Part B. Radiation sources

1. Interaction of electrons-e with the matter

$m_e = 9.11\times10^{-31}$ kg ; $E = m_e c2 = 0.511$ MeV; $q_e = -e$

2. Interaction of photons-γ with the matter

$m\gamma = 0$ kg ; $E\gamma = 0$ eV; $q\gamma = 0$

3. Interaction of neutrons-n with the matter

$m_n = 1.68 \times 10^{-27}$ kg ; $E_n = 939.57$ MeV; $q_n = 0$

4. Interaction of protons-p with the matter

$m_p = 1.67 \times 10^{-27}$ kg ; $E_p = 938.27$ MeV; $q_p = +e$

Note: for any nucleus

$A = Z + N$
- A: mass number – nucleons number
- Z: atomic number – proton (charge) number
- N: neutron number

1. Interaction of electrons with the matter

The physical processes:

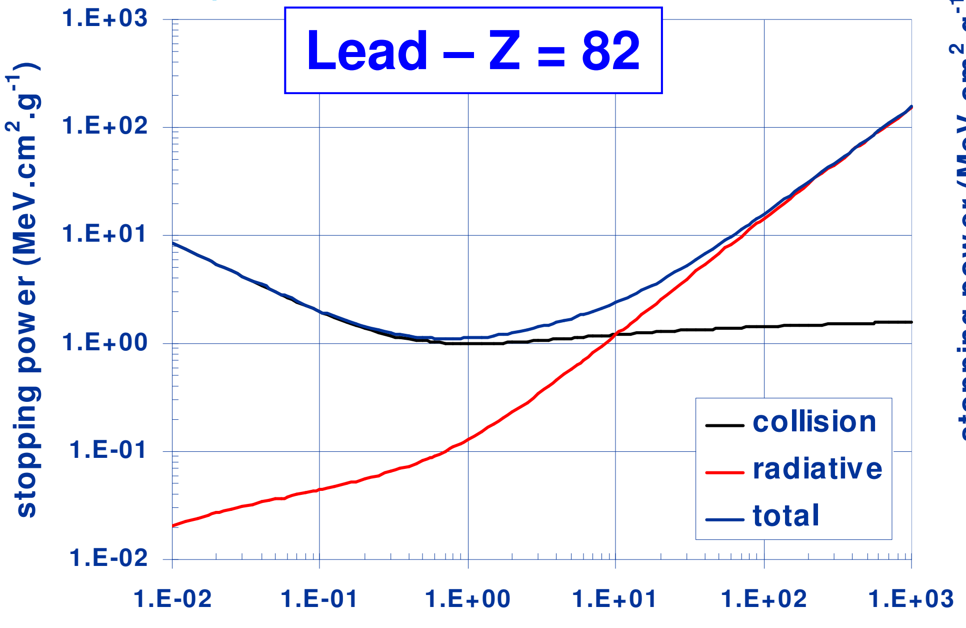
1. Ionization losses
   inelastic collisions with orbital electrons

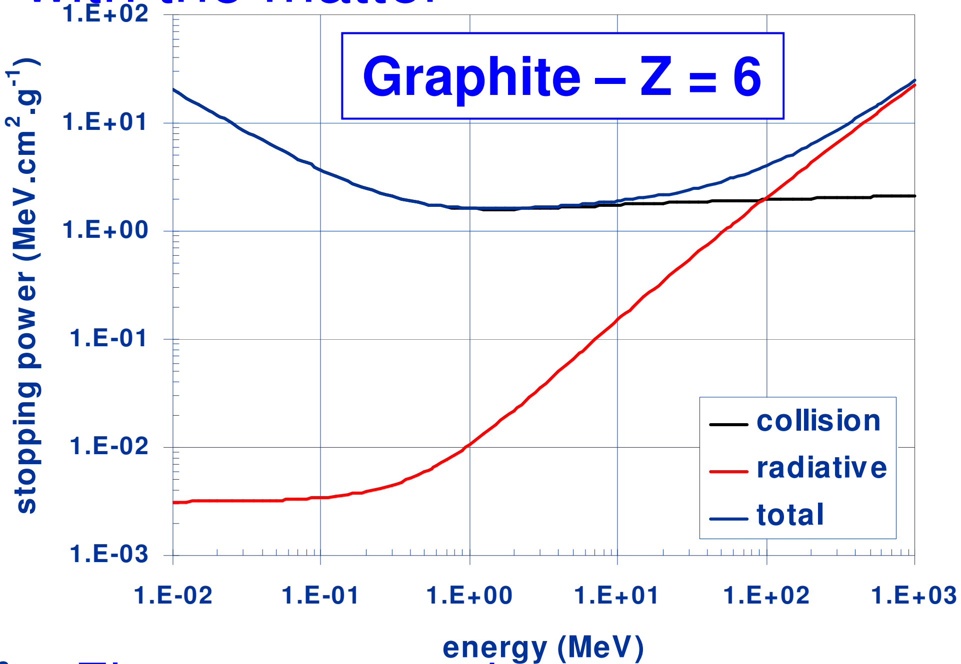
2. Bremsstrahlung losses
   inelastic collisions with atomic nuclei

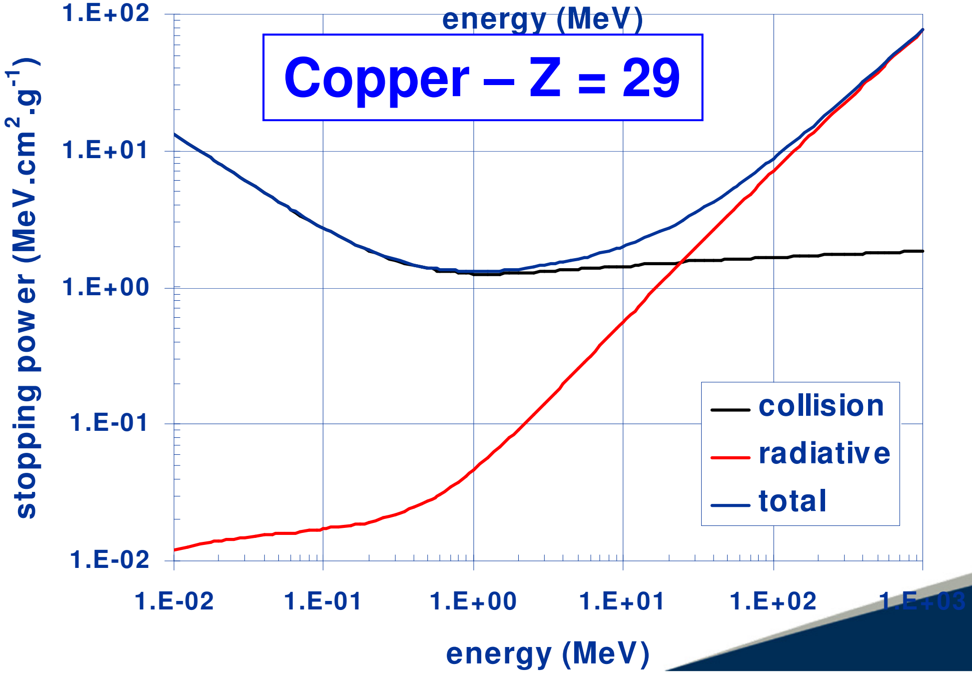
3. Rutherford scattering
   elastic collisions with atomic nuclei

Positrons
at nearly rest energy: annihilation
emission of two 511 keV photons

1. Interaction of electrons with the matter







Electrons – stopping power

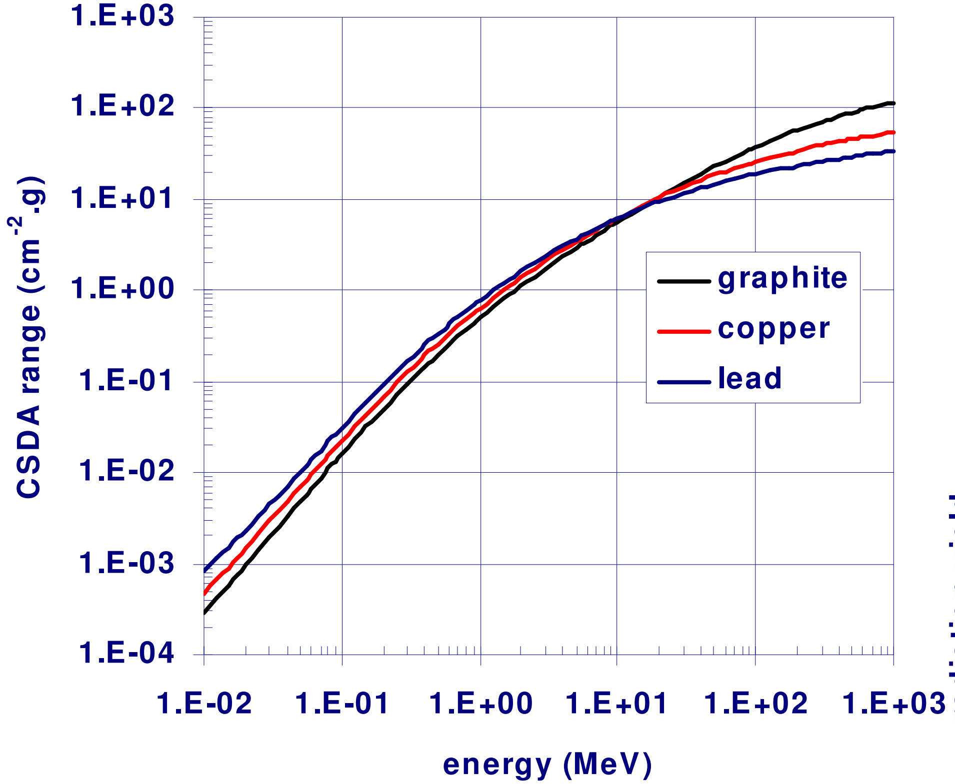
$$\frac{S}{\rho} = \frac{1}{\rho}\frac{dE}{dl}$$

$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{coll} + \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{rad}$$

$\frac{1}{\rho}\frac{dE}{dl}$: mass stopping power ($MeV.cm^2.g^{-1}$)

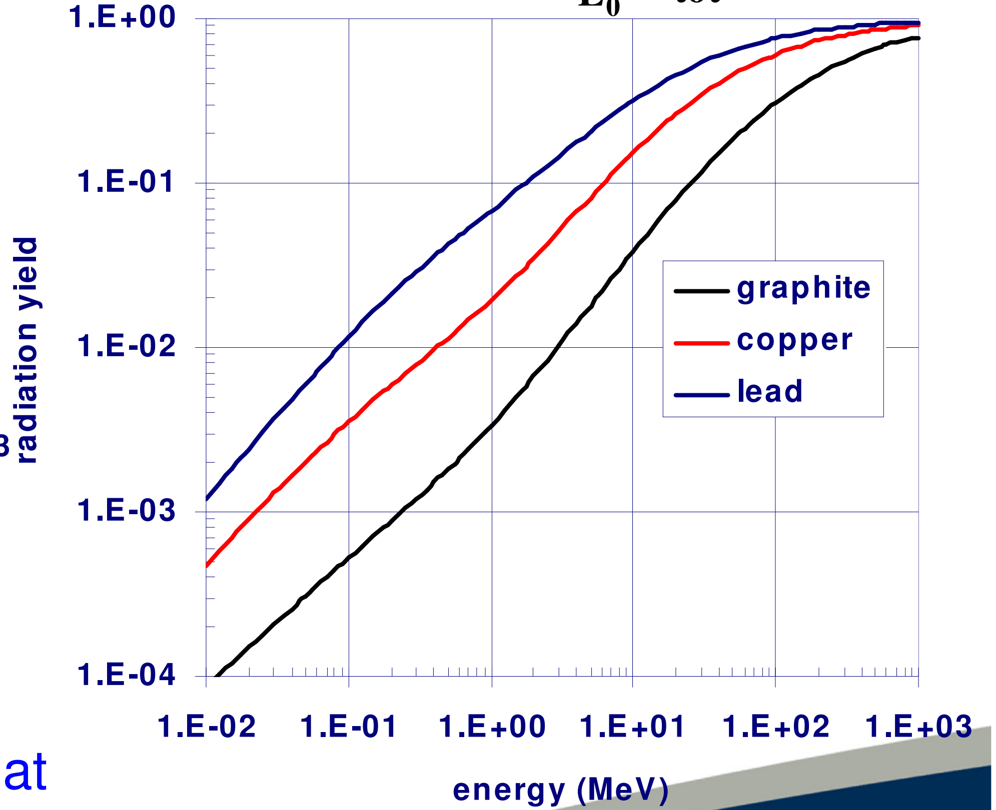
$\frac{dE}{dl}$: linear stopping power ($MeV.cm^{-1}$)

1. Interaction of electrons with the matter



Continuous Slowing Down Approximation range:

$$r_{CSDA} = \int_{E_0}^{0} \frac{1}{S_{tot}} dE$$



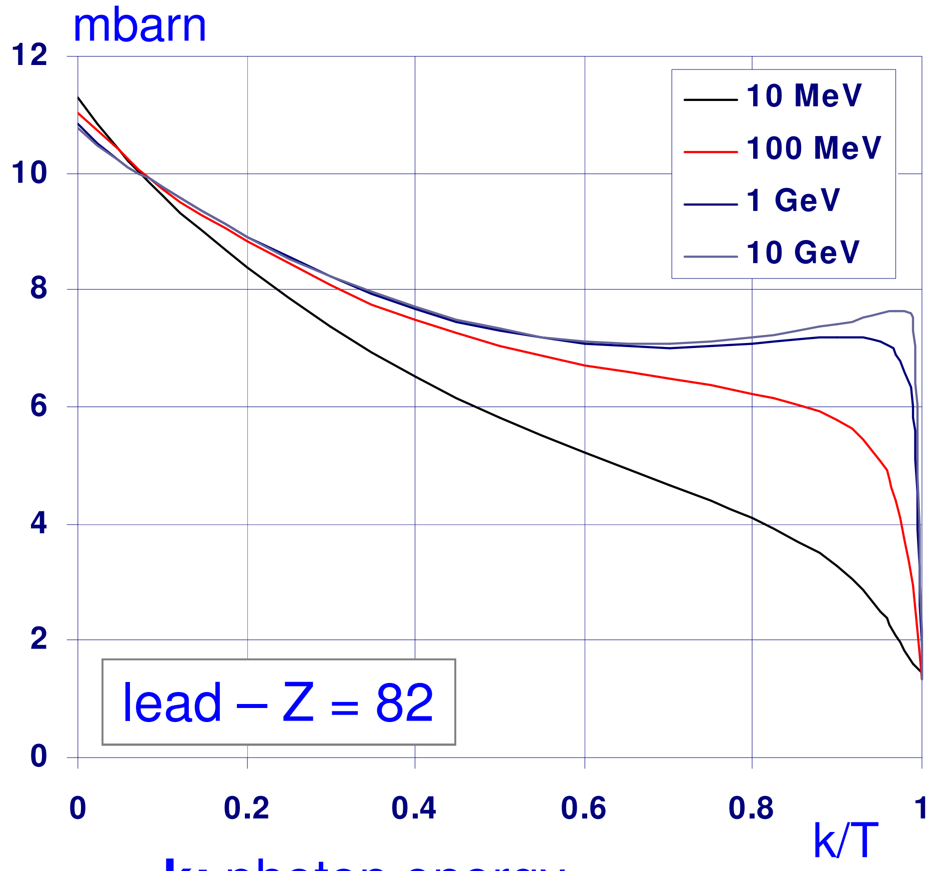
Radiation yield:

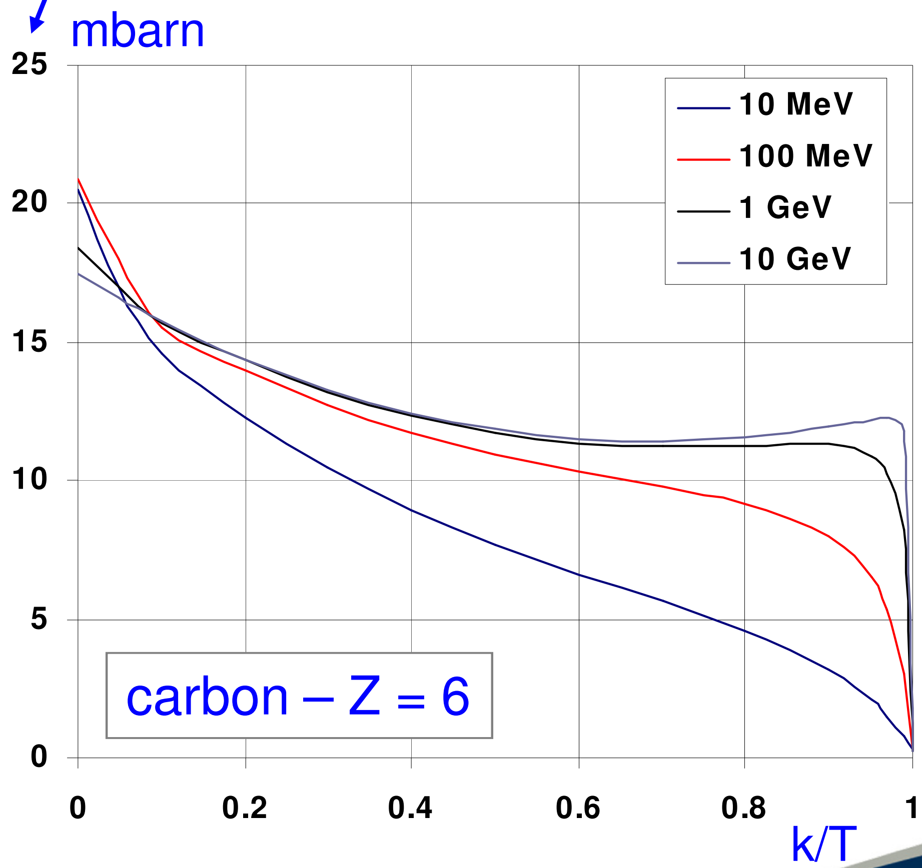
Fraction of the initial kinetic energy that is converted to Bremsstrahlung energy as the electron slows down to rest.

1. Interaction of electrons with the matter

Differential Bremsstrahlung cross section:

$$\frac{1}{Z^2} k \times \frac{d\sigma}{dk}$$





k: photon energy

T: electron kinetic energy

$$T = m\gamma c^2 - m c^2 = m c^2 / \{1 - v^2/c^2\}^{1/2} - m c^2$$

1. Interaction of electrons with the matter

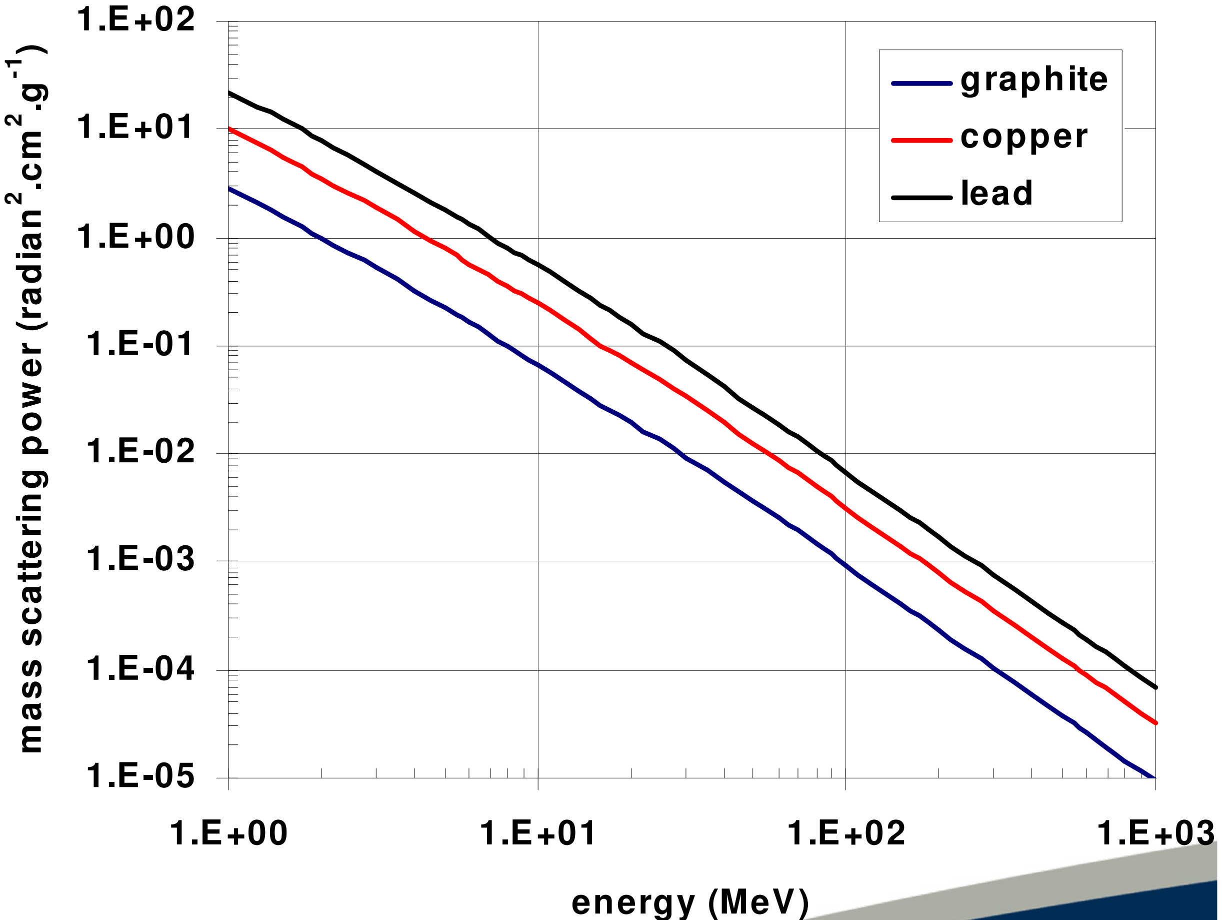
Multiple scattering

mean scattering angle

$$\langle \theta^2 \rangle = \left(\frac{E_s}{\beta p} \right)^2 \frac{X}{X_0}$$

mass scattering power S_{sc}

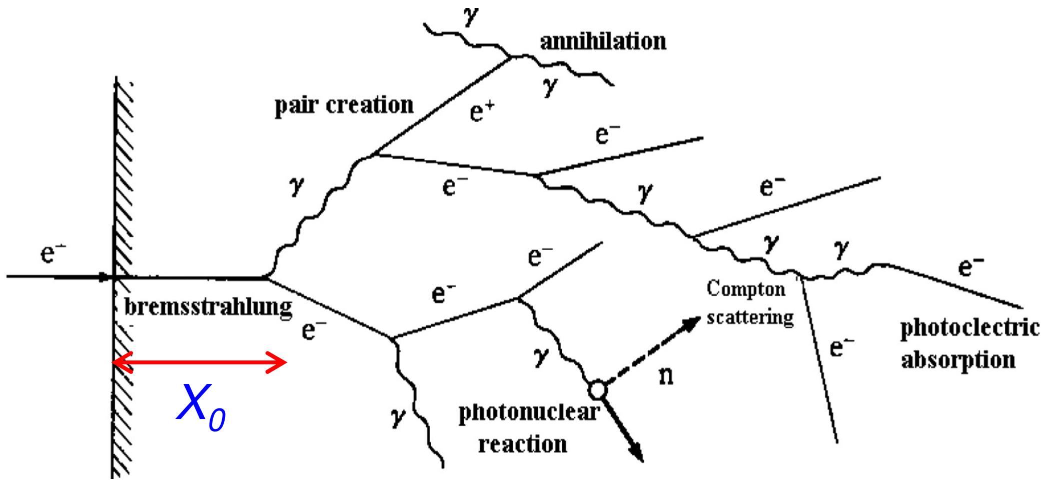
$$S_{sc} = \frac{1}{\rho} \frac{d\langle \theta^2 \rangle}{dx}$$



E_s = 21.2 MeV
X_0: radiation length
β: v/c
p: momentum

2. Interaction of electrons with the matter

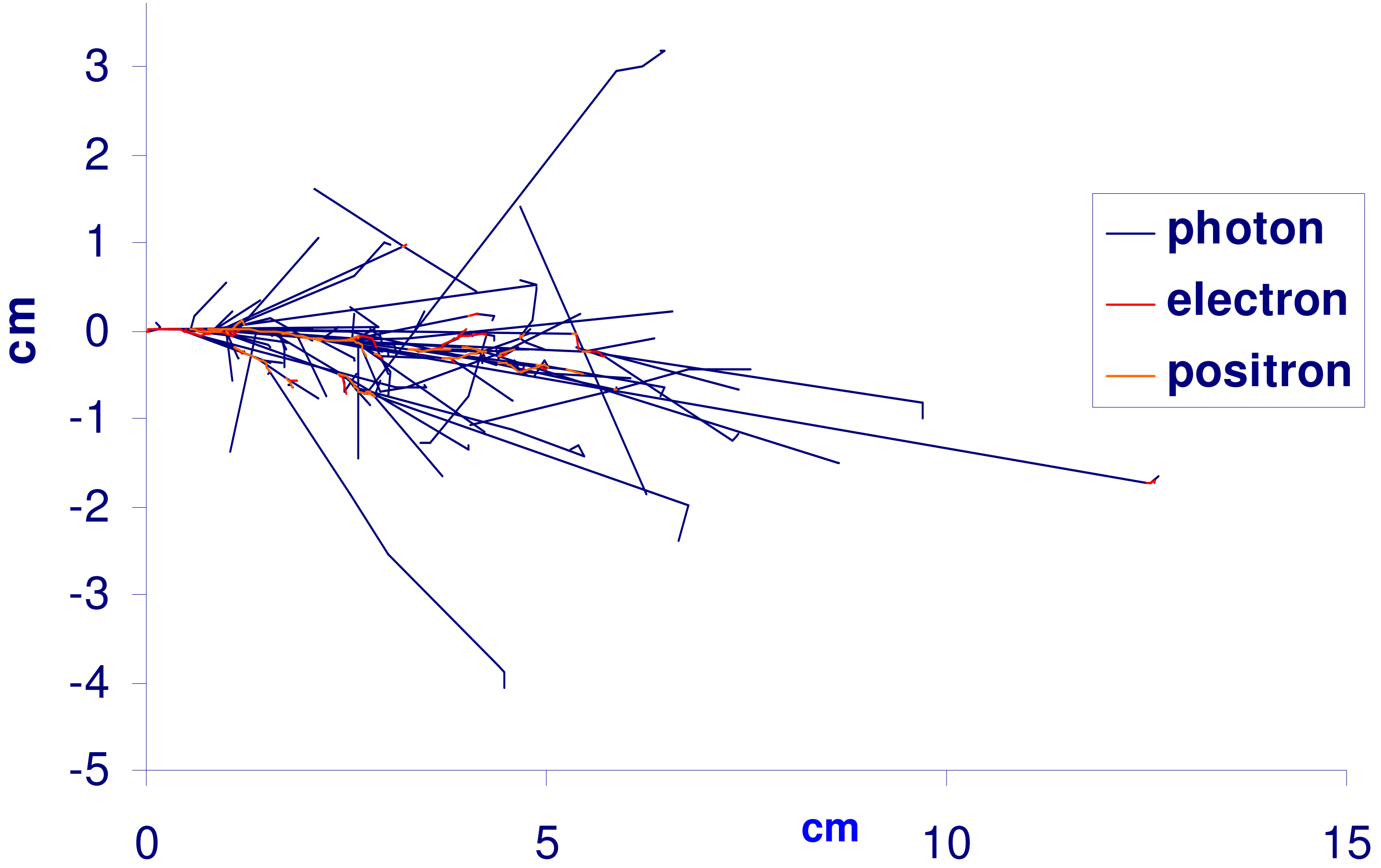
- Particles involved:
  - Electrons / Positrons
  - Photons
  - Neutrons



X_0: radiation length

2. Interaction of electrons with the matter

Electromagnetic cascade



one 500 MeV electron interacting
with lead target

2. Interaction of photons with the matter

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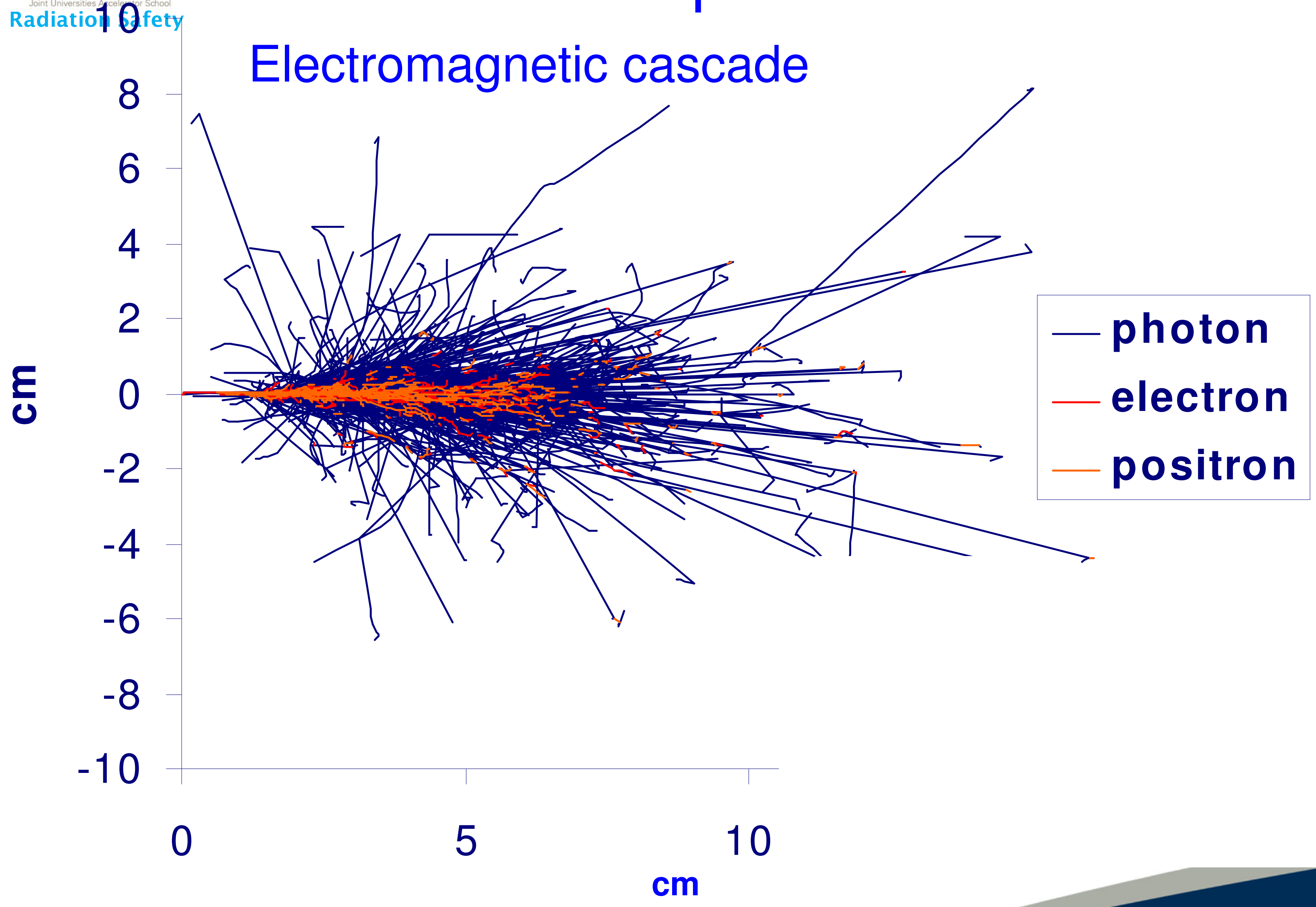
Electromagnetic cascade



one 6 GeV electron interacting with lead target

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2. Interaction of photons with the matter

The physical processes:

1. Photo-electric effect
   removal of an orbital electron of the inner shells (K,L,M)

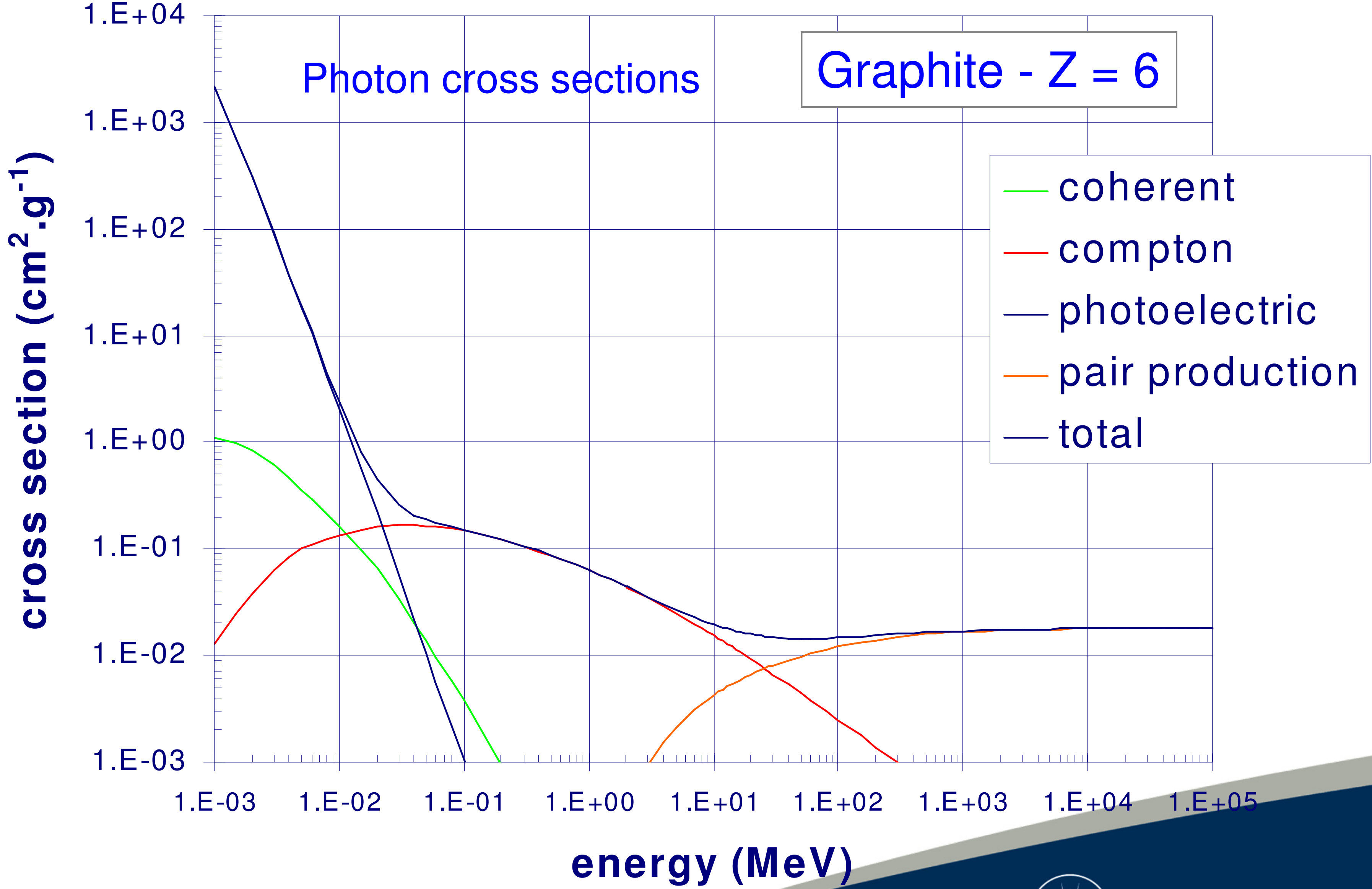
2. Compton scattering
   inelastic scattering on loosely bound electrons

3. Pair production
   production of e^-/e^+ pair
   essentially with nuclei

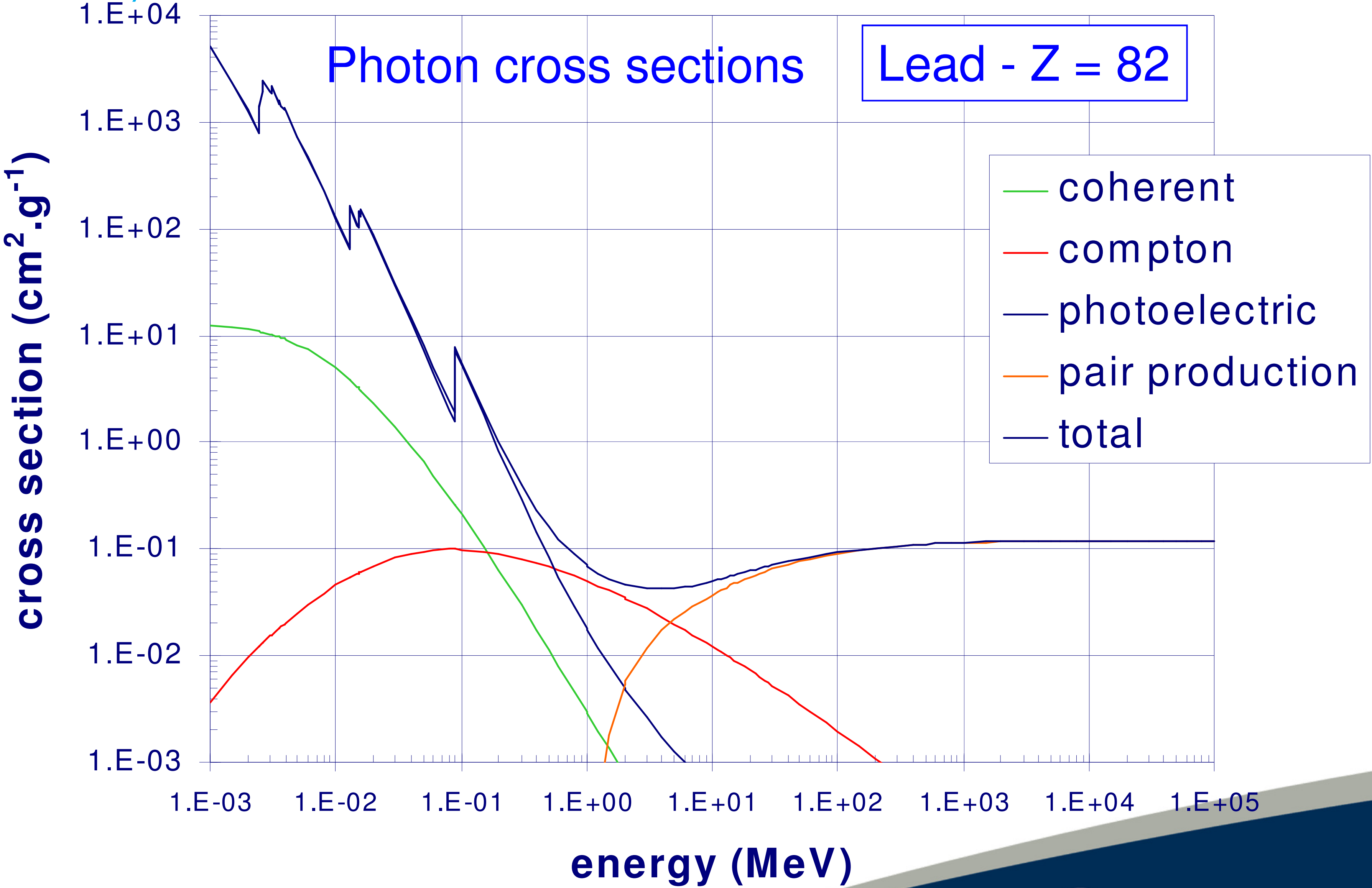
---

4. Rayleigh (coherent) scattering
   elastic scattering
   not important for radiation physics

2. Interaction of photons with the matter

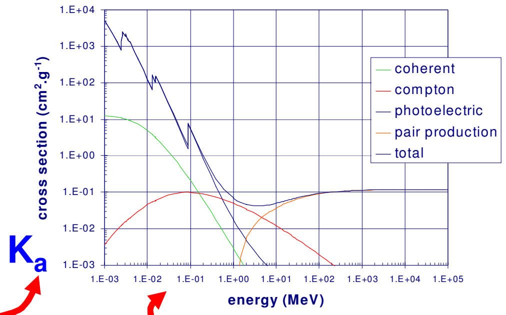


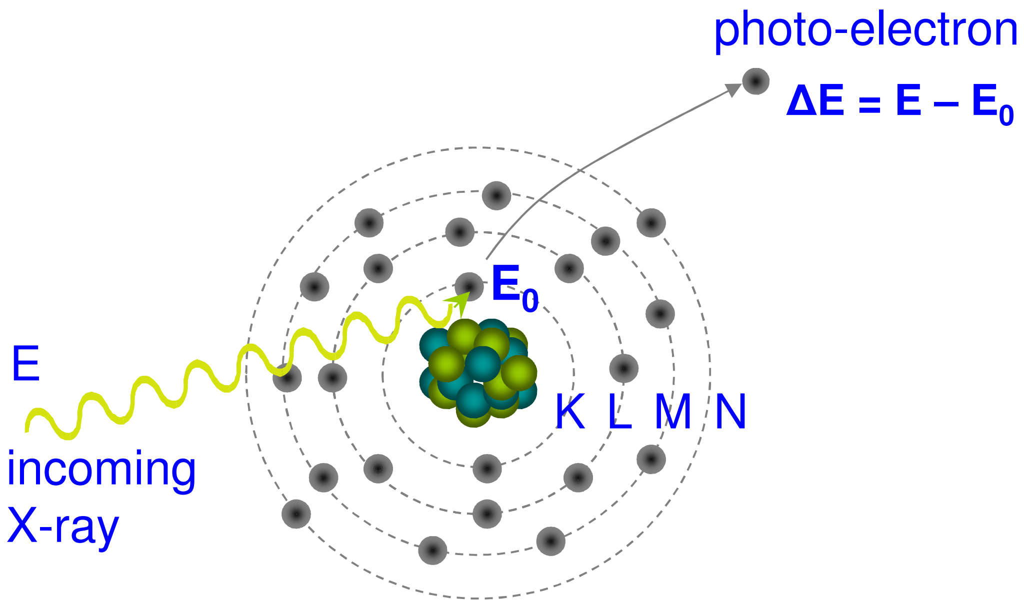
2. Interaction of photons with the matter

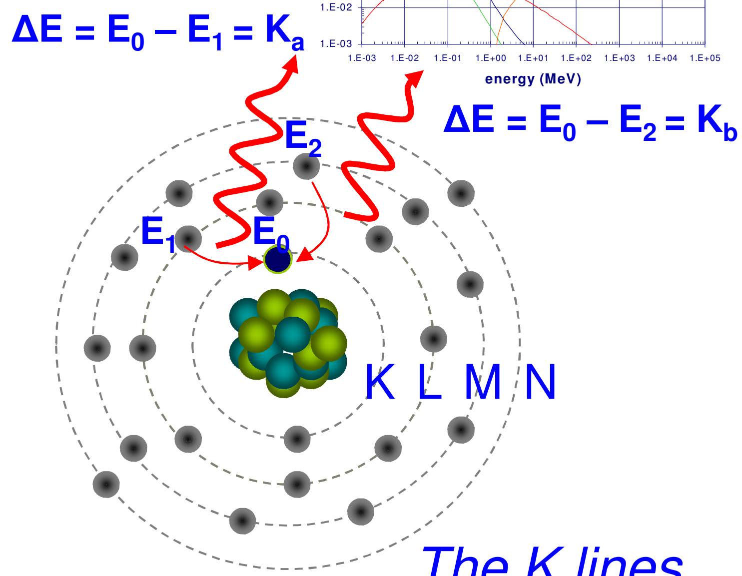


2. Interaction of photons with the matter

Photo-electric effect:

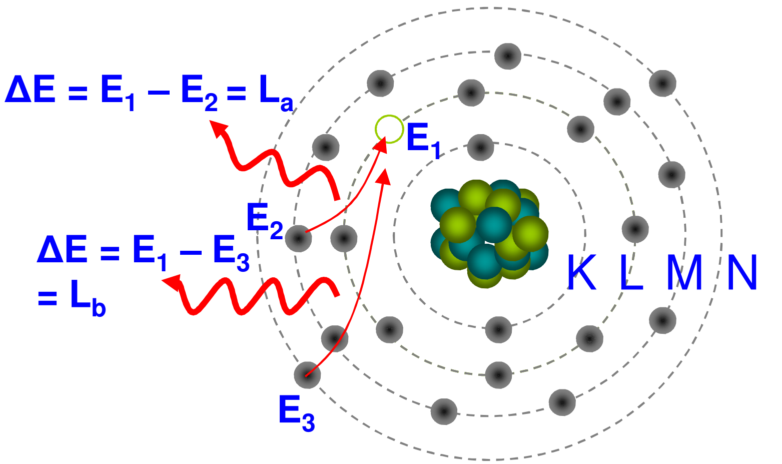




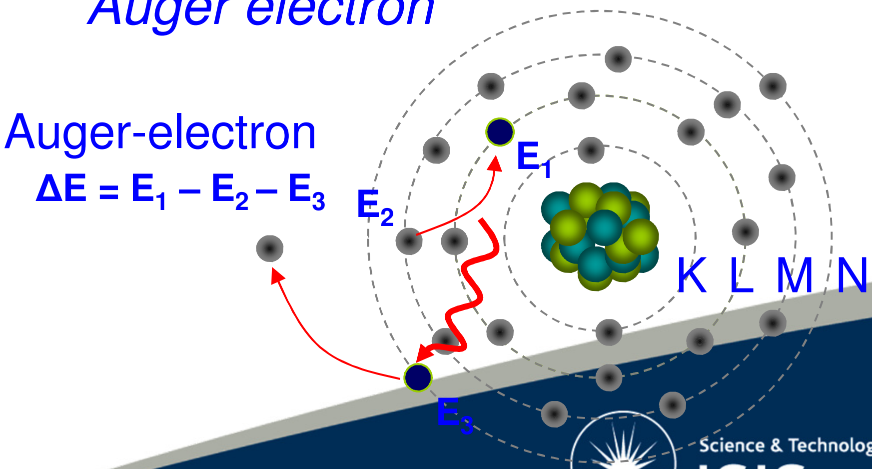


The K lines

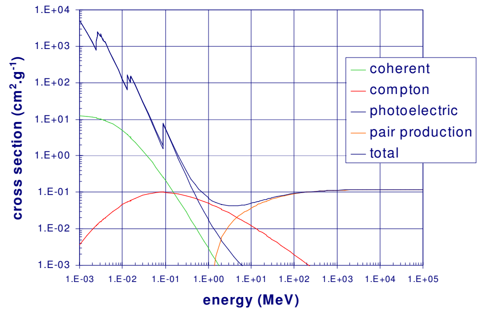
Auger electron



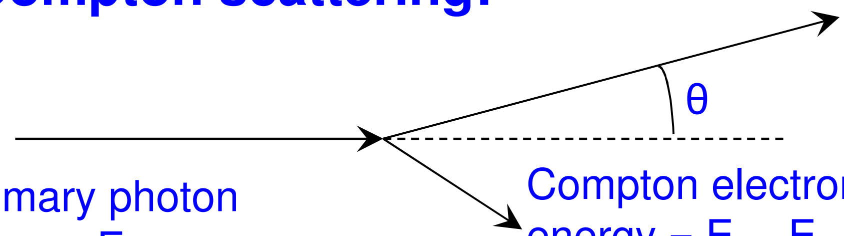
The L lines



2. Interaction of photons with the matter



Compton scattering:



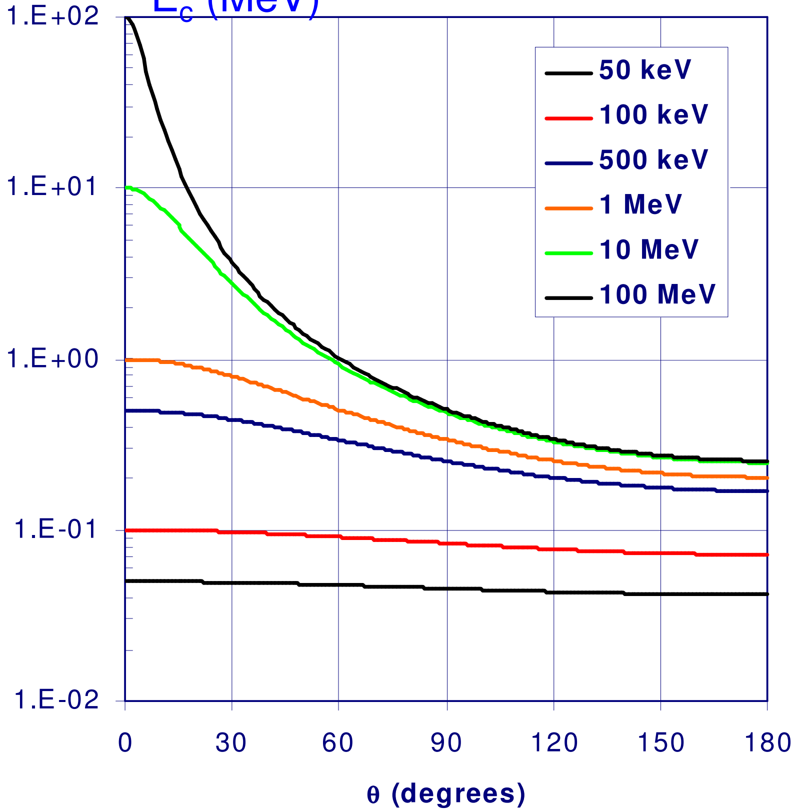
scattered photon
energy E_c

$$E_c = \frac{E_0}{1 + \frac{E_0}{m_0 c^2}(1 - \cos\theta)}$$

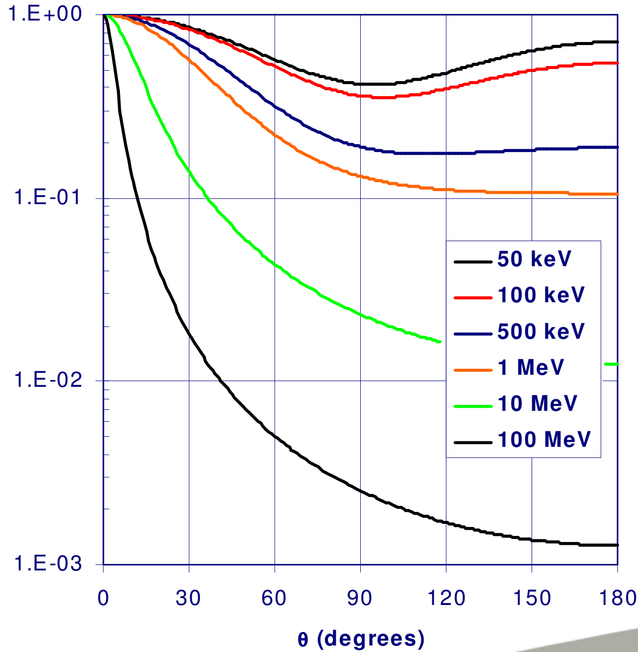
primary photon
energy E_0

Compton electron
energy = E_0 - E_c

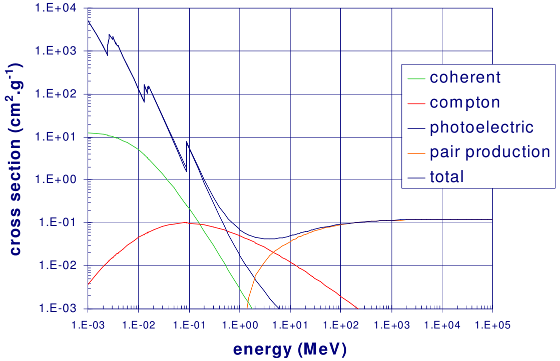
E_c (MeV)



dσ/dW (r_e^2 x cm² / electron)



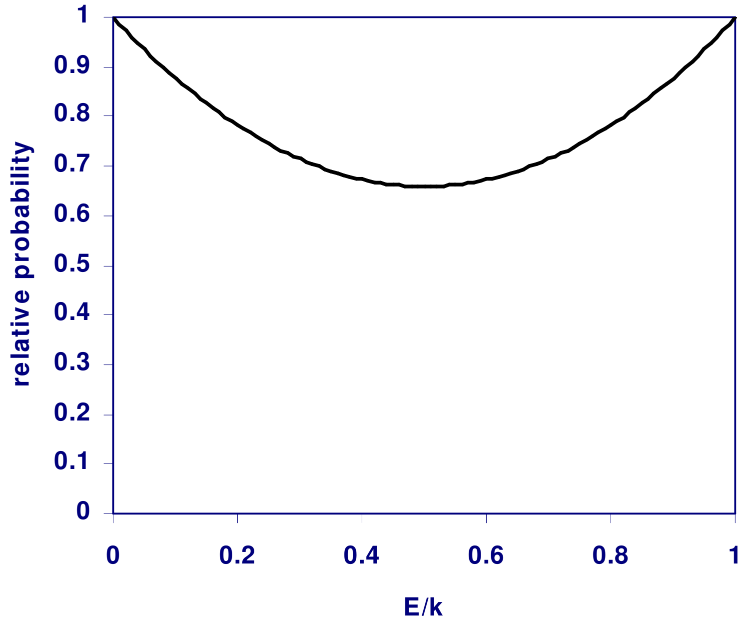
2. Interaction of photons with the matter



Pair production:

$\sigma_{nucleus} \propto Z^2$
threshold: 1.022 MeV

$\sigma_{electron} \propto Z$
threshold: 2.044 MeV



2. Interaction of photons with the matter

Interaction of photons with matter
Macroscopic description - Attenuation factors

The mass attenuation coefficient μ/ρ:

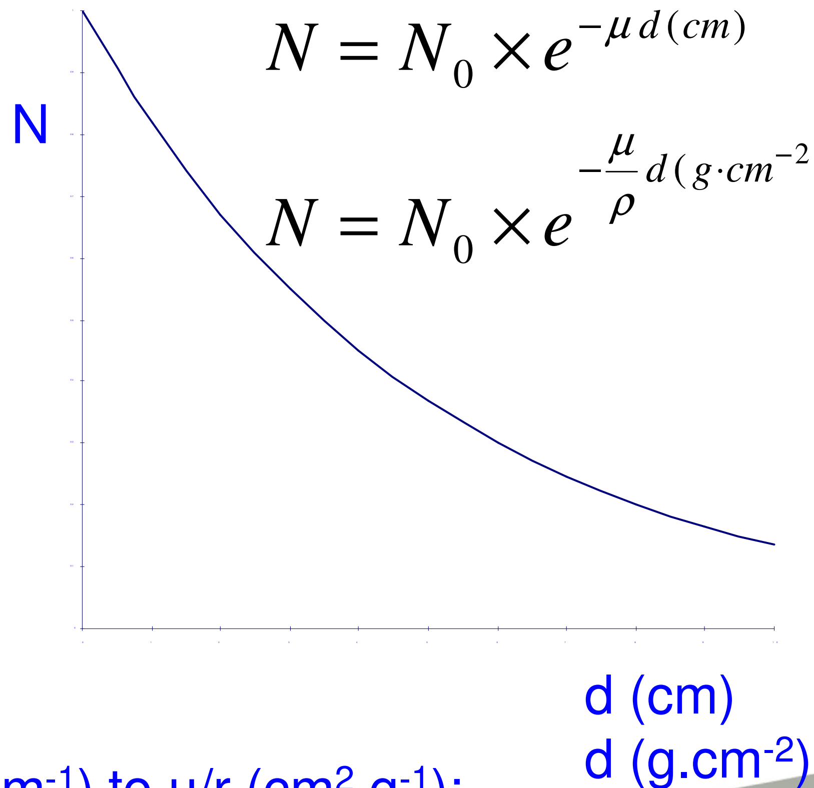
$$\frac{\mu}{\rho} = \frac{1}{\rho N}\frac{dN}{dl}$$

units: $cm^2.g^{-1}$

The linear attenuation coefficient μ:

$$\mu = \frac{1}{N}\frac{dN}{dl}$$

units: cm^{-1}



$$N = N_0 \times e^{-\mu d(cm)}$$

$$N = N_0 \times e^{-\frac{\mu}{\rho} d(g \cdot cm^{-2})}$$

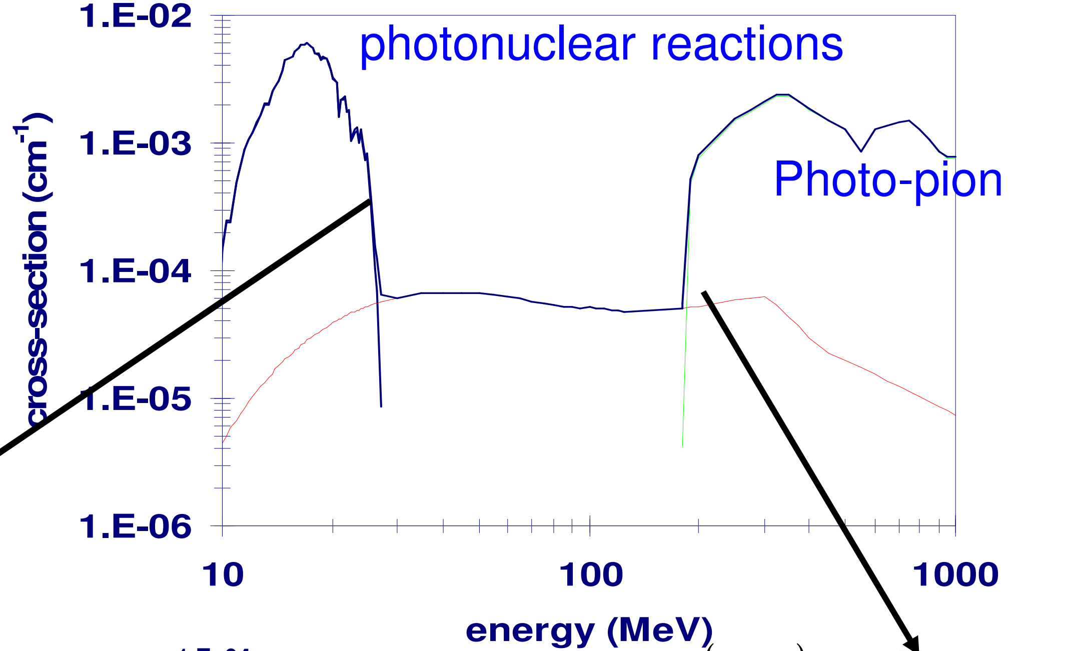
The conversion factor from σ ($barns.atom^{-1}$) to μ/r ($cm^2.g^{-1}$):

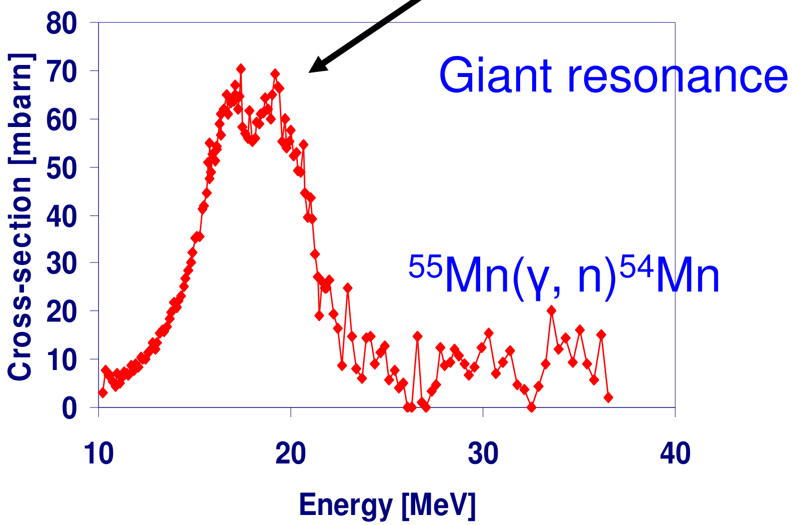
$$\frac{\mu}{\rho} = 10^{-24}\frac{N_A}{A}\sigma$$

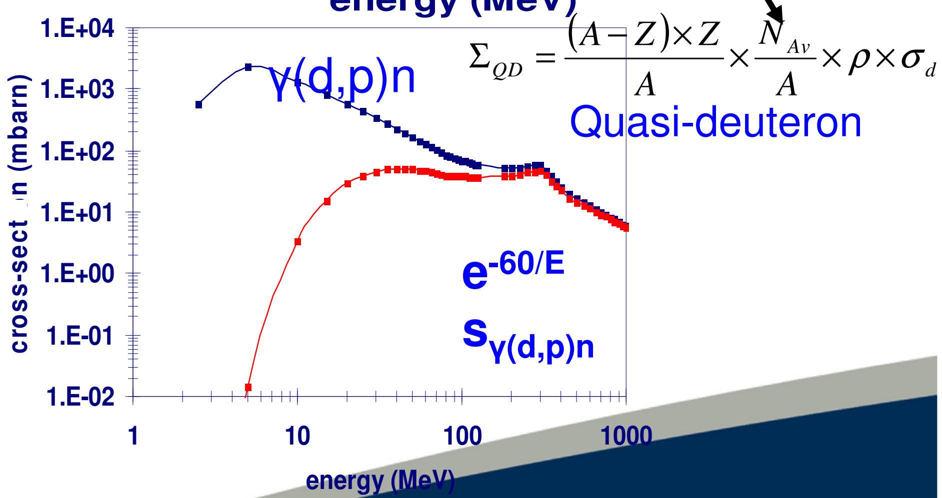
2. Interaction of photons with the matter

Photonuclear reactions:

Neutron production



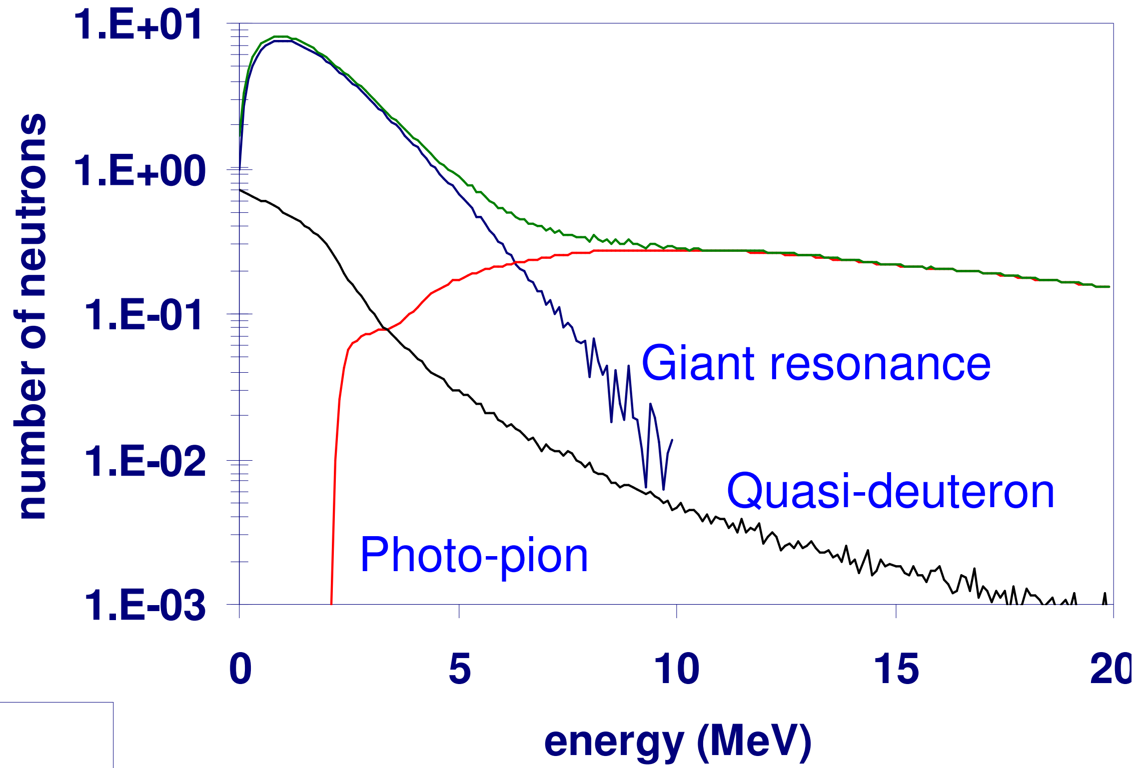


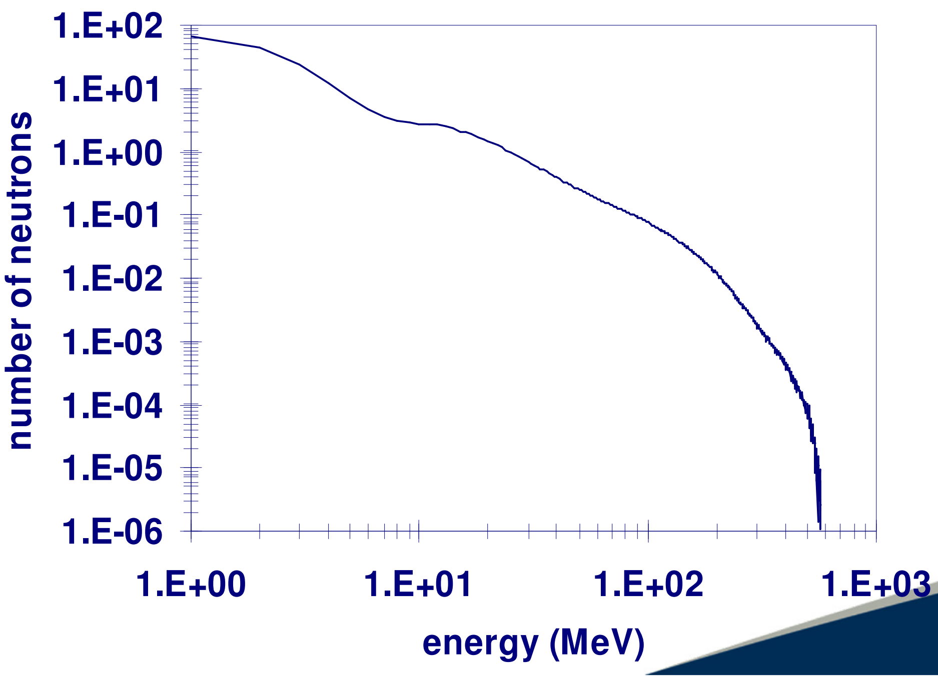


2. Interaction of photons with the matter

Photonuclear reactions:

Neutron production





<u>Example:</u> neutron spectrum produced by 600 MeV electrons on Cu target

3. Interaction of neutrons with the matter

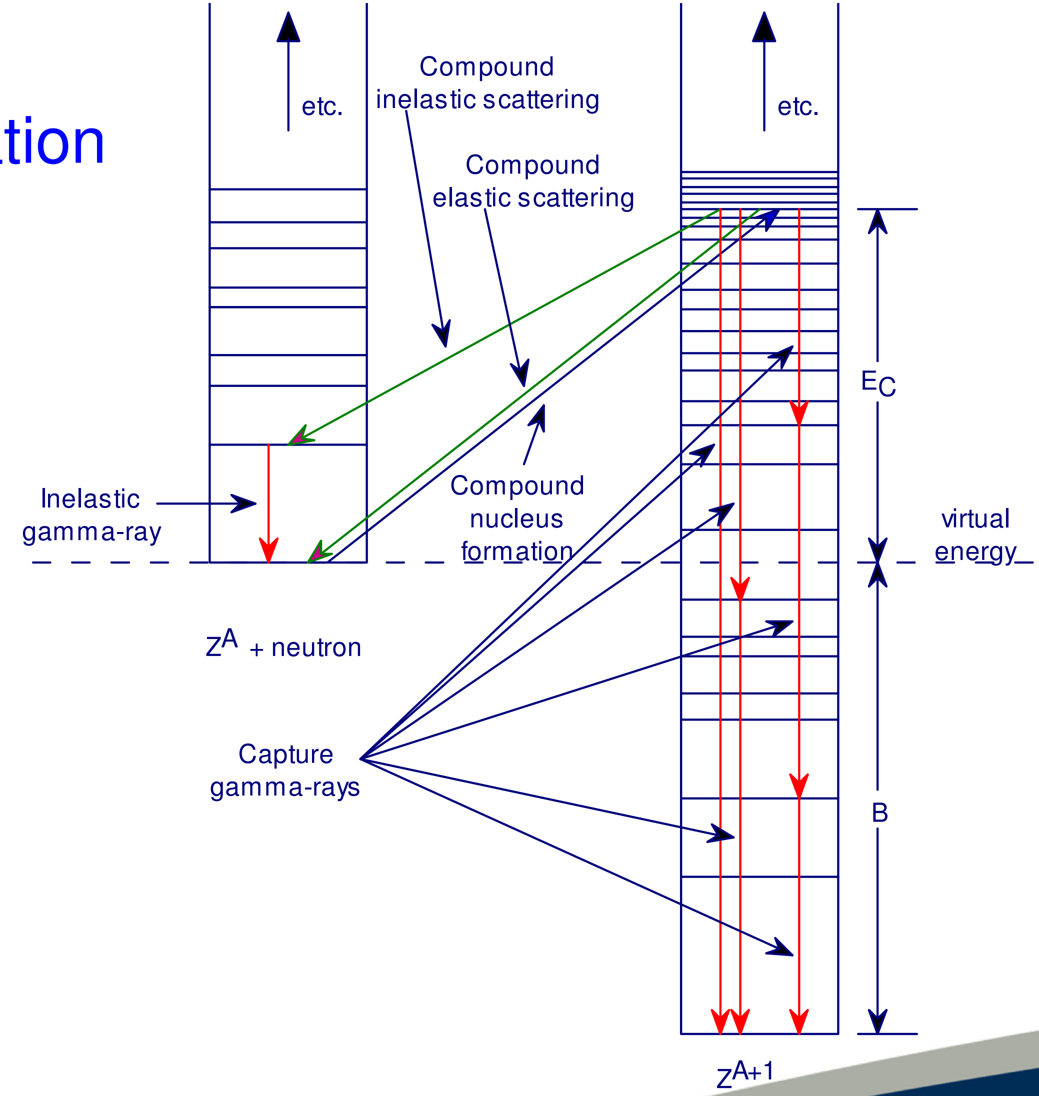
The physical processes:

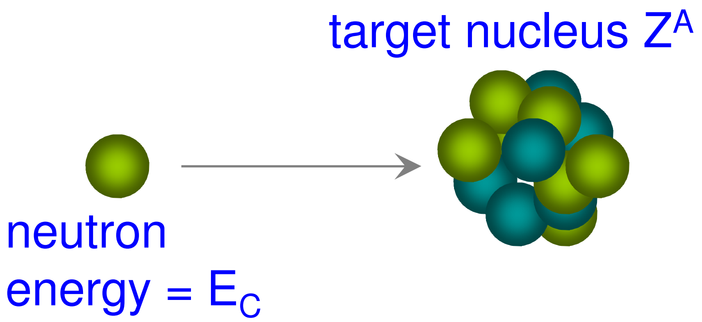
1. Elastic scattering
   - compound elastic scattering
   - potential scattering
2. Inelastic scattering (n,n’)
3. Other inelastic reactions: (n,p), (n,α), …
4. Absorption reactions
   - radioactive capture
   - charged particle reactions

5. Direct reactions: spallation

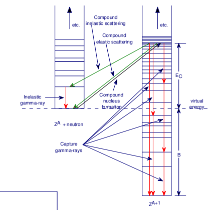
3. Interaction of neutrons with the matter

Compound nucleus formation

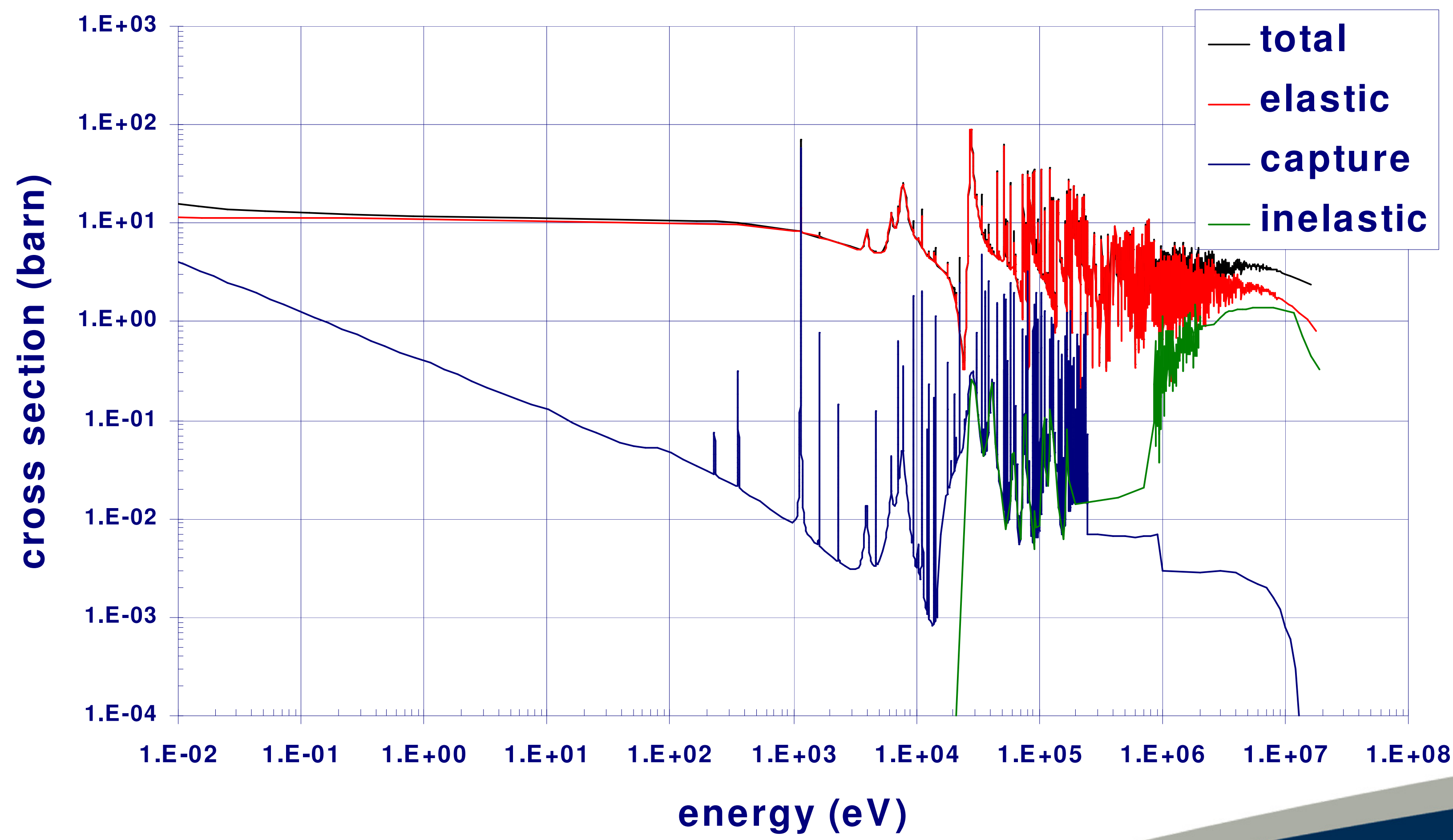




3. Interaction of neutrons with the matter

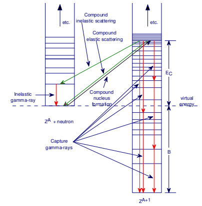


Neutron cross sections

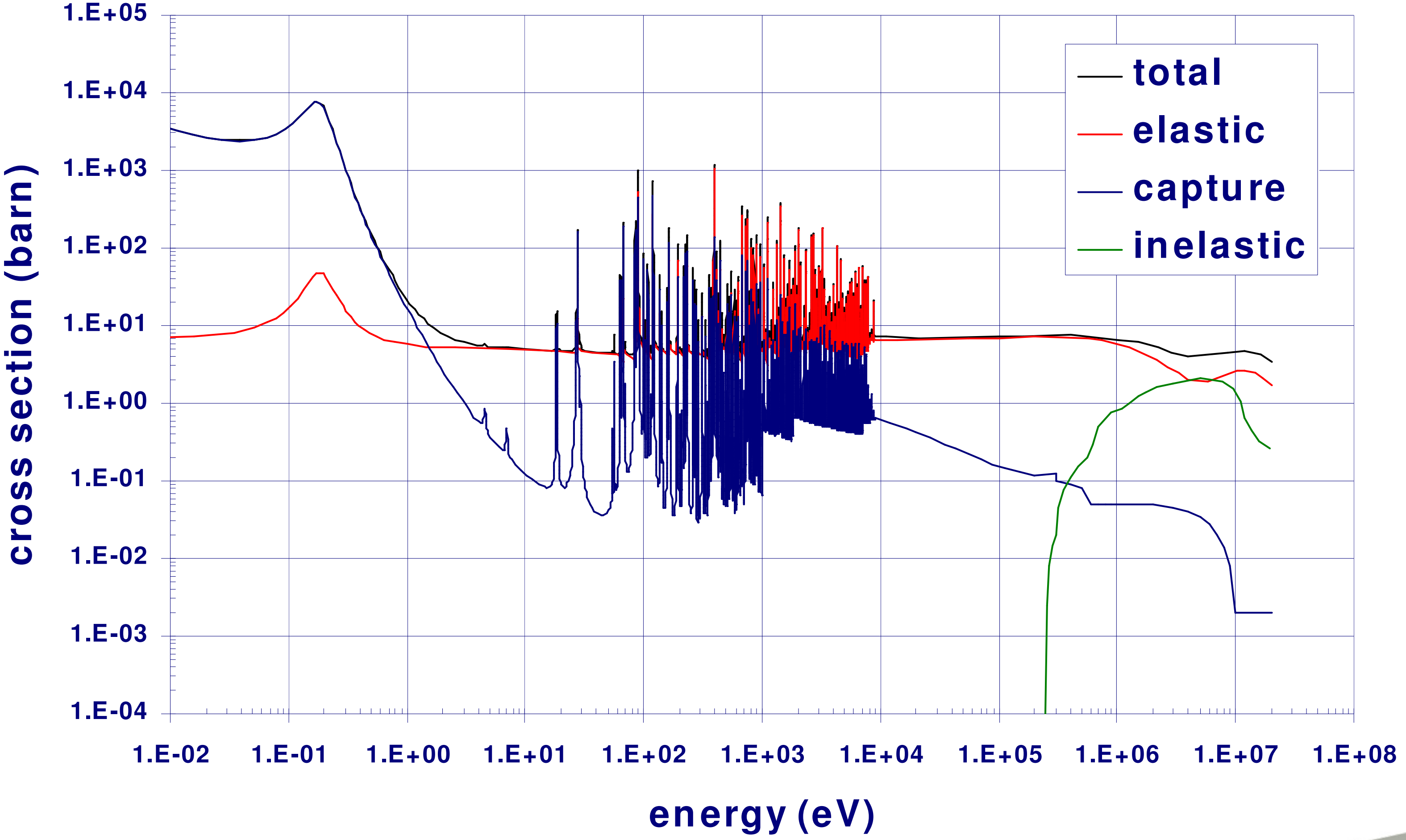


Example 1: iron

3. Interaction of neutrons with the matter

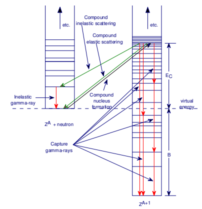


Neutron cross sections

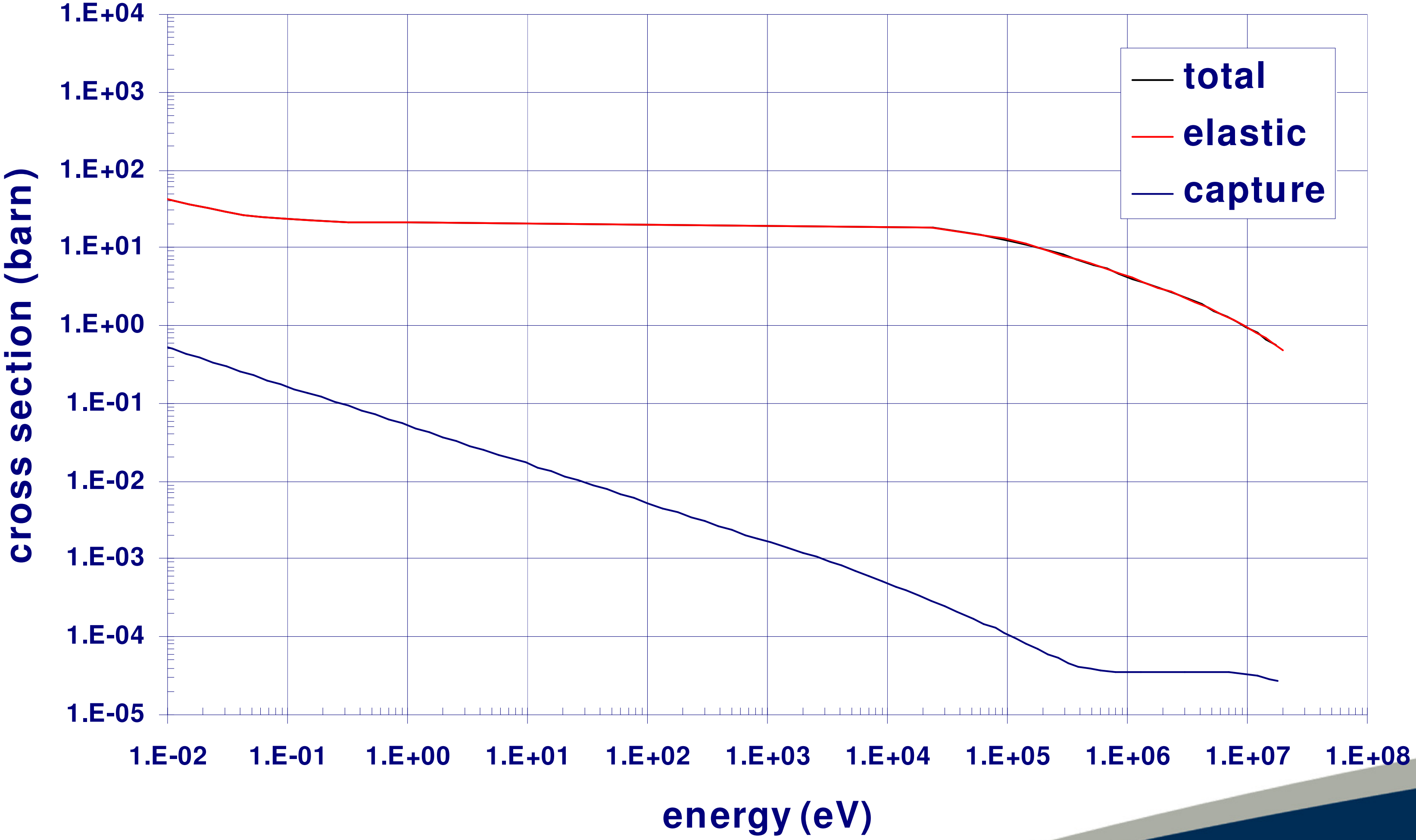


Example 2: cadmium

3. Interaction of neutrons with the matter

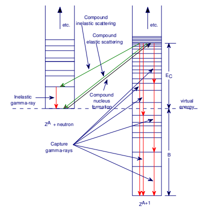


Neutron cross sections

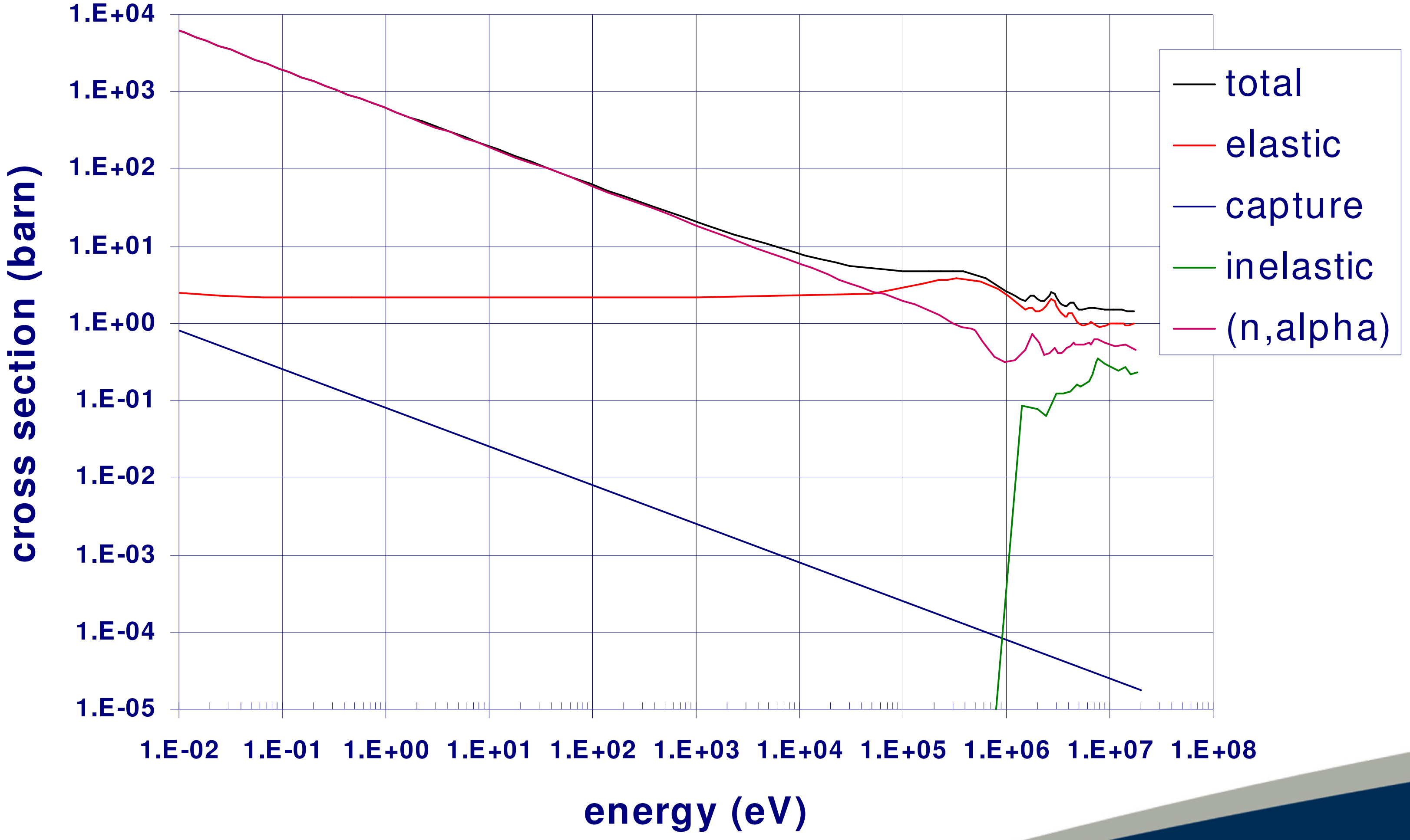


Example 3: hydrogen

3. Interaction of neutrons with the matter



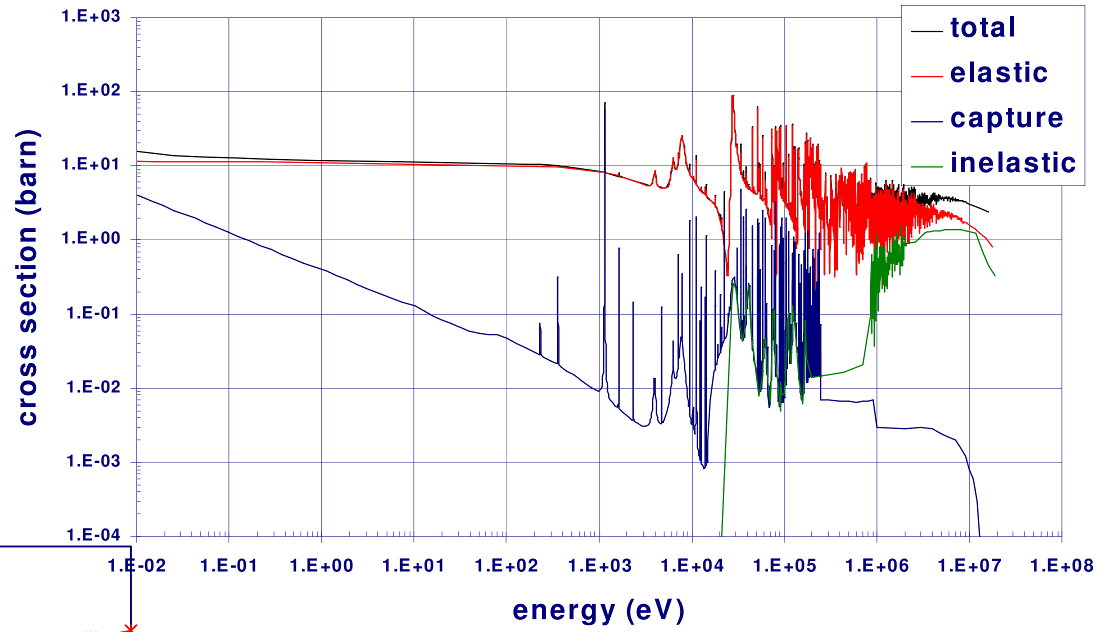
Neutron cross sections

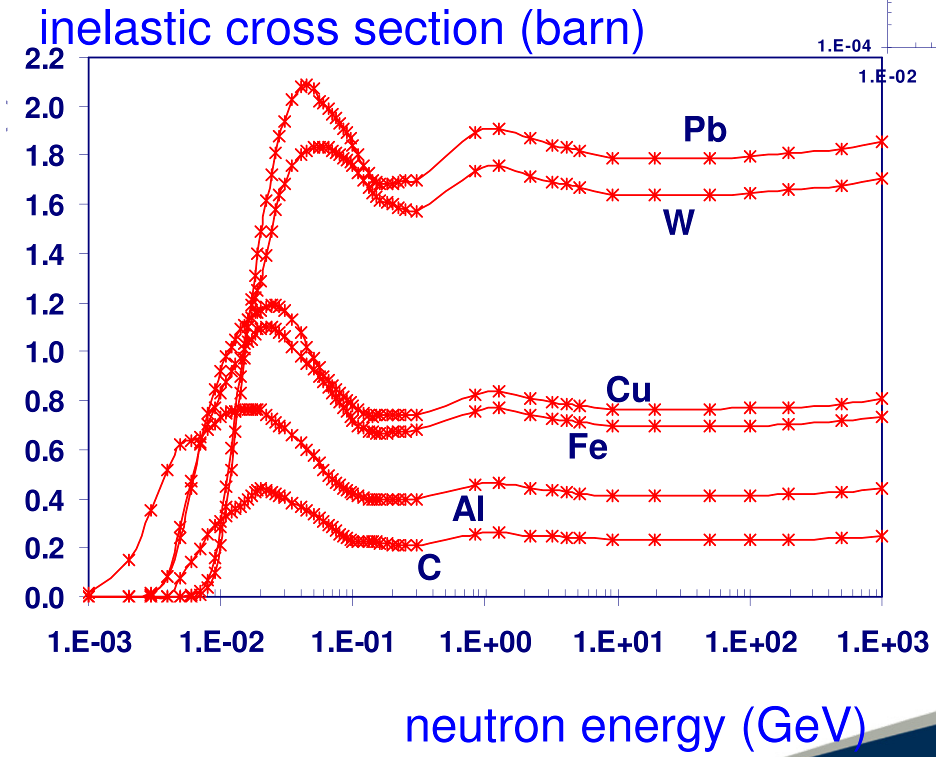


Example 4: boron

3. Interaction of neutrons with the matter

Neutron cross sections

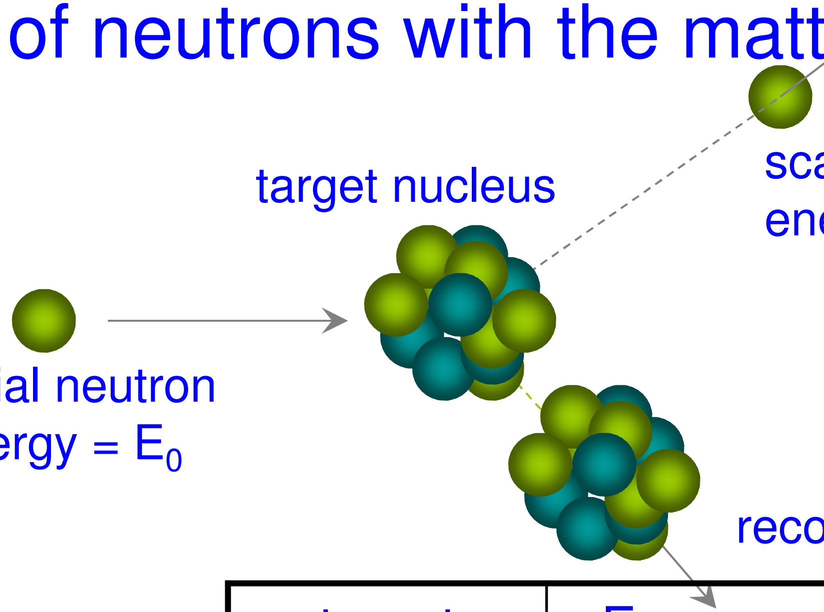




Example: iron

3. Interaction of neutrons with the matter

Elastic scattering



Minimum energy of scattered neutron:

$$E_{1,minimum} = \left(\frac{A-1}{A+1}\right)^2 E_0 = \alpha E_0$$

Average energy loss per collision:

$$\bar{\Delta E} = \frac{1}{2}(1-\alpha)E_0$$

target	$E_{1,minimum}$	$\bar{\Delta E}$
Hydrogen (A=1)	0	0.5 E_0
Iron (A=56)	0.93 E_0	0.034 E_0
Lead (A=207)	0.98 E_0	0.0096 E_0

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4. Interaction of protons with the matter

The physical processes:

1. ionization
2. inelastic proton-nucleus scattering
   spallation

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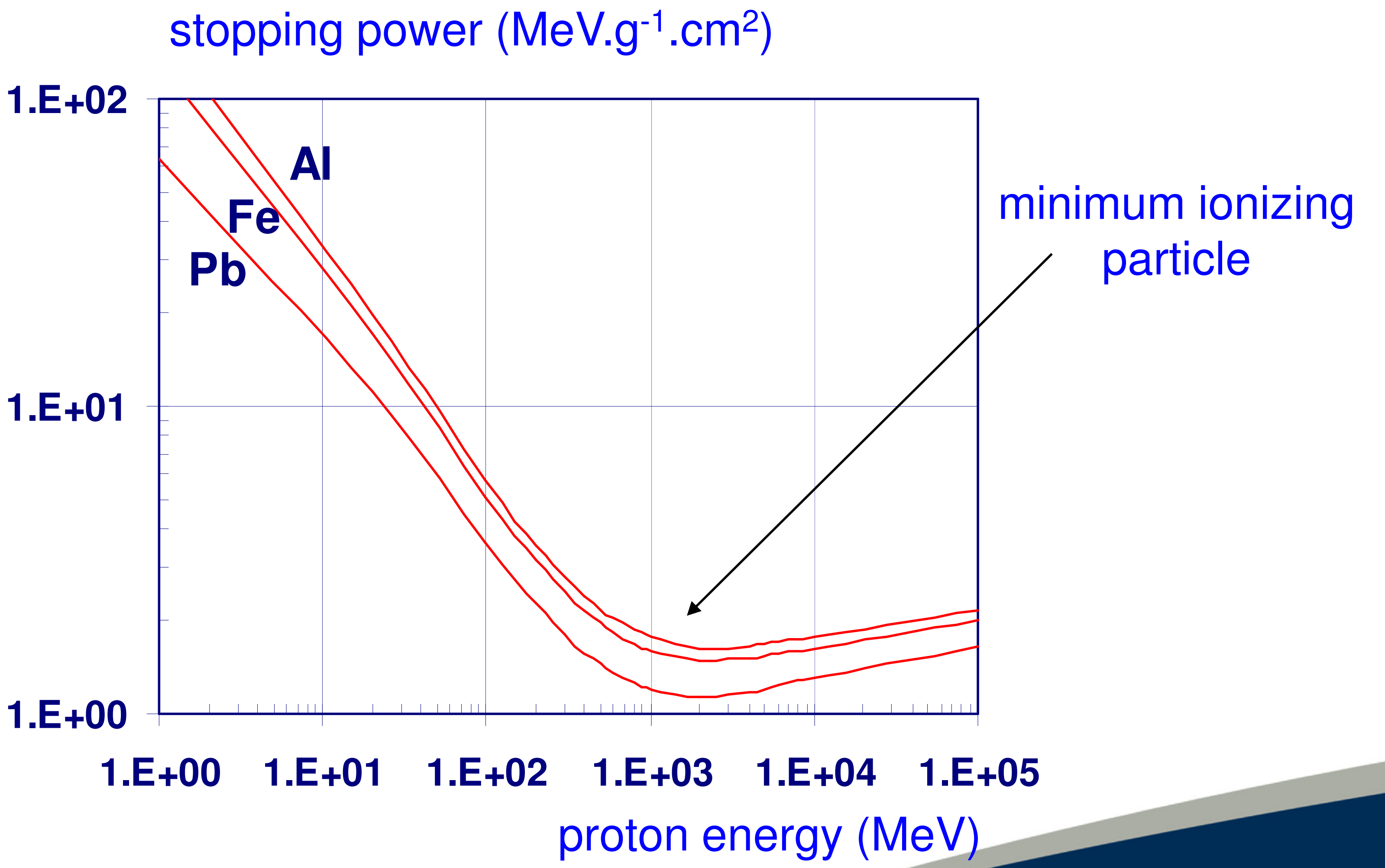
4. Interaction of protons with the matter

Proton ionization loss – Stopping power



4. Interaction of protons with the matter

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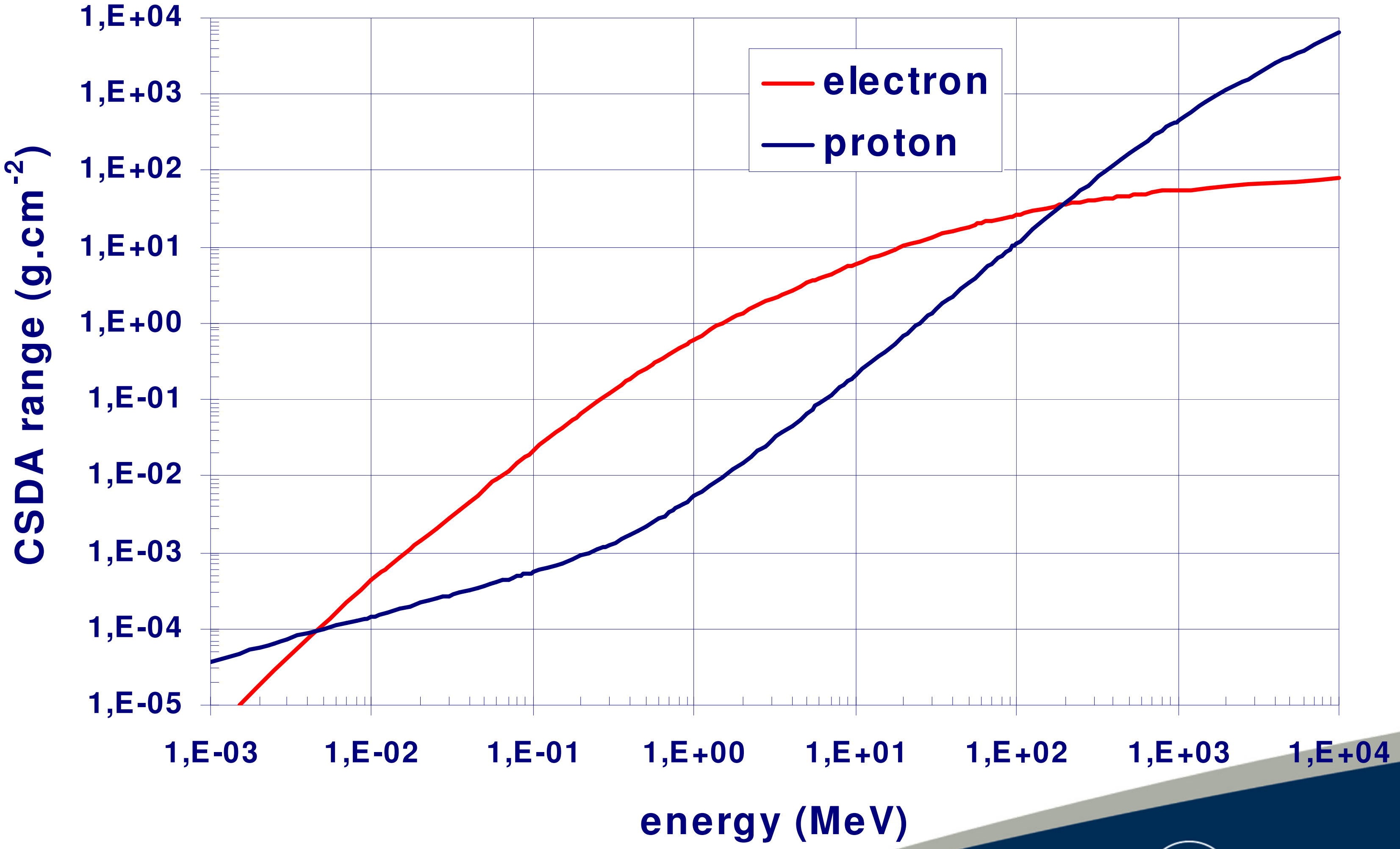
Comparison CSDA range of protons and electrons <u>in iron</u>



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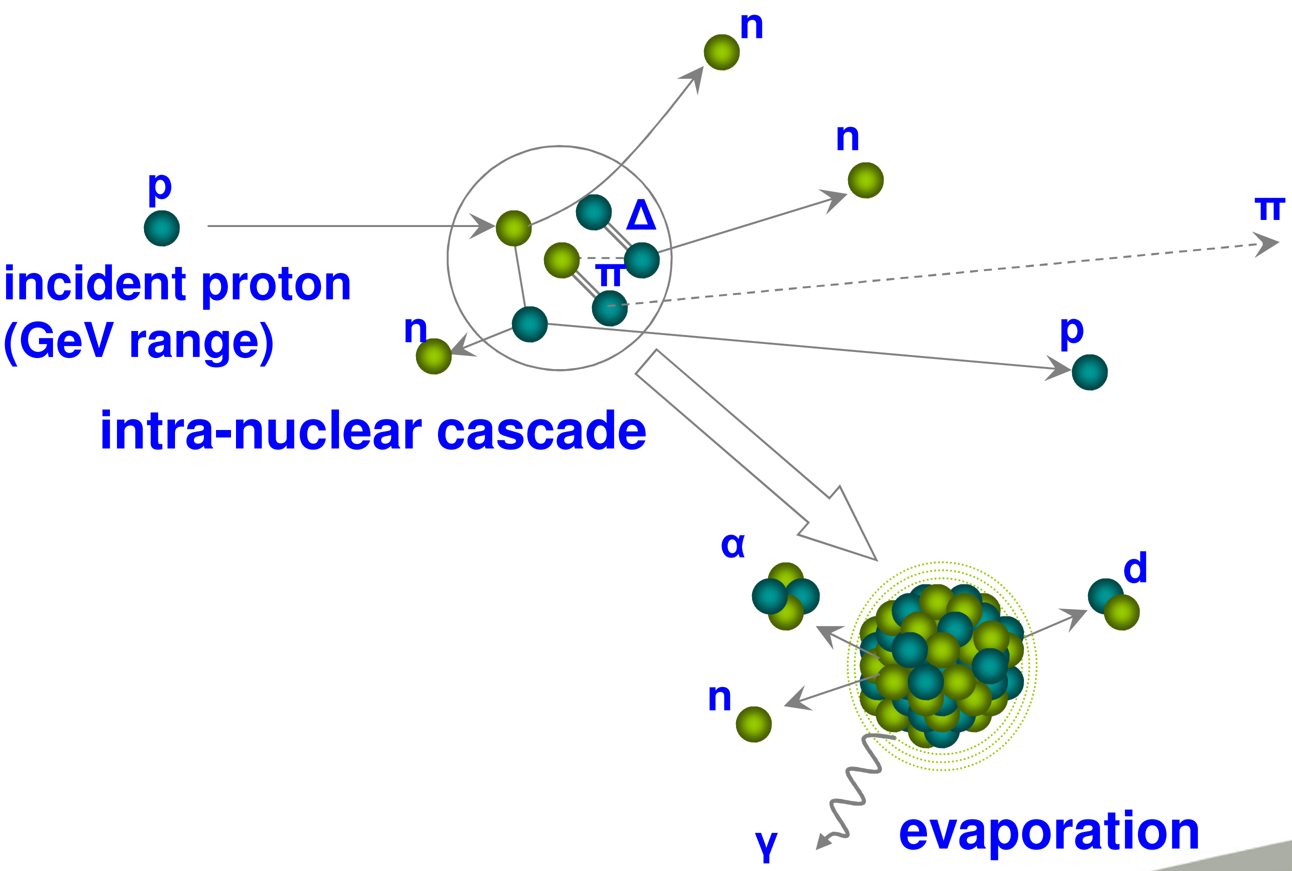
4. Interaction of protons with the matter

Inelastic proton – nucleus scattering:

Spallation reaction

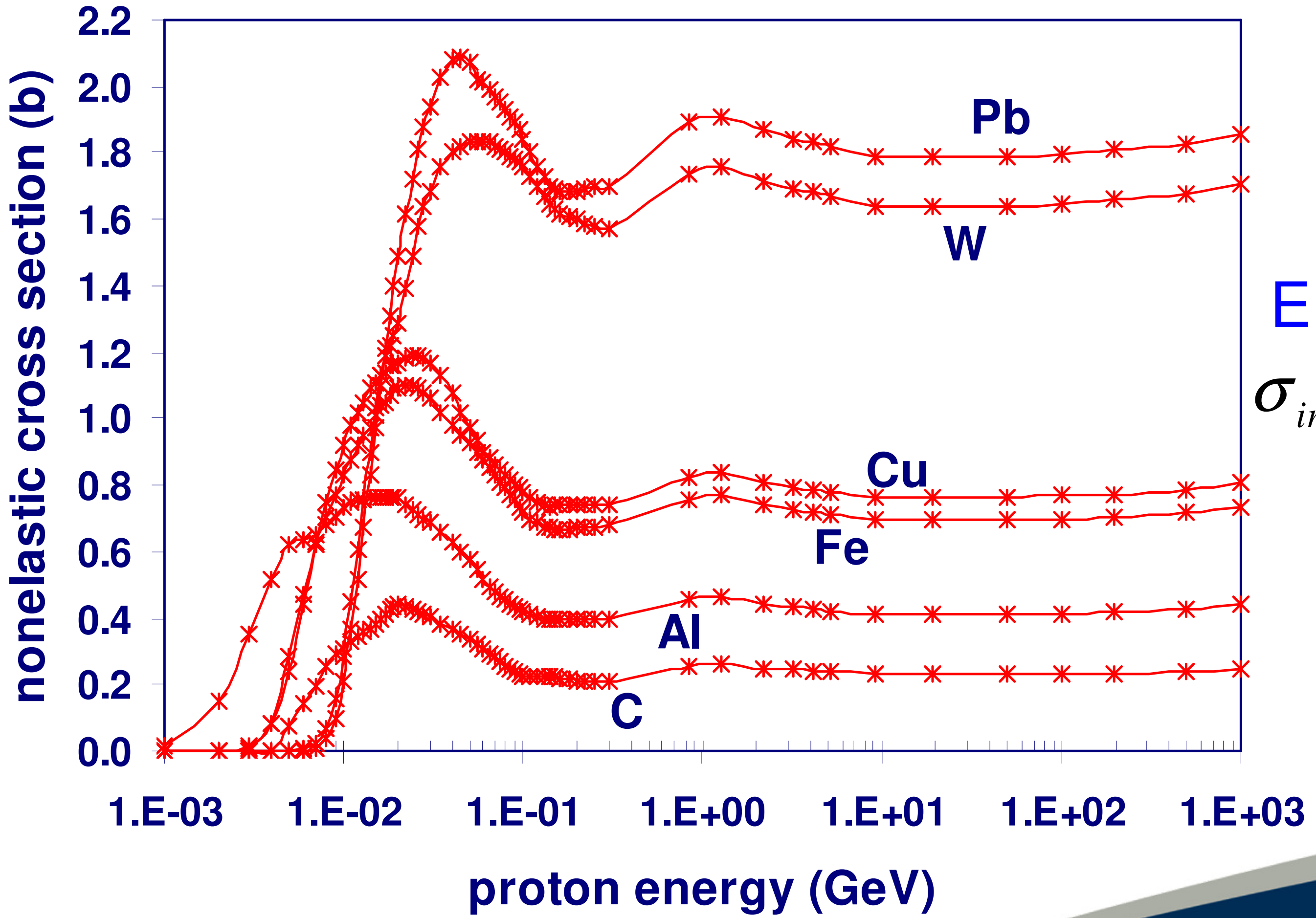


4. Interaction of protons with the matter

Inelastic proton – nucleus scattering

Spallation reaction

Inelastic cross section



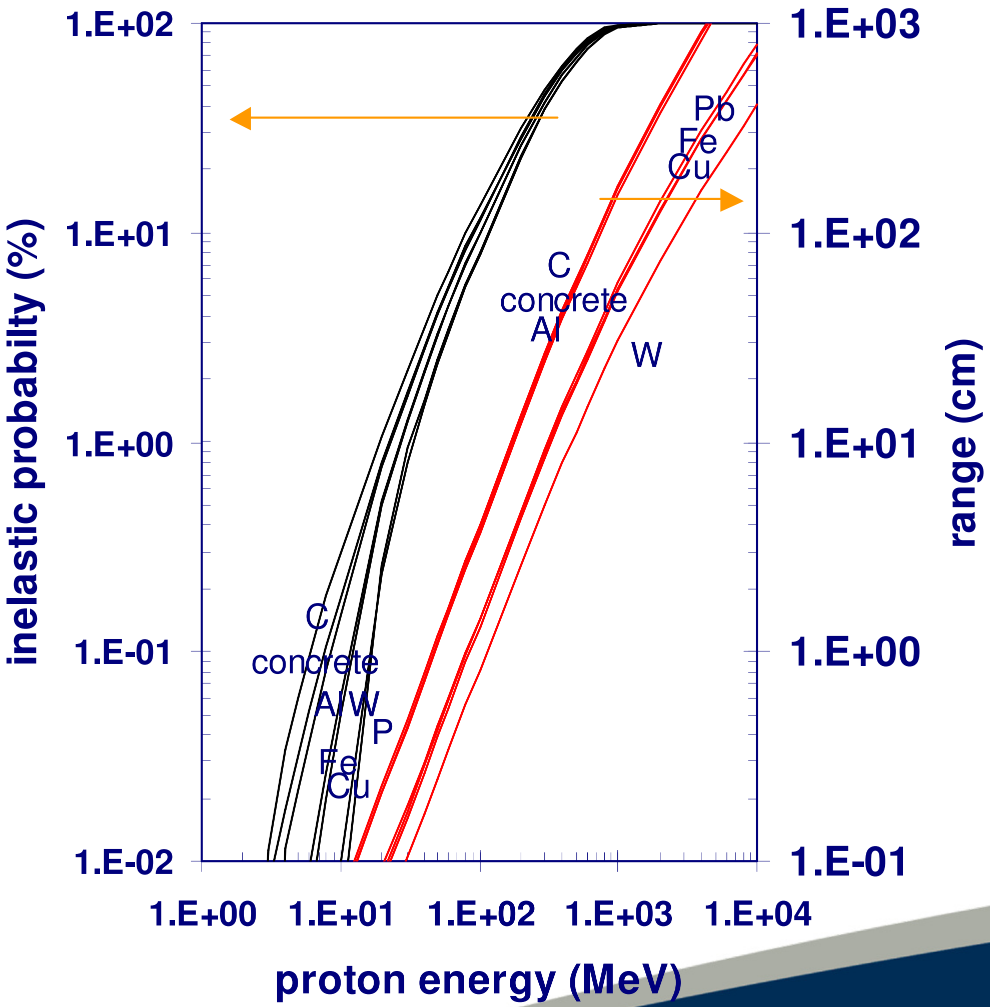
E > 1 GeV

$$\sigma_{inel} = 0.042 \times A^{0.7} barn.$$

4. Interaction of protons with the matter

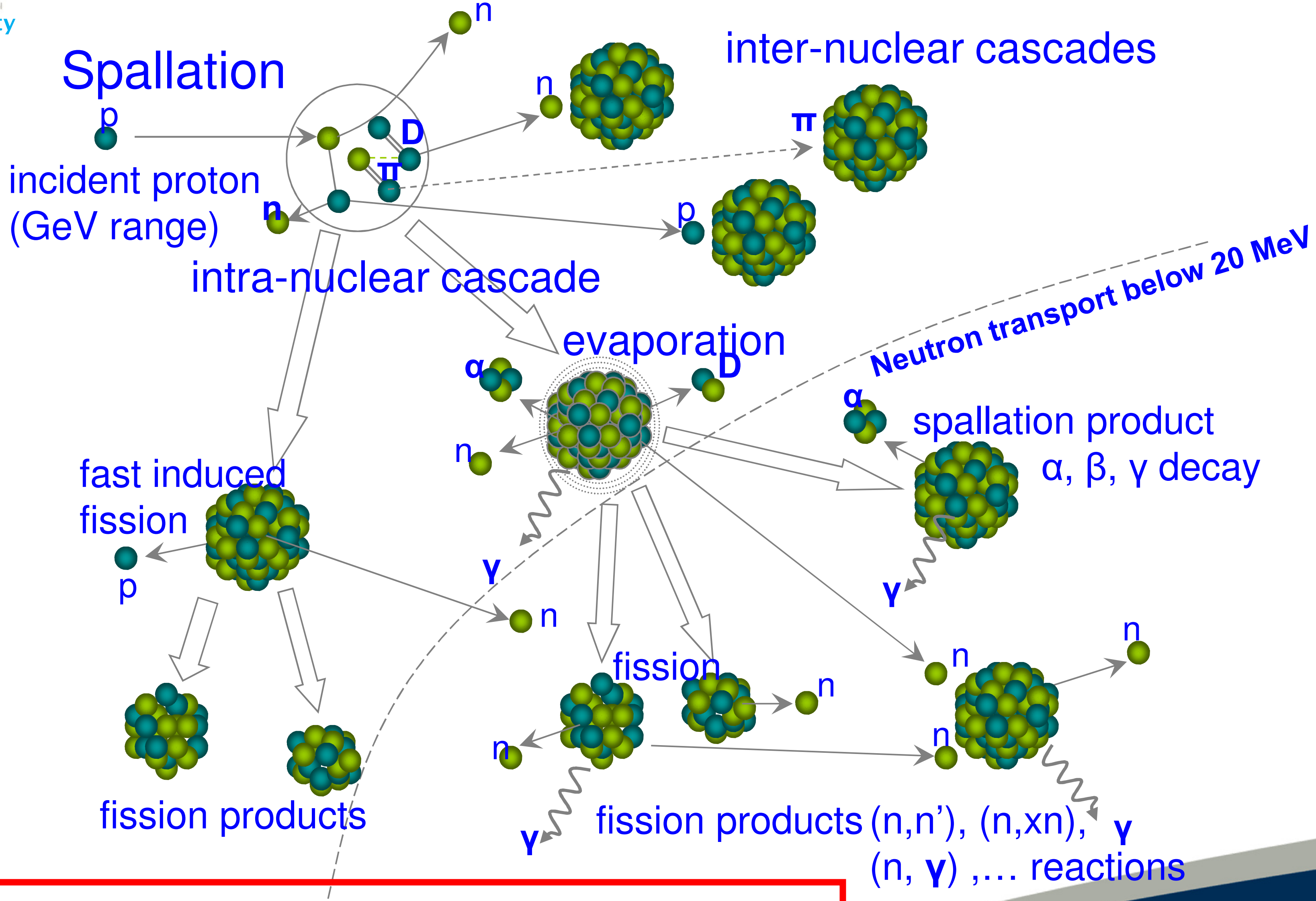
Inelastic proton – nucleus scattering

Comparison ionization energy loss and inelastic scattering



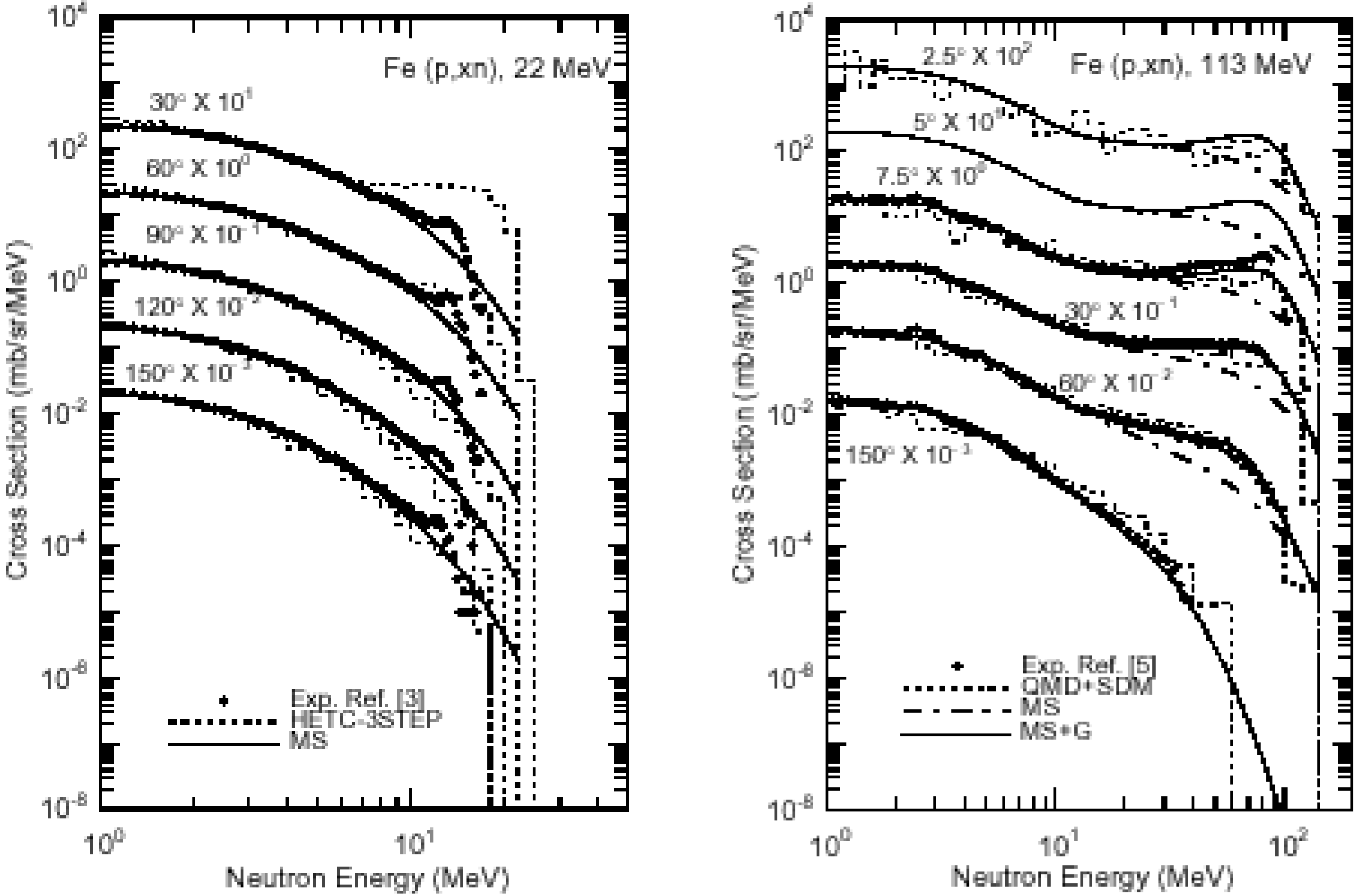
→ E > 1 GeV:
100 % probability
for spallation reaction

4. Interaction of protons with the matter

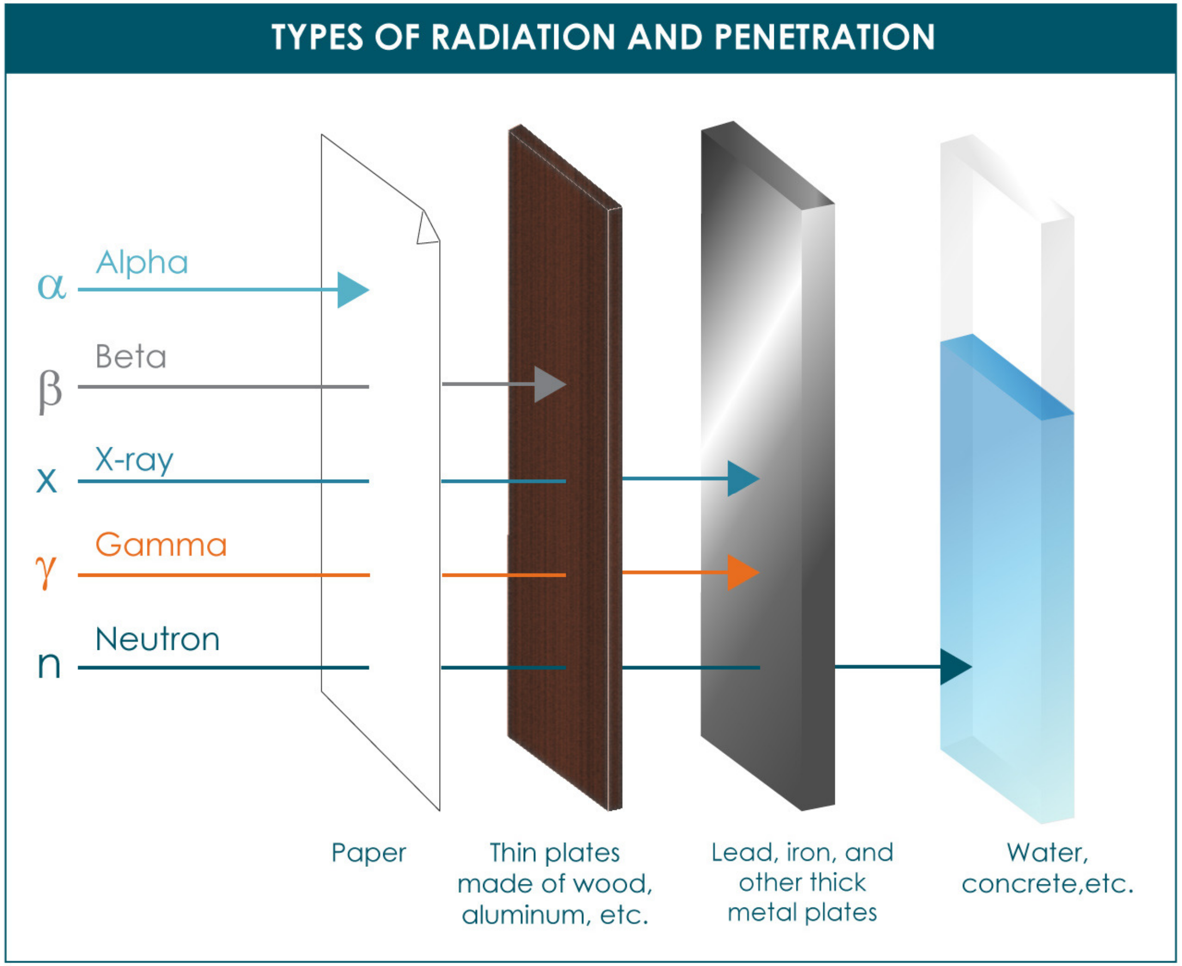


- **At ISIS:** 1 proton produces 15-20 neutrons

4. Interaction of protons with the matter
Spallation



Summary: Interaction of the radiation with the matter



From https://www.mirion.com/introduction-to-radiation-safety/types-of-ionizing-radiation/