Chapter V: Interactions of neutrons with matter

Content of the chapter

- Introduction
- Interaction processes
- Interaction cross sections
- Moderation and neutrons path
- For more details → see « Physique des Réacteurs Nucléaires »

Introduction

- Neutrons are neutral particles → no Coulomb interactions as for charged particles
- Neutrons only interact with nuclei via nuclear forces → extremely weak cross sections (compared to cross sections of a proton with same mass for instance) → neutrons are deeply penetrating particles
- Neutrons are not directly ionizing particle → they produce secondary charged particles which are directly ionizing → neutrons are indirectly ionizing particles as photons
- In many applications → neutrons have same formalism as photons
- Remark → neutron has a negative magnetic dipolar momentum → sensitive to intense magnetic fields

Classification of neutrons

- High energy neutrons: E > 20 MeV
- Fast neutrons: 10 keV < E < 1 MeV
- Epithermal neutrons: 1 eV < E < 10 keV
- Slow neutrons: 0.025 eV < *E* < 1 eV
- Thermal neutrons E ≈ 0.025 eV (most probable energy at a temperature of 290 K after moderation)
- Cold neutrons: E < 0.025 eV

Attention: Different classifications exist !

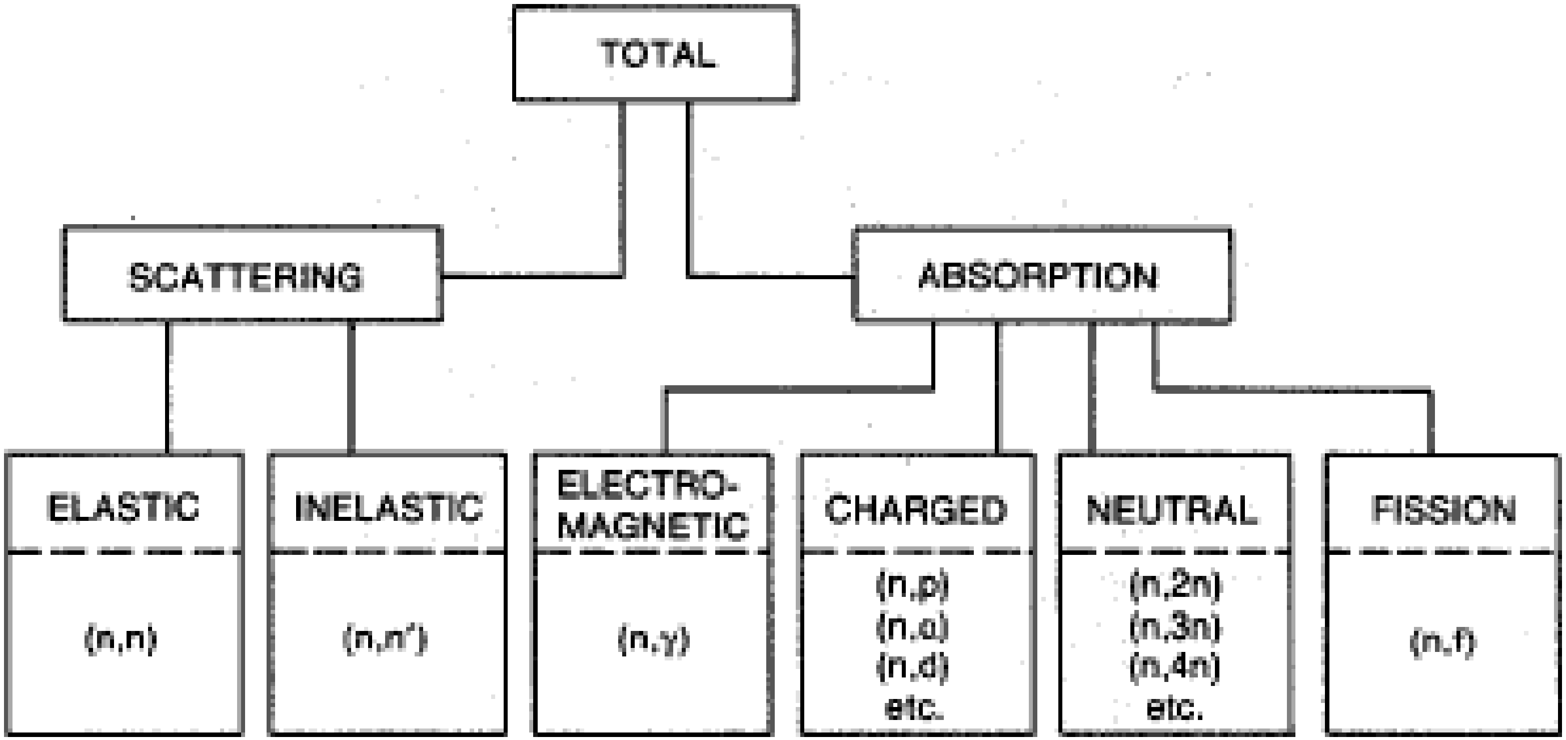
Remarks on this classification (1)

- For high energy neutrons → it is necessary to individually consider the collisions with the nucleons of the nuclei → use of (measured) nucleon-nucleon cross sections
- However → interferences between nucleons exist → they affect the nucleon-nucleon interactions → necessary corrections for the nucleon-nucleon cross sections
- The incident neutron can put into motion a nucleon of the nucleus → this nucleon can also interact with another nucleon of the nucleus and so on… → intranuclear cascade → complex model

Remarks on this classification (2)

- Fast neutrons → neutrons sources always produce neutrons with energy of about 1MeV or more (in particular fission reactions)
- Epithermal neutrons → in this energy range interaction cross sections vary very quickly and often show resonances
- Thermal neutrons → neutrons (regardless of their origin) slow down in matter → thermalization → thermal neutrons are in thermic equilibrium with their background at ≈ 20 °C → mean energy close to 0.025 eV ($E = kT$ with k the Boltzmann constant)

Neutron interactions



2 principal interaction modes:

1. Scattering: Modification of the energy and of the trajectory of the neutron but the nucleus keeps an equal number of protons and neutrons
2. Absorption: Modification of the target nucleus → radiation emission

Elastic scattering (n,n) (1)

- During an elastic scattering → total kinetic energy of neutron and nucleus is not modified
- The target nucleus of mass m_2 initially at rest receive from the neutron (mass m_n and kinetic energy E) a kinetic energy T_c in the rage $[0,T_{max}]$ →

$$T_{max} = \frac{4m_n m_2}{(m_n + m_2)^2} E$$

- One neutron can give all its kinetic energy to one hydrogen atom → the elastic scattering is an efficient process to slow down neutrons if $m_2 \approx m_n$

Elastic scattering (n,n) (2)

- By conservation of energy and momentum → we obtain equation between transferred energy by the neutron to the nucleus as a function of the recoil angle of the nucleus θ_r →

$$T_c = \frac{4m_n m_2}{(m_n + m_2)^2} E \cos^2 \theta_r$$

- That is generally written →

$$T_c = \frac{4\alpha}{(\alpha + 1)^2} E \cos^2 \theta_r$$

with $\alpha = m_2/m_n$

- To know the mean energy transferred by the neutron → it is necessary to determine the angle-differential cross section

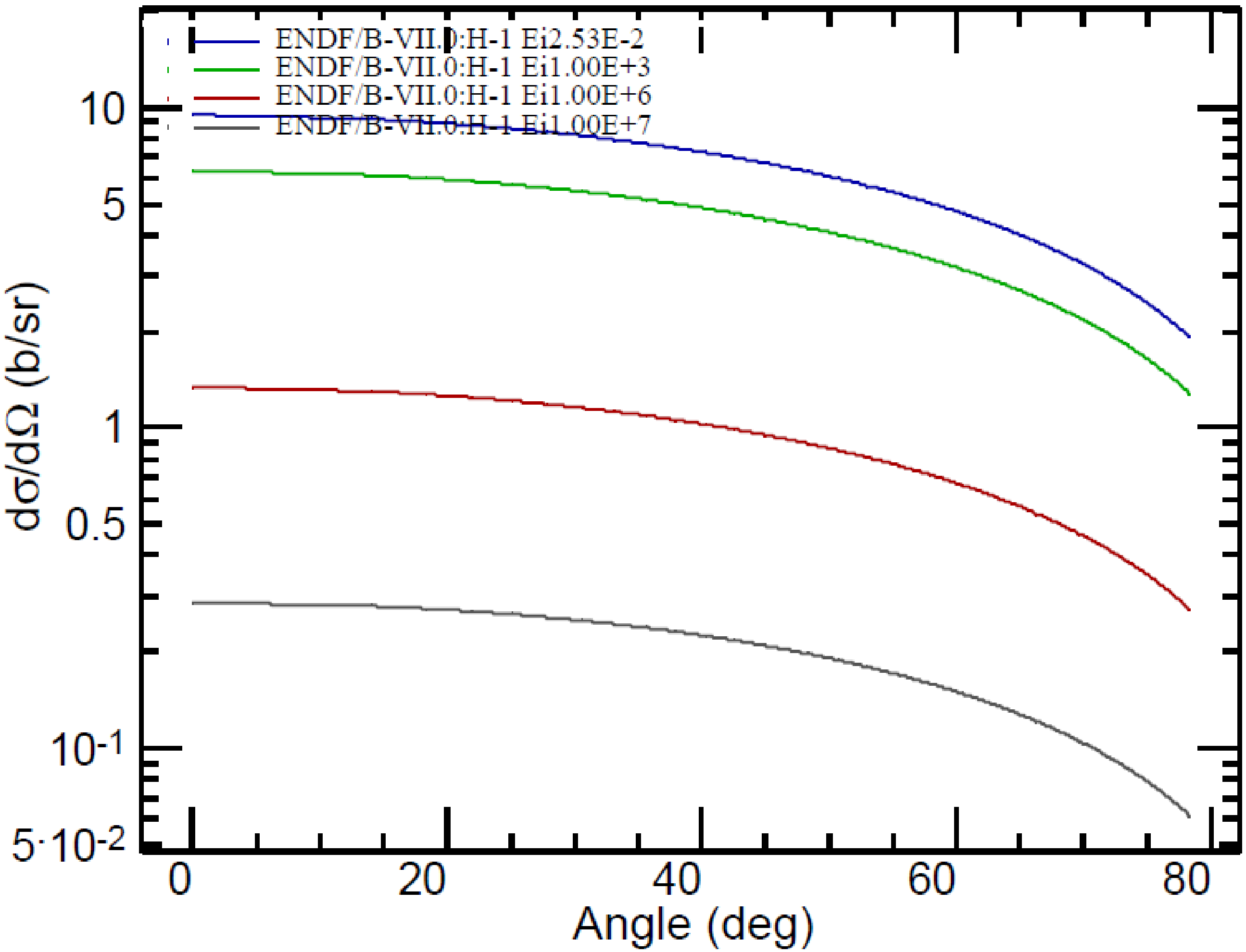
Elastic scattering (n,n) (3)

- Theory consider 2 types of elastic scattering →

1. Direct interaction between neutron and nucleus → For weak energies this cross section tends towards $4\pi R^2$ with R is the nucleus radius → typically ≈ *1* barn
2. The scattering in two steps → first creation of a composed nucleus in an excited state then emission of one neutron to find back the initial nucleus → the energy-differential cross section for this process has resonances because the composed nucleus has only precisely defined states (weak nuclei → well separated states → well separated resonances – heavy nuclei → high density of states → resonances superposition → continuous variation of the cross section)

- These two processes interfere → the total elastic scattering cross section is not simply the addition of the 2 cross sections
- For $\alpha = 1$ → the angular distribution varies as $\cos\theta_r$ (for $\alpha \neq 1$ → more complicated)

Angular distribution θ_n



For α = 1 → the angular distribution of θ_n is = to the angular distribution of θ_r

Elastic scattering (n,n) (4)

- Thus we have $\langle T_c \rangle \propto \langle cos^2\theta_r \rangle = 1/2$ → the mean value of the transferred energy →

$$\langle T_c \rangle = \frac{2\alpha}{(\alpha+1)^2} E$$

- For hydrogen → $\alpha = 1$ → $\langle T_c \rangle = E/2$
- In a general way → the neutron energy $E'^{(n)}$ after n elastic scattering →

$$\langle E'^{(n)} \rangle = \left[\frac{(\alpha^2+1)}{(\alpha+1)^2} \right]^n E$$

Elastic scattering (n,n) (5)

- To reach an energy $E'^{(n)}$ from an initial energy E → the neutron has to undergo on average n elastic scattering with

$$n = \frac{\log\left(E'^{(n)}/E\right)}{\log\left[(A^2+1)/(A+1)^2\right]}$$

- Example: For 2 MeV neutrons interacting with hydrogen → 27 collisions to be thermalized (mean value)

Element	Atomic Weight	Number of Collisions
Hydrogen	1	27
Deuterium	2	31
Helium	4	48
Beryllium	9	92
Carbon	12	119
Uranium	238	2175

Elastic scattering (n,n) (6)

- After an elastic scattering with fast neutron → the nucleus is displaced → if it has enough kinetic energy → it can displace other nuclei → cascade of atomic displacements
- Generally → the cascade is localized in a volume with radius ≈ 100 Å
- The atoms are displaced up to the energy transferred during the collision is larger than a characteristic energy called displacement threshold (energy necessary to break the bonds and move the atom far from its site in such a way it is no more sensitive to its attractive potential)
- Displacement threshold ≈ 25 eV

Inelastic scattering (n,n') (1)

- During an inelastic scattering → the recoil nucleus is elevated to one of its excited states → the neutron loses a part of its kinetic energy which is transformed into kinetic and potential energy of the target atom
- There is always formation of the intermediate state of a composed nucleus and then neutron emission to finally obtain the initial nucleus in an excited state
- Generally → the excited nucleus gets to its fundamental state by emission of one or more γ
- The inelastic cross section has resonances which correspond to the different energy states of the composed nucleus

Inelastic scattering (n,n') (2)

- Inelastic collisions can happen if the kinetic energy of the neutron exceeds a threshold energy T_t (with E_{exc} the excitation energy of the nucleus) →

$$T_t = \frac{m_n + m_2}{m_2} E_{exc}$$

- For ^{12}C → the first excited state is such as E_{exc} = 4.43 MeV → the neutron must have a kinetic energy > à 4.81 MeV
- The energy lost in a inelastic collision is greater than in an elastic collision

Absorption

After an absorption, a secondary radiation will be emitted → this radiation can then be generally detected. This secondary radiation can be:

- a γ ray (electromagnetic or radiative absorption) → (n,γ)
- a charged particle (p, α) → (n,p) or (n,α)
- neutrons → (n,2n), (n,3n),… (if 1 → equivalent to elastic scattering → sometimes considered as elastic scattering but presence of resonances)
- products of fission → (n,f)

Electromagnetic absorption

- Reaction (n,γ) → the neutron is absorbed by the nucleus → formation of an excited nucleus that emits one (or more) γ

- The radiative absorption dominates for small energies

- Its cross section shows resonances for particular energies

Absorption + emission of charged particles

- Principally reactions such as (n,p) or (n,α)

- The reactions dominate for fast neutrons because they are often endoenergetic → moreover the transferred energy to the charges particle in the nucleus has to be important enough to allow the crossing of the wall potential of the nucleus

- For a few number of light nucleus → reactions (n,p) et (n,α) are exoenergetic → can happen for thermal neutrons → examples: ^{3}He(n, p)^{3}H, ^{6}Li(n,α)^{3}H et ^{10}B(n,α)^{7}Li

Absorption + fission

- Fission reaction happens for media with high Z → split of the nucleus → production of heavy fragments + nuclei with large kinetic energy

- For example → fission of ^{235}U → release of ≈ 200 MeV shared between the fission fragments, 2 or 3 neutrons, β particles and photons

- The neutrons emission induces other fission reactions de → nuclear chain reactor → fission reactor

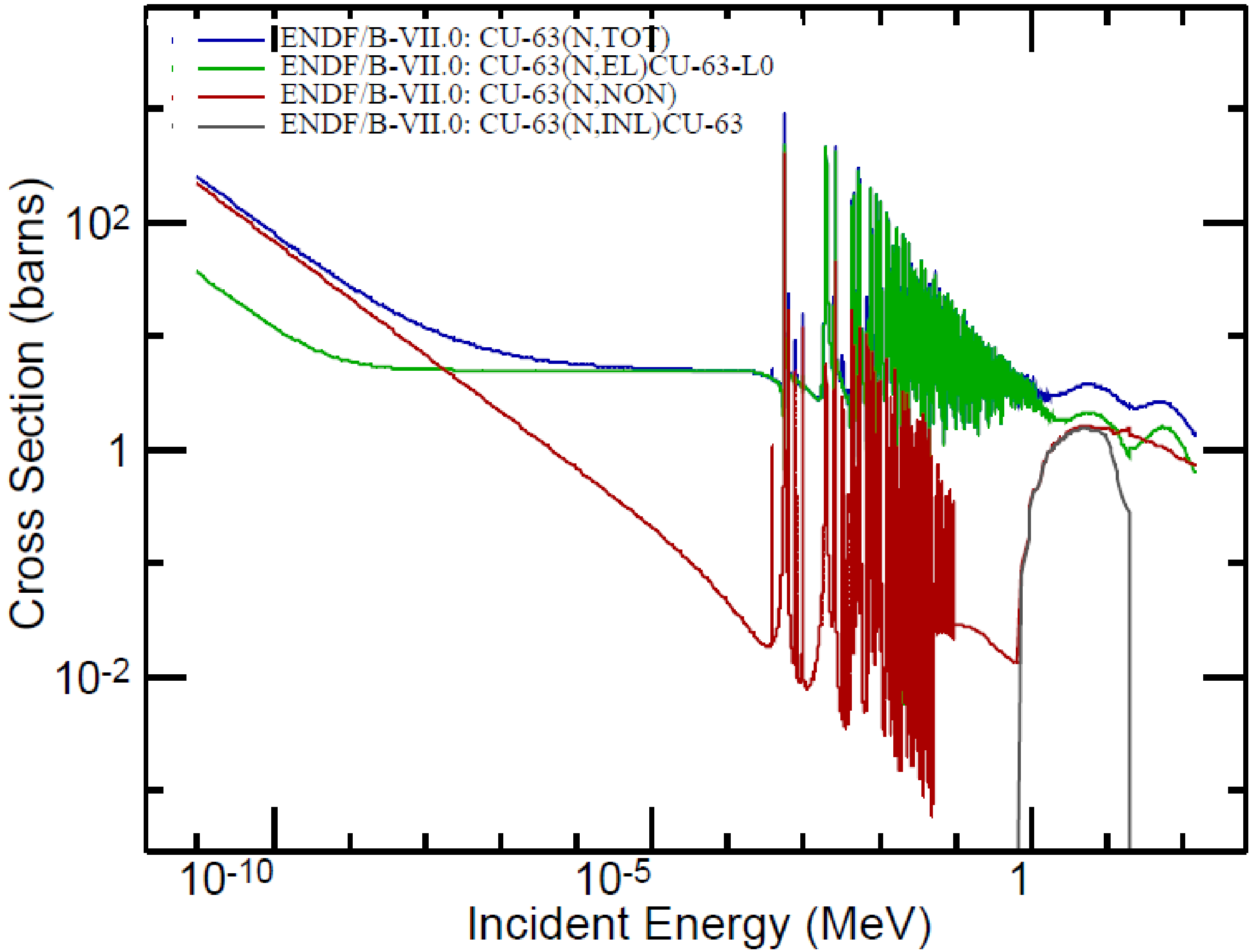
Interaction cross sections (1)

- The total cross section is the sum of the cross sections of ≠ processes
- No « complete » calculations → compilation of theoretical calculations + experimental data
- Strongly depends on the medium → difficult to establish general « rules »
- For media with small Z
  - → elastic diffusion is important for all energies
  - → inelastic diffusion is (potentially) important for fast neutrons
  - → absorption is (potentially) important for thermal neutrons (essentially due to radiative absorption)
- For media with large Z
  - → absorption is completely dominant for thermal neutrons (due to fission reaction)
  - → for large energies → elastic diffusion is important

Interaction cross sections (2)

- In a general way→ total cross section ↘ for neutron energy ↗
- Elastic scattering cross section is ≈ constant (except for very small energies: $E < 10^{-3}$ eV)
- Absorption cross section varies in *1/v* (*v*: neutron velocity)
- total cross section is either constant either varies in *1/v* as a function of the dominant process
- For media with high Z → numerous resonances for fission reaction (dominating sometimes the law in *1/v*)

Cross sections for ^{63}Cu



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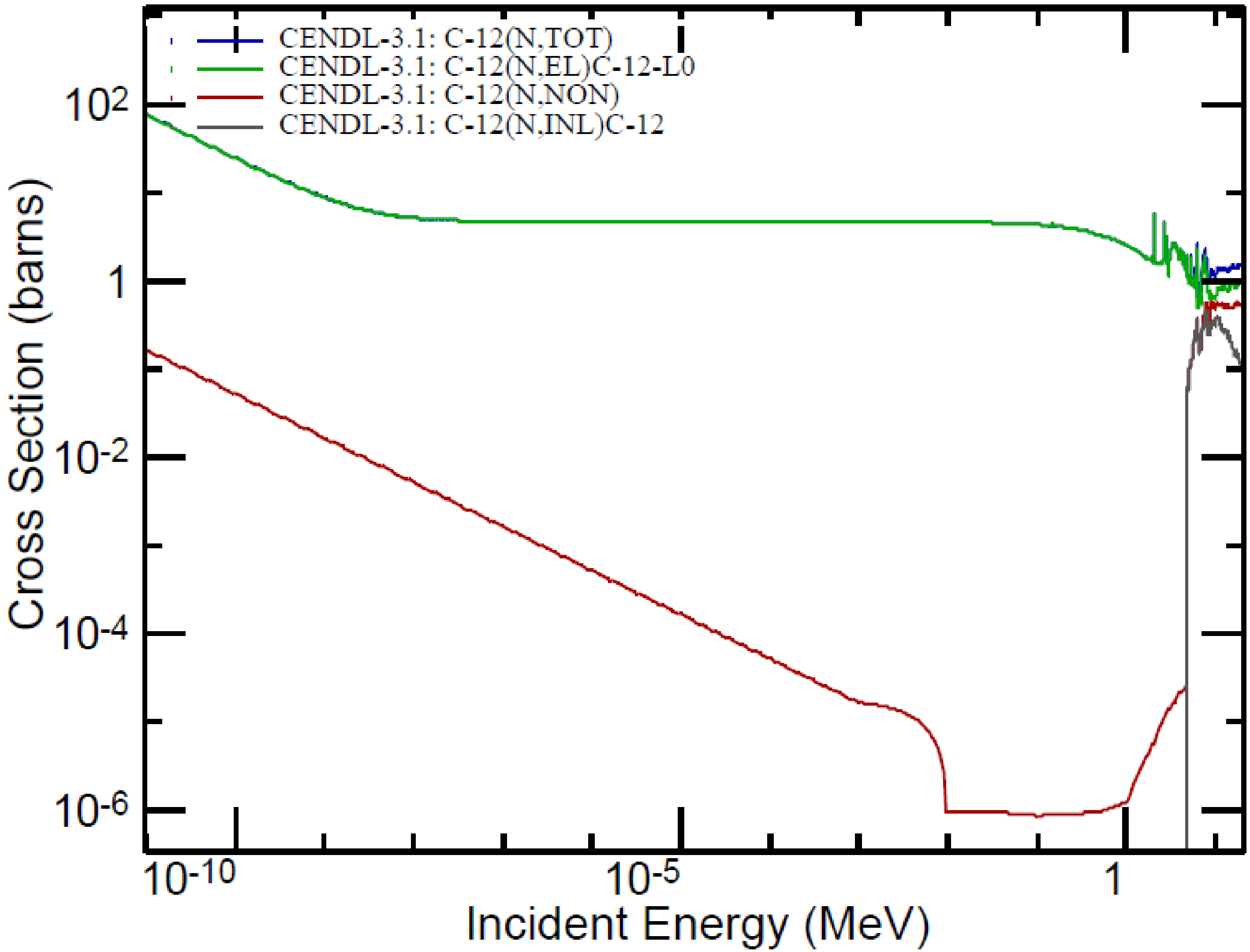
Cross sections for ^{12}C



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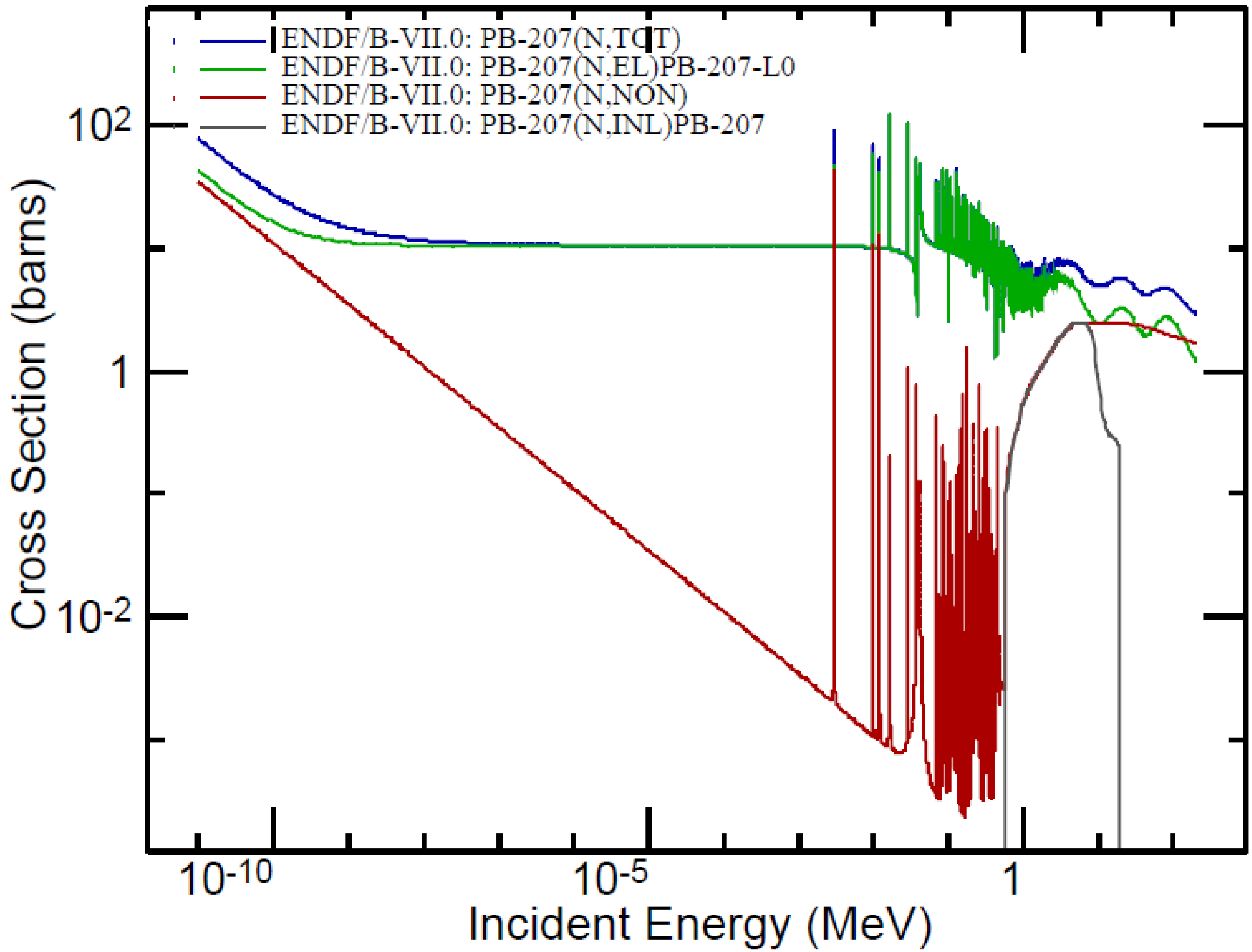
Cross sections for ^{207}Pb



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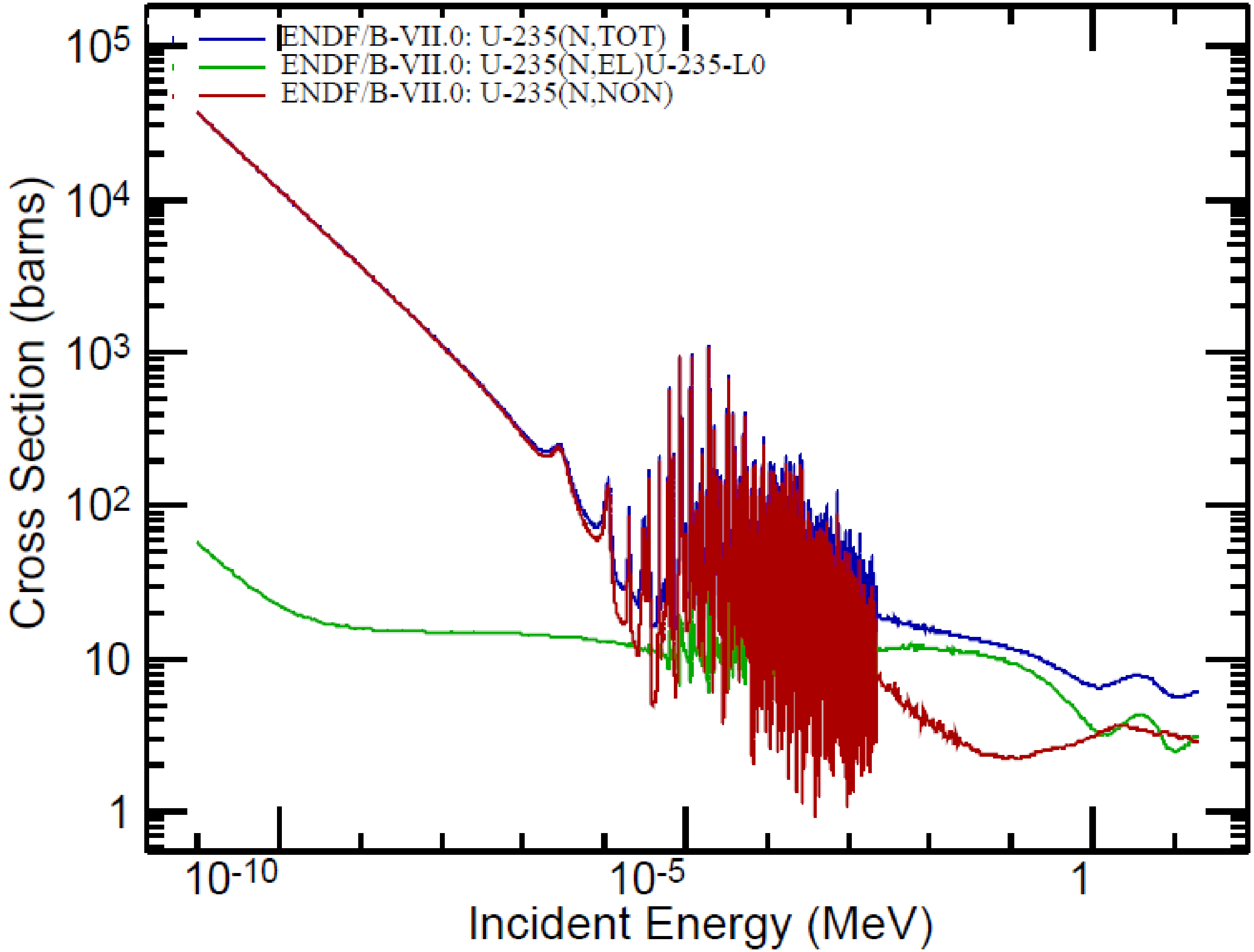
Cross sections for ^{235}U



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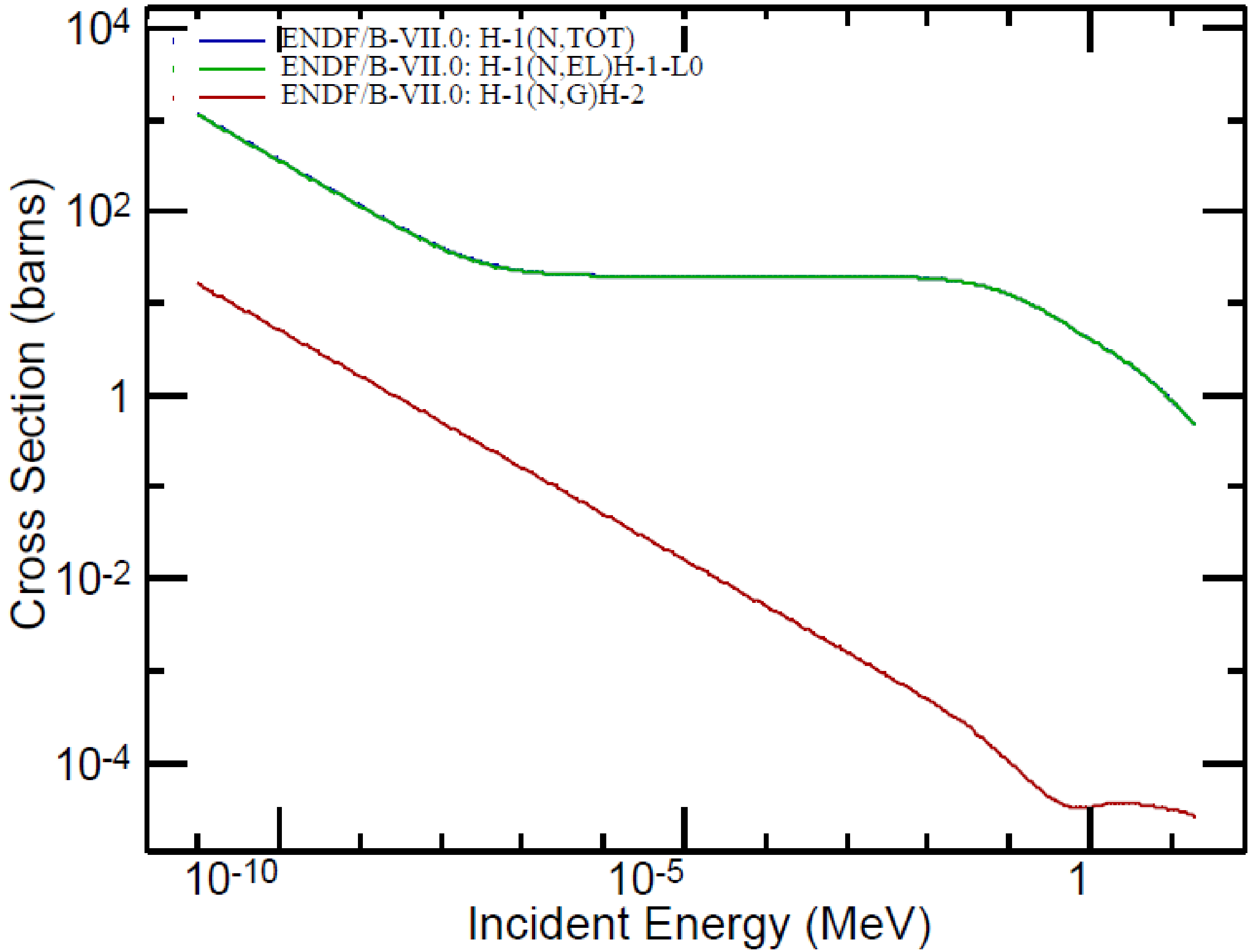
Cross sections for ^{1}H



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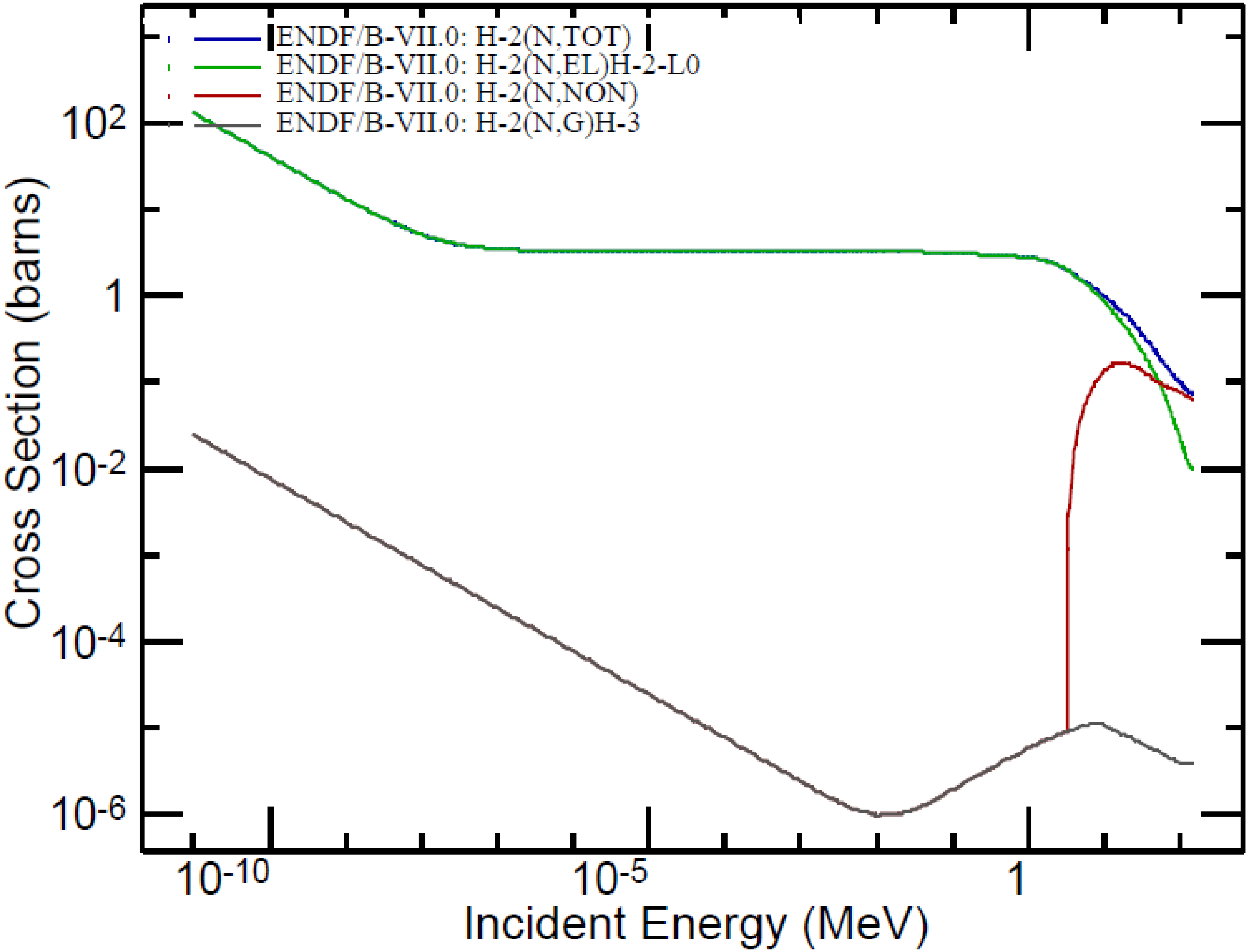
Remark → no resonance

Cross sections for ^2H



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Remark → no resonance

Macroscopic cross section

- As for photons → we consider the transmission of a neutrons beam crossing a thick target (I: final intensity, I_0: initial intensity, *x*: thickness, *N*: atomic density, σ_t: total cross section) →

$$I = I_0 \exp\left(-N\sigma_t x\right)$$

- We define the macroscopic cross section (m^{-1}) such as →

$$\Sigma_t = N\sigma_t$$

- Attention → due mainly to the multiplication phenomenon but also to multiple scattering→ the equation of the intensity after a distance *x* is often false

Moderating power

- To moderate (slow down) fast neutrons → 2 parameters are important
    1. The probability of scattering
    2. The mean energy change for the neutron after scattering → to have a good moderator → a light nucleus is necessary → rich into hydrogen
- The moderating power is defined as →

$$MP = \xi\Sigma_s$$

with ξ, the average logarithmic energy decrement($\xi = ln(E_{\text{before}})- ln(E_{\text{after}})$) and Σ_s, the macroscopic scattering cross section

Moderating ratio (1)

- However a medium with a high moderating power but with also a high absorption scattering cross section is not considered as a good moderator → the neutron energy would be reduced but the fraction of surviving neutrons would be too weak
- Finally to moderate fast neutrons → high moderating power is necessary but also a small absorption probability → we define the moderation ratio (with Σ_a, the macroscopic absorption cross section) →

$$MR = \frac{\xi \Sigma_t}{\Sigma_a}$$

Moderating ratio (2)

MP and MR for ≠ materials for initial and final energies of 100 keV and 1 eV

Moderator	Moderating Power (1 eV to 100 keV)	Moderating Ratio (Approximate)
Water	1.28	58
Heavy Water	0.18	21 000
Helium at STP	0.00001	45
Beryllium	0.16	130
Graphite	0.064	200
Polyethylene (CH_2)	3.26	122

water has MP larger than heavy water (D_2O or ^2H_2O) because the mass of hydrogen is 2 times smaller than the mass of deuterium but hydrogen absorb neutron (to form deuterium) more easily than deuterium (to form tritium) → MR larger for heavy water (attention: heavy water more expensive)

Moderation: Conclusion

To moderate fast neutrons → use of materials with a mass close to the mass of the neutron → materials rich in hydrogen (water, paraffin) → **never** lead

Mean free path

- It is often interesting to consider another parameter → the mean free path λ →

$$\lambda = \frac{1}{\Sigma_t}$$

  i.e. the mean distance between 2 interactions

- Useful parameter for calculations of trajectories of neutrons in matter by Monte Carlo simulations

Neutron path: examples

1 MeV neutrons incident on cylinders of polyethylene, aluminium and lead (Monte Carlo calculations)