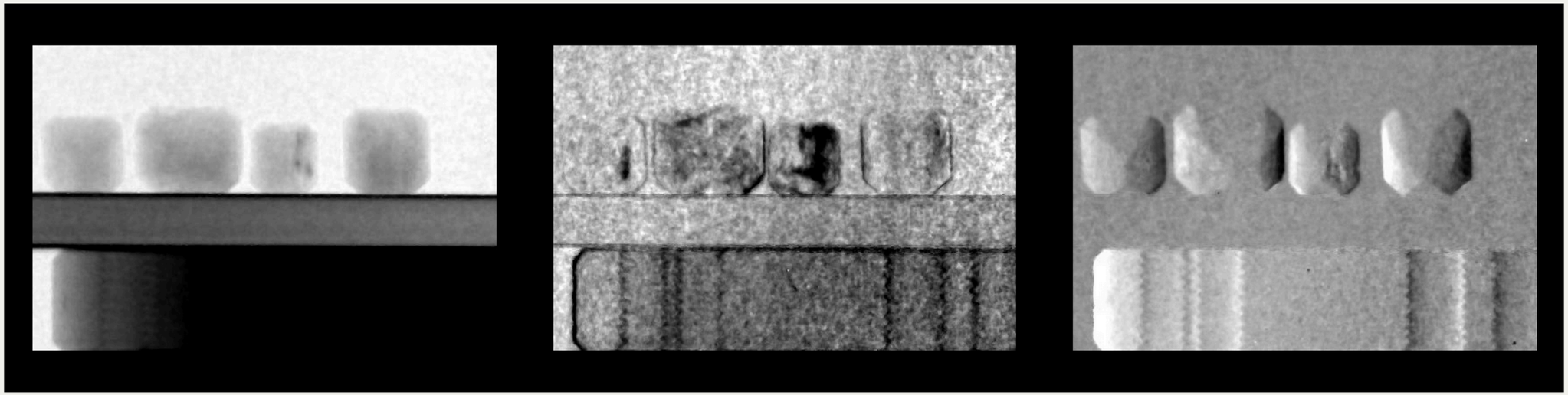


Transmission

Sources of error:

- Inelastic scattering
- Gamma spots
- Sample thickness

Interactions and their impact on images



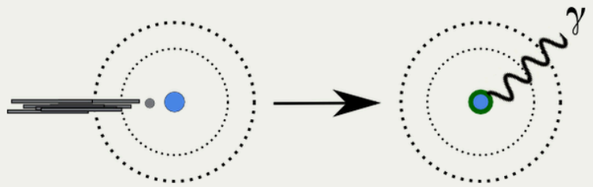
Transmission

Dark-field

Phase change

Things to remember

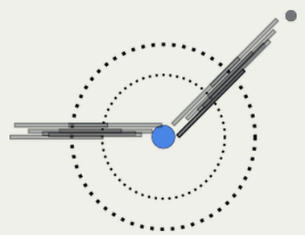
Absorption



Attenuation

$$I = I_0 \cdot e^{-\Sigma_{tot} \cdot t}$$

Scattering



Activation