

Part B. Radiation sources

1. Interaction of electrons-e with the matter

$$m_e = 9.11 \times 10^{-31} \text{ kg} ; E = m_e c^2 = 0.511 \text{ MeV} ; q_e = -e$$

2. Interaction of photons- γ with the matter

$$m_\gamma = 0 \text{ kg} ; E_\gamma = 0 \text{ eV} ; q_\gamma = 0$$

3. Interaction of neutrons-n with the matter

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

4. Interaction of protons-p with the matter

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

Note: for any nucleus

$$A = Z + N \left\{ \begin{array}{l} A: \text{mass number – nucleons number} \\ Z: \text{atomic number – proton (charge) number} \\ N: \text{neutron number} \end{array} \right.$$



1. Interaction of electrons with the matter

The physical processes:

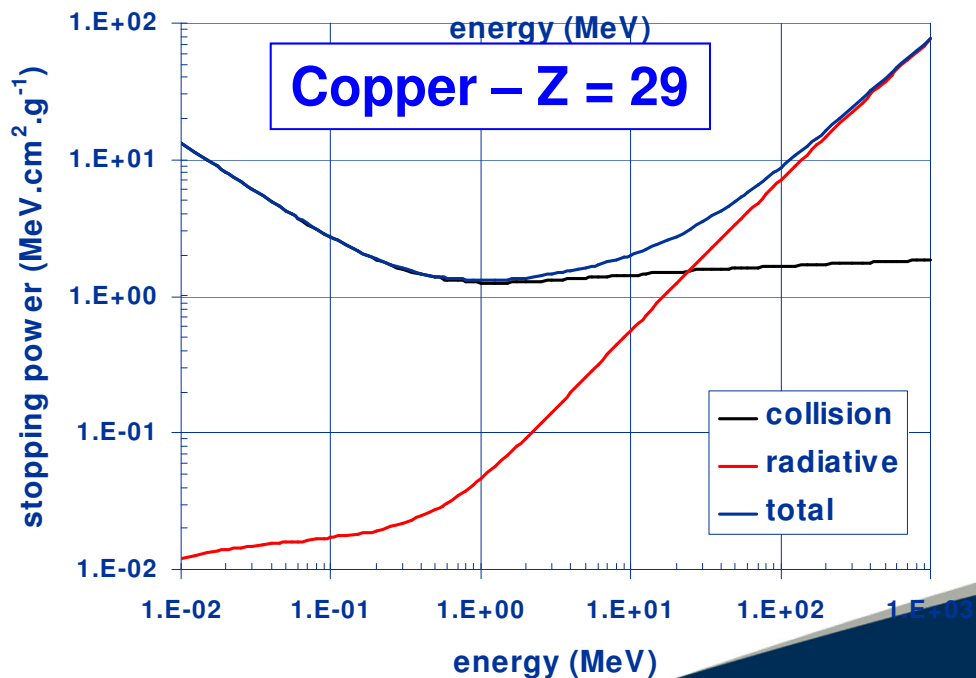
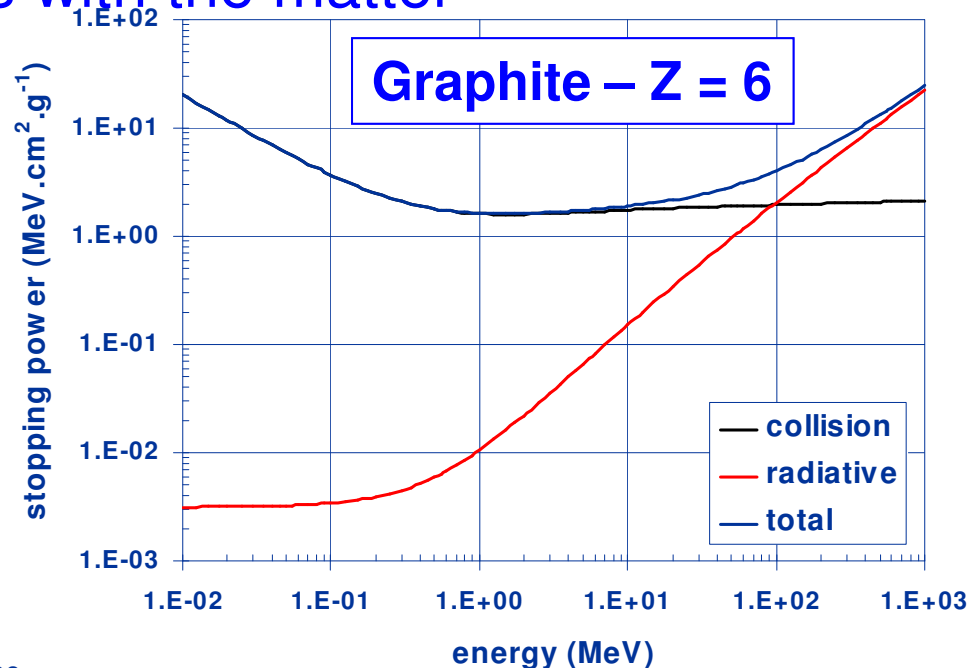
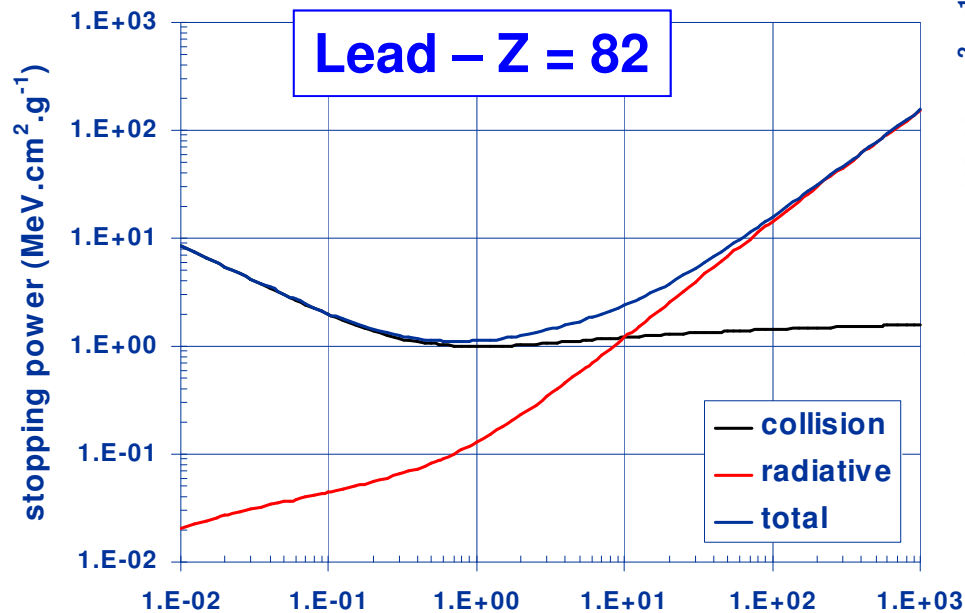
1. Ionization losses
inelastic collisions with orbital electrons
2. Bremsstrahlung losses
inelastic collisions with atomic nuclei
3. Rutherford scattering
elastic collisions with atomic nuclei

Positrons

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



1. Interaction of electrons with the matter



Electrons – stopping power

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

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

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

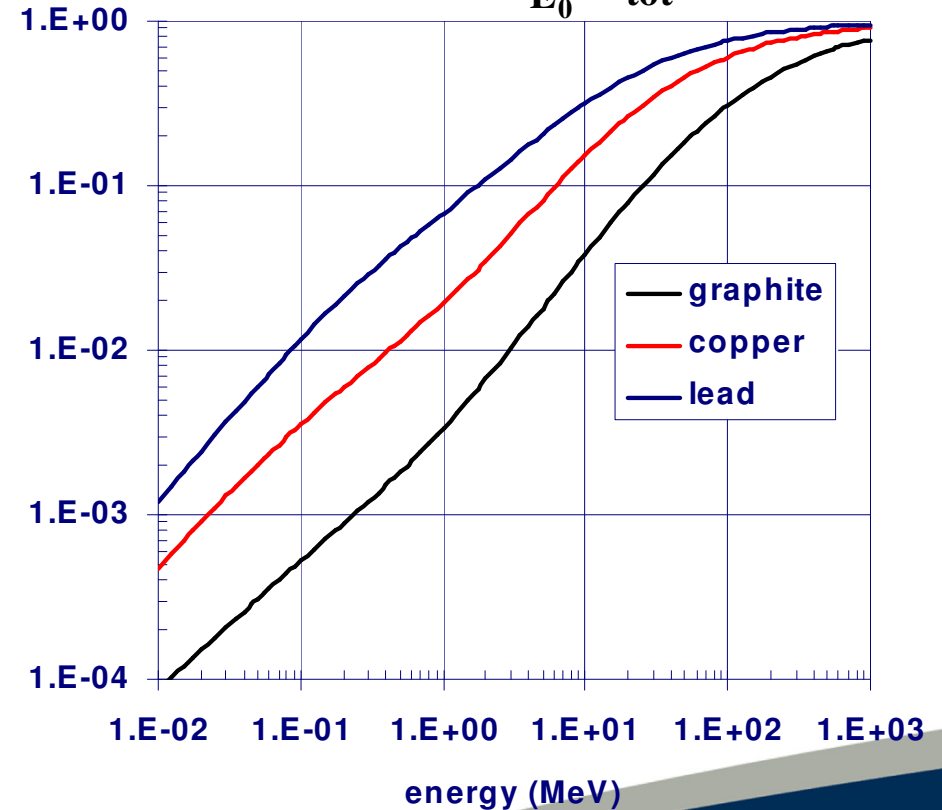
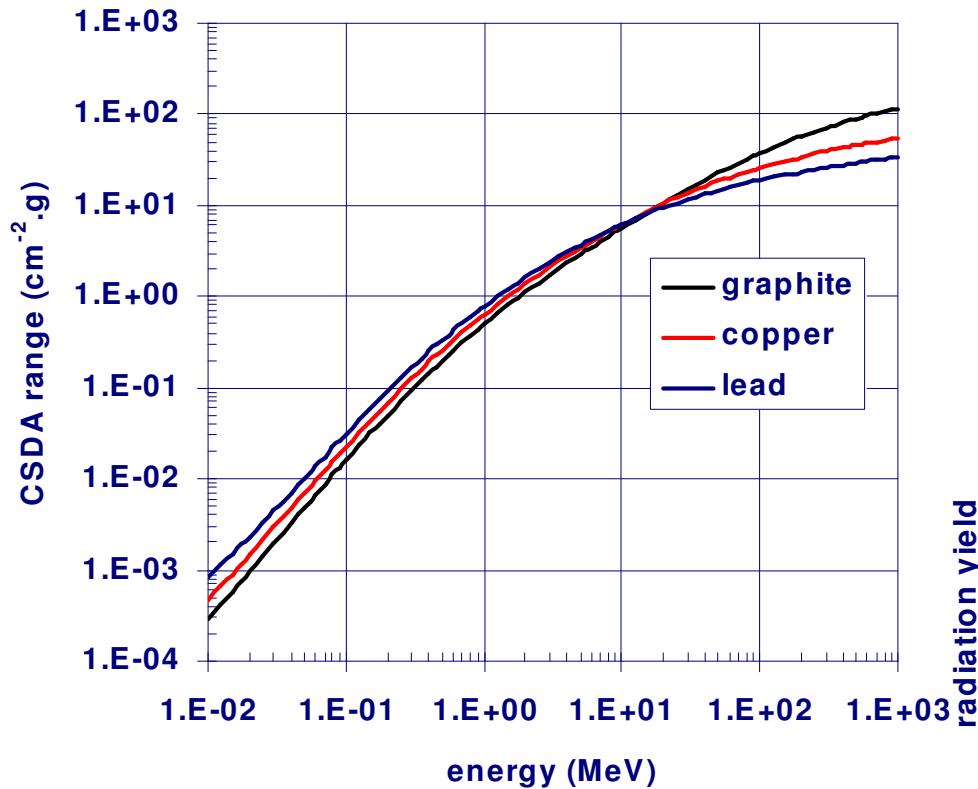
$$\frac{dE}{dl} : \text{linear stopping power (MeV.cm}^{-1}\text{)}$$



1. Interaction of electrons with the matter

Continuous Slowing Down Approximation range:

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



Radiation yield:

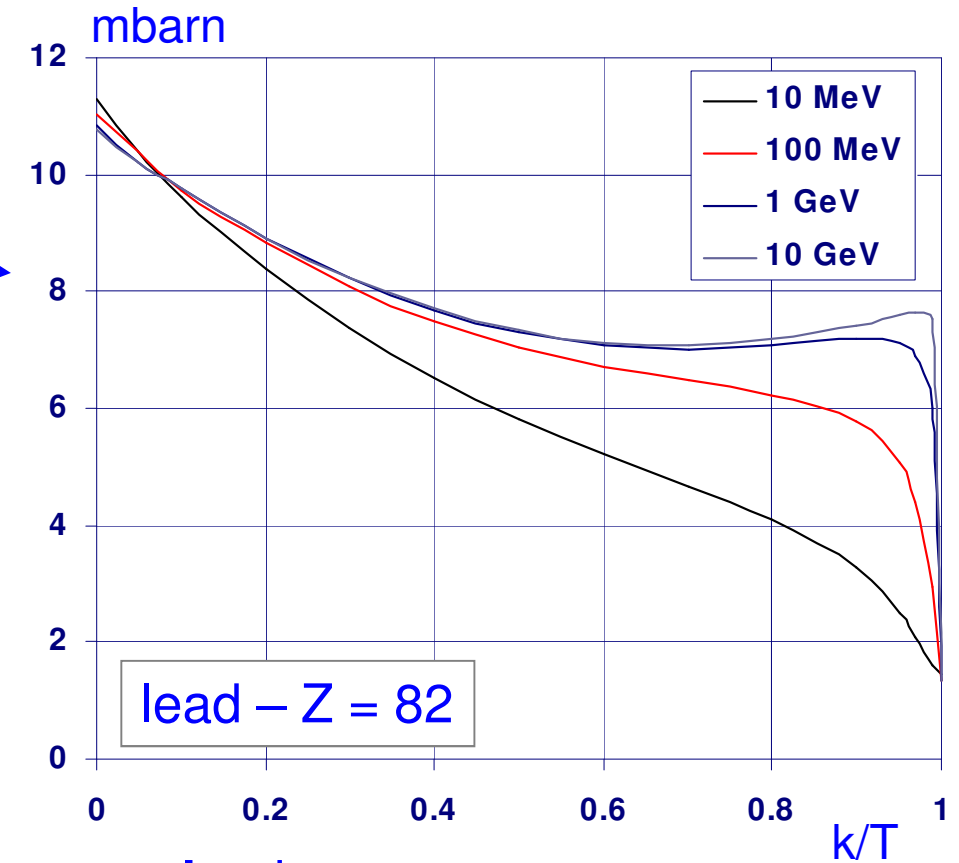
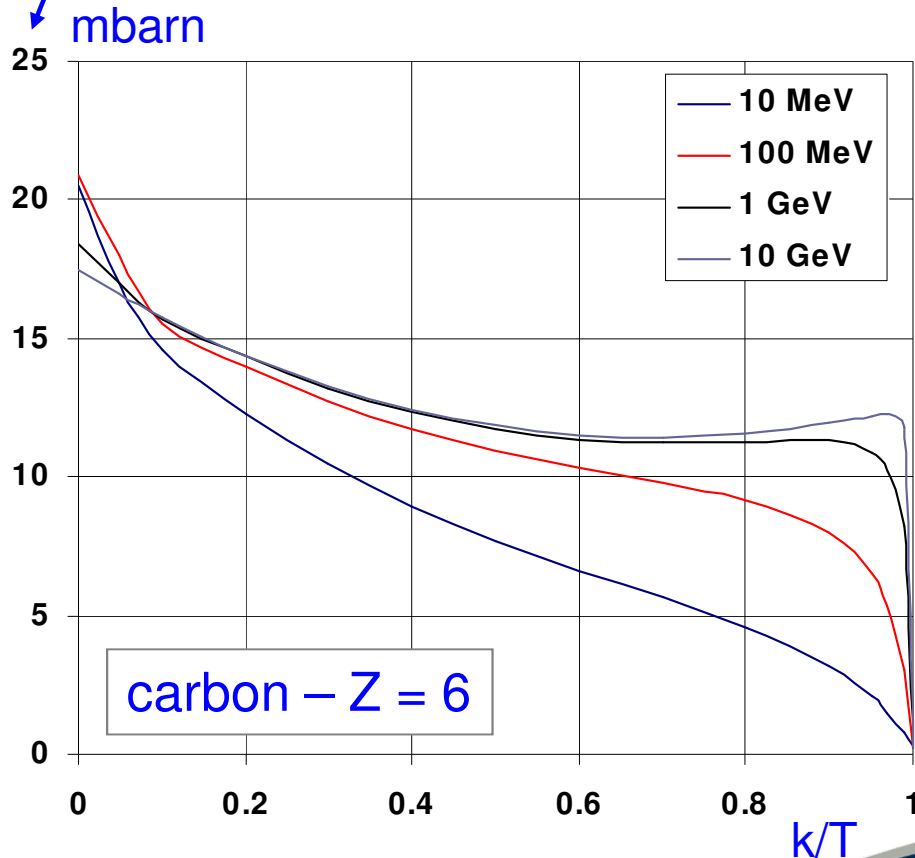
Fraction of the initial kinetic energy that is converted to Bremsstrahlung energy as the electron slows down to rest.



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}

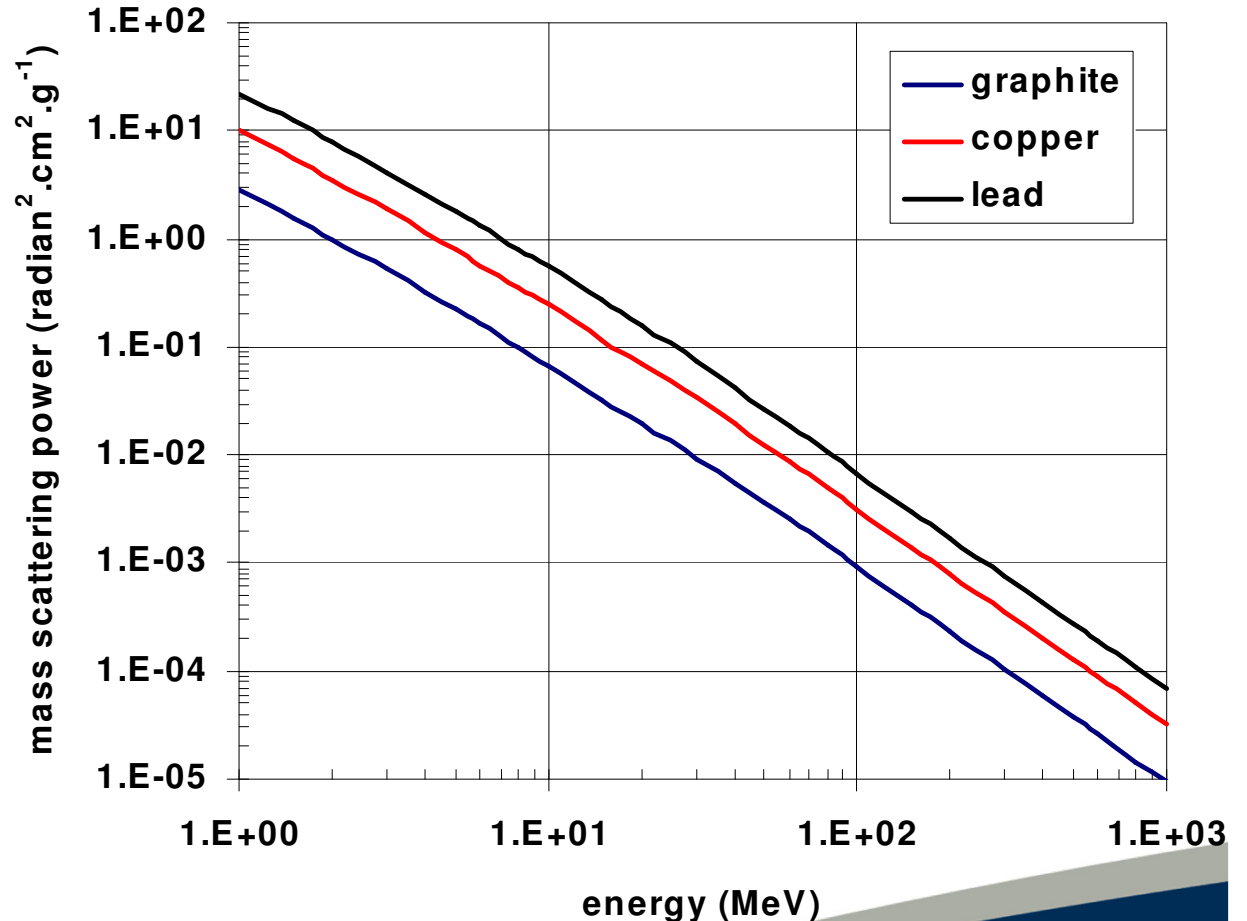
$$S_{sc} = \frac{1}{\rho} \frac{d\langle \theta^2 \rangle}{dx} \quad \longrightarrow$$

$$E_s = 21.2 \text{ MeV}$$

X_0 : radiation length

β : v/c

p : momentum



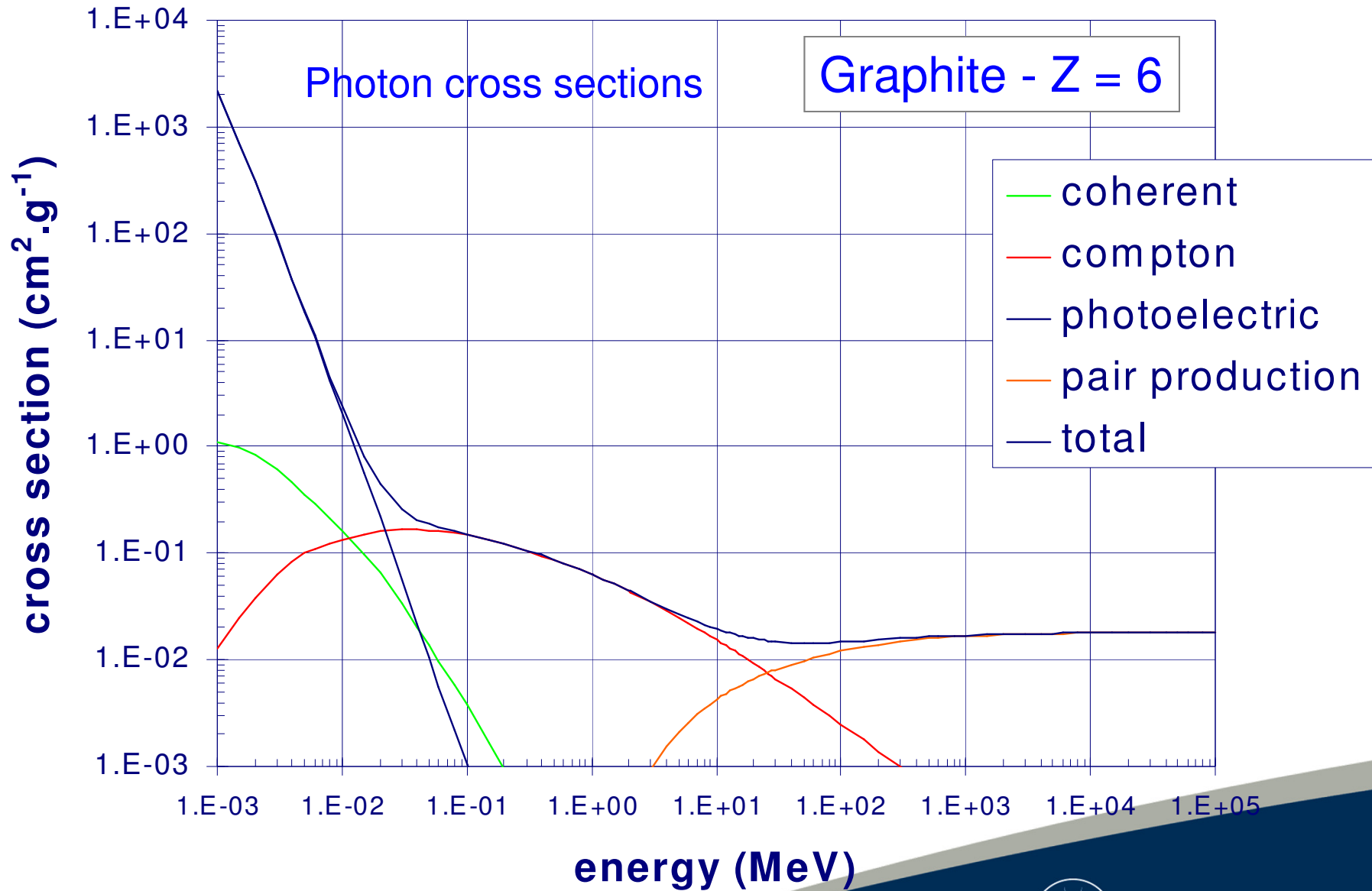
2. Interaction of photons with the matter

The physical processes:

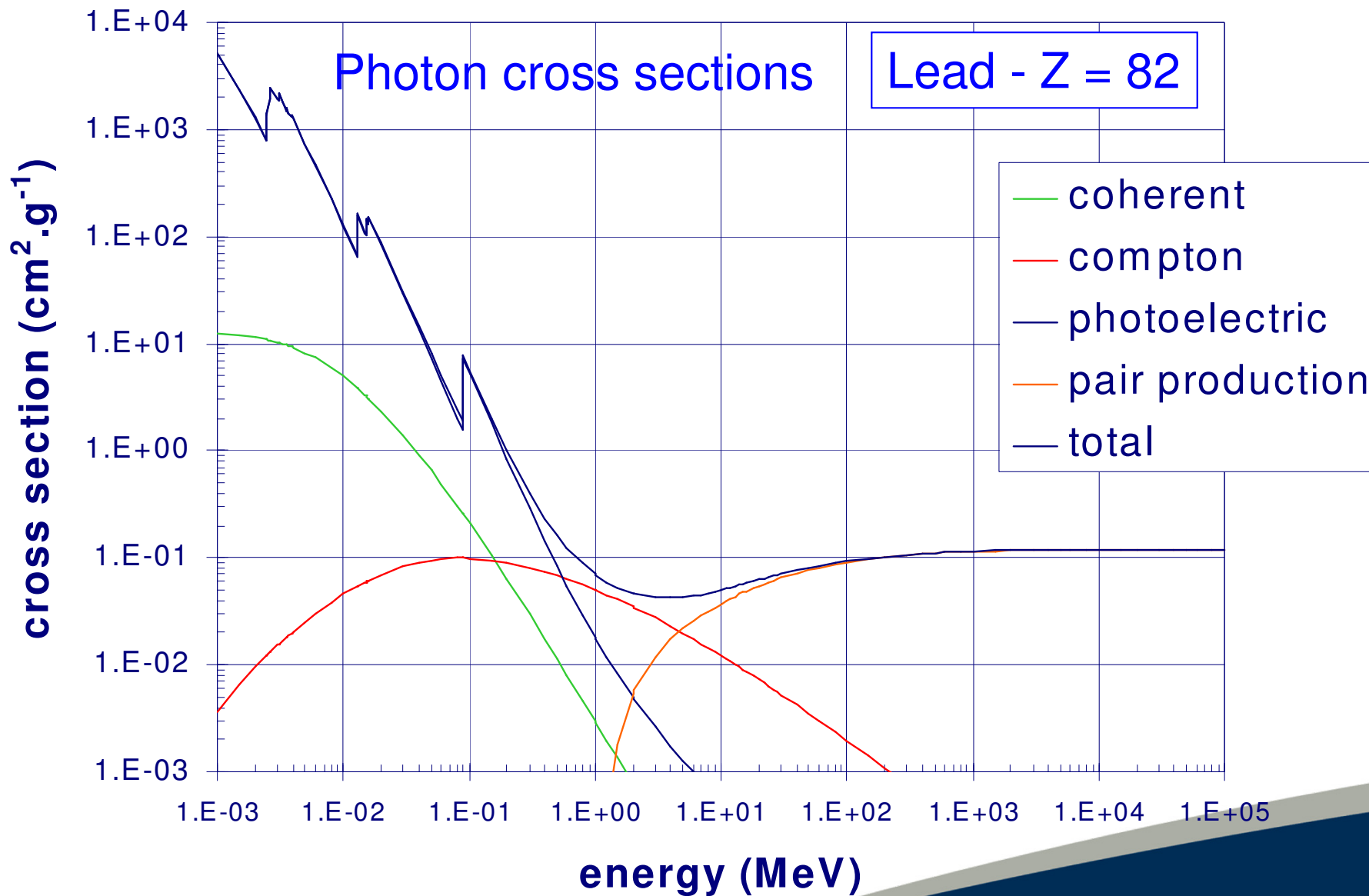
1. Photo-electric effect
removal of an orbital electron of the inner shells (K,L,M)
 2. Compton scattering
inelastic scattering on loosely bound electrons
 3. Pair production
production of e^-/e^+ pair
essentially with nuclei
-
4. Rayleigh (coherent) scattering
elastic scattering
not important for radiation physics



2. Interaction of photons with the matter

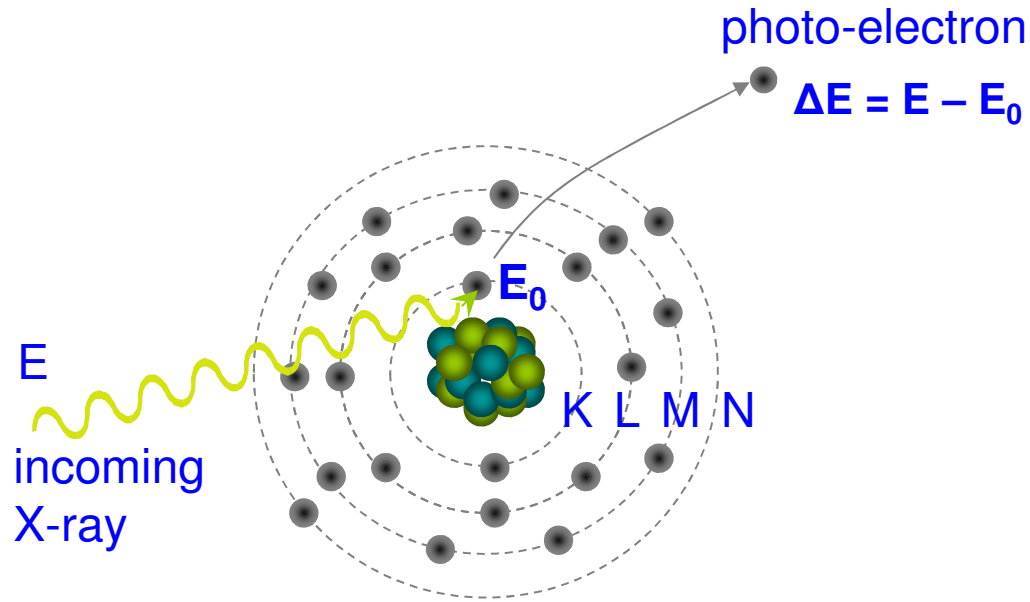


2. Interaction of photons with the matter



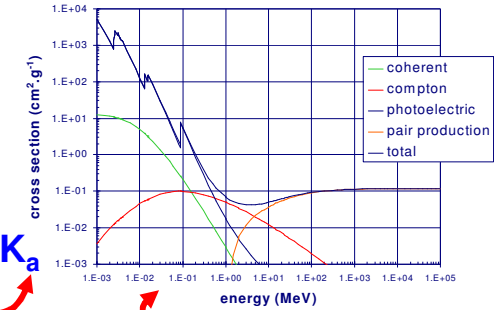
2. Interaction of photons with the matter

Photo-electric effect:



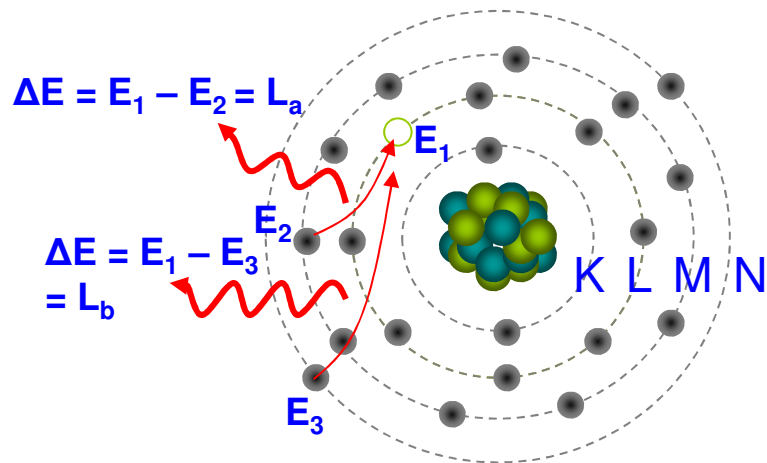
$\Delta E = E_0 - E_1 = K_a$

$\Delta E = E_0 - E_2 = K_b$



Auger electron

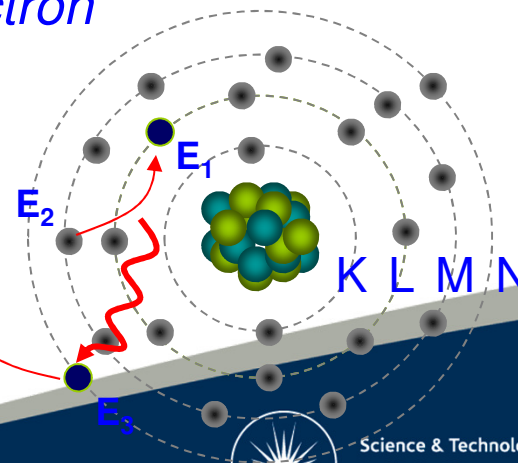
The K lines



The L lines

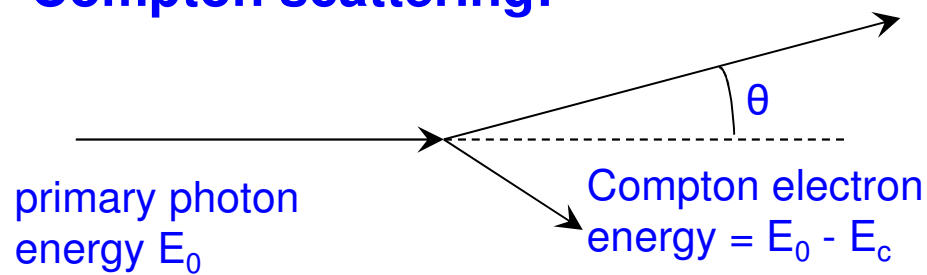
Auger-electron

$\Delta E = E_1 - E_2 - E_3$



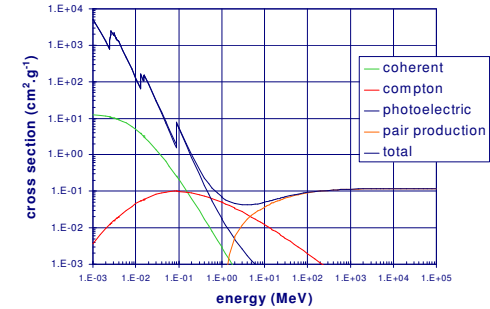
2. Interaction of photons with the matter

Compton scattering:

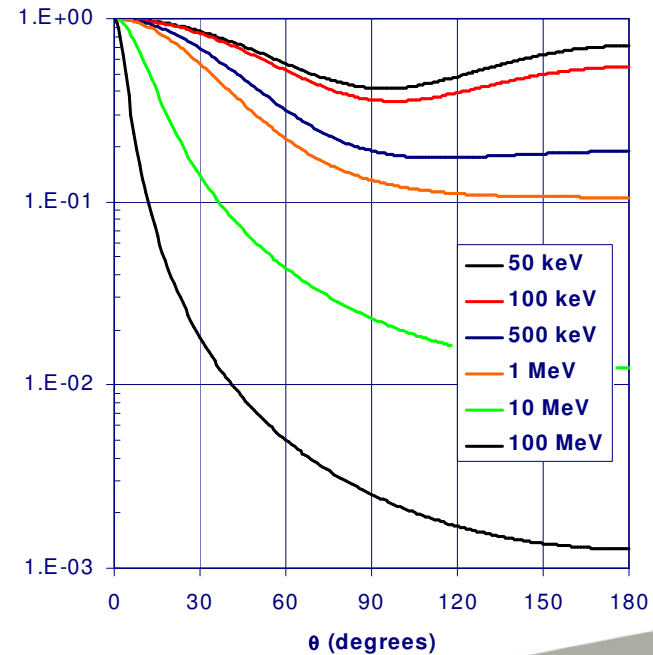
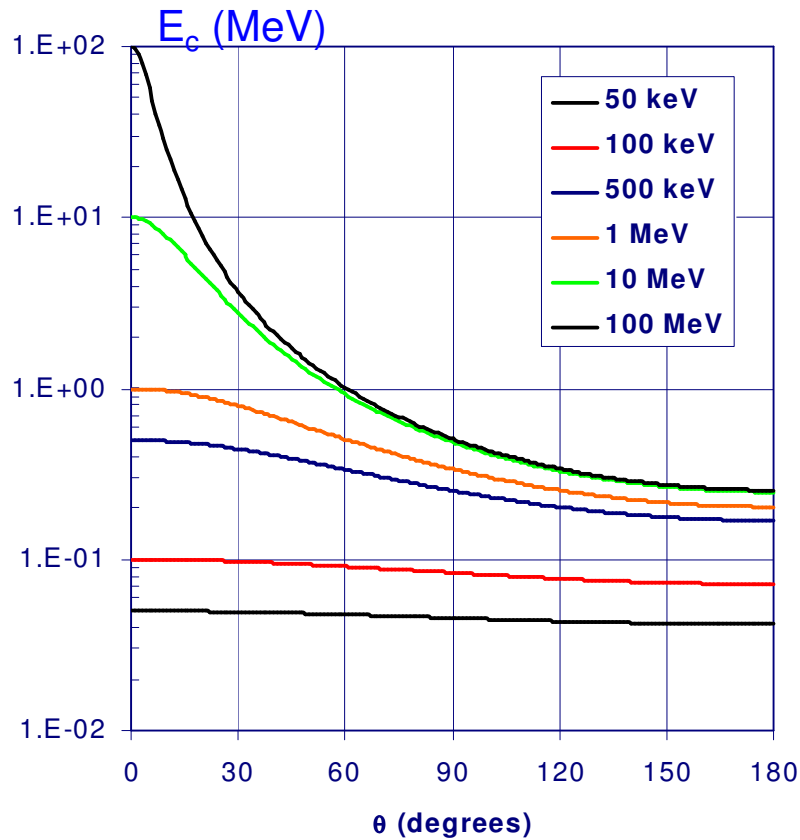


scattered photon energy E_c

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



$d\sigma/dW$ ($r_e^2 \times \text{cm}^2 / \text{electron}$)

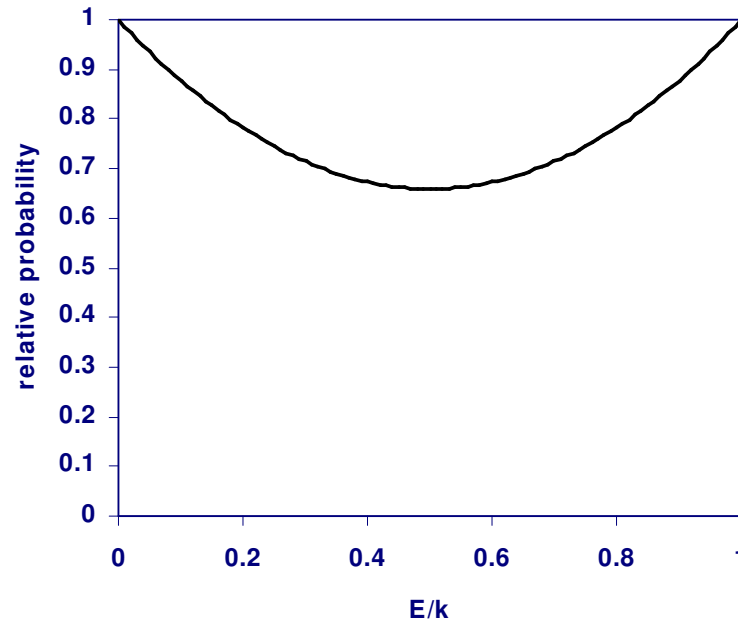
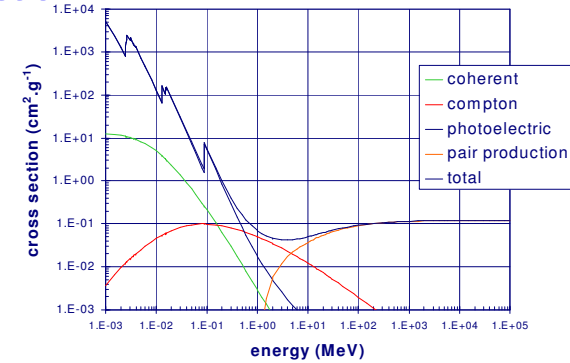


2. Interaction of photons with the matter

Pair production:

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

$\sigma_{\text{electron}} \propto Z$
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: $\text{cm}^2 \cdot \text{g}^{-1}$

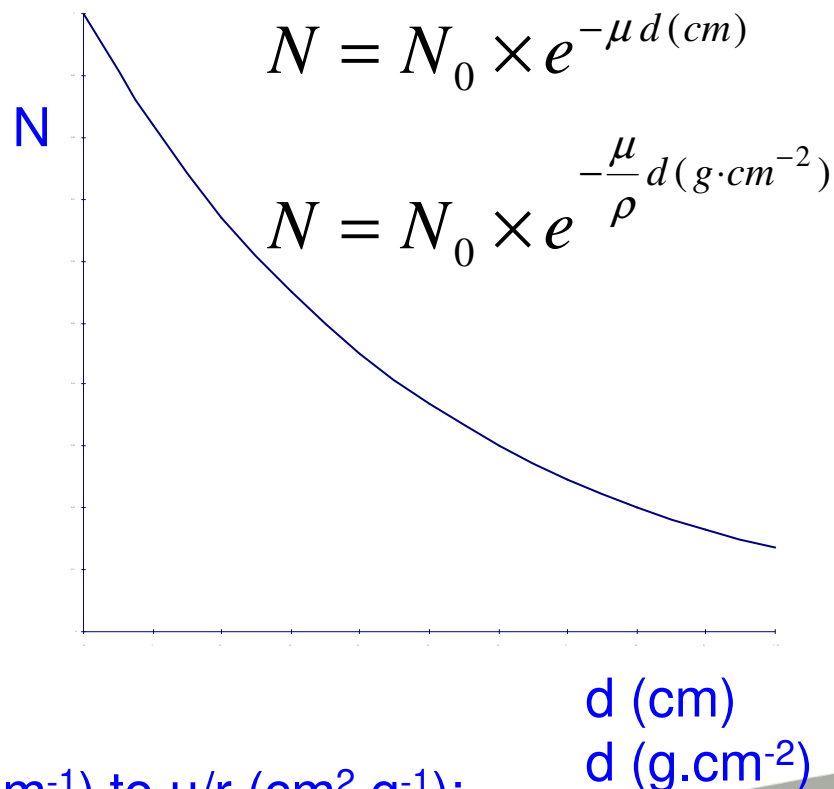
The linear attenuation coefficient μ :

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

units: cm^{-1}

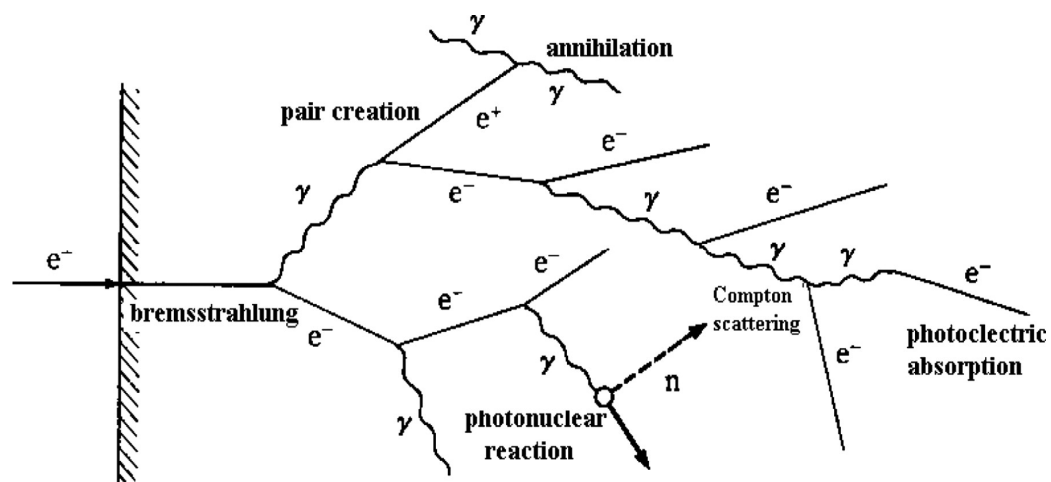
The conversion factor from σ (barns.atom⁻¹) to μ/ρ ($\text{cm}^2 \cdot \text{g}^{-1}$):

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



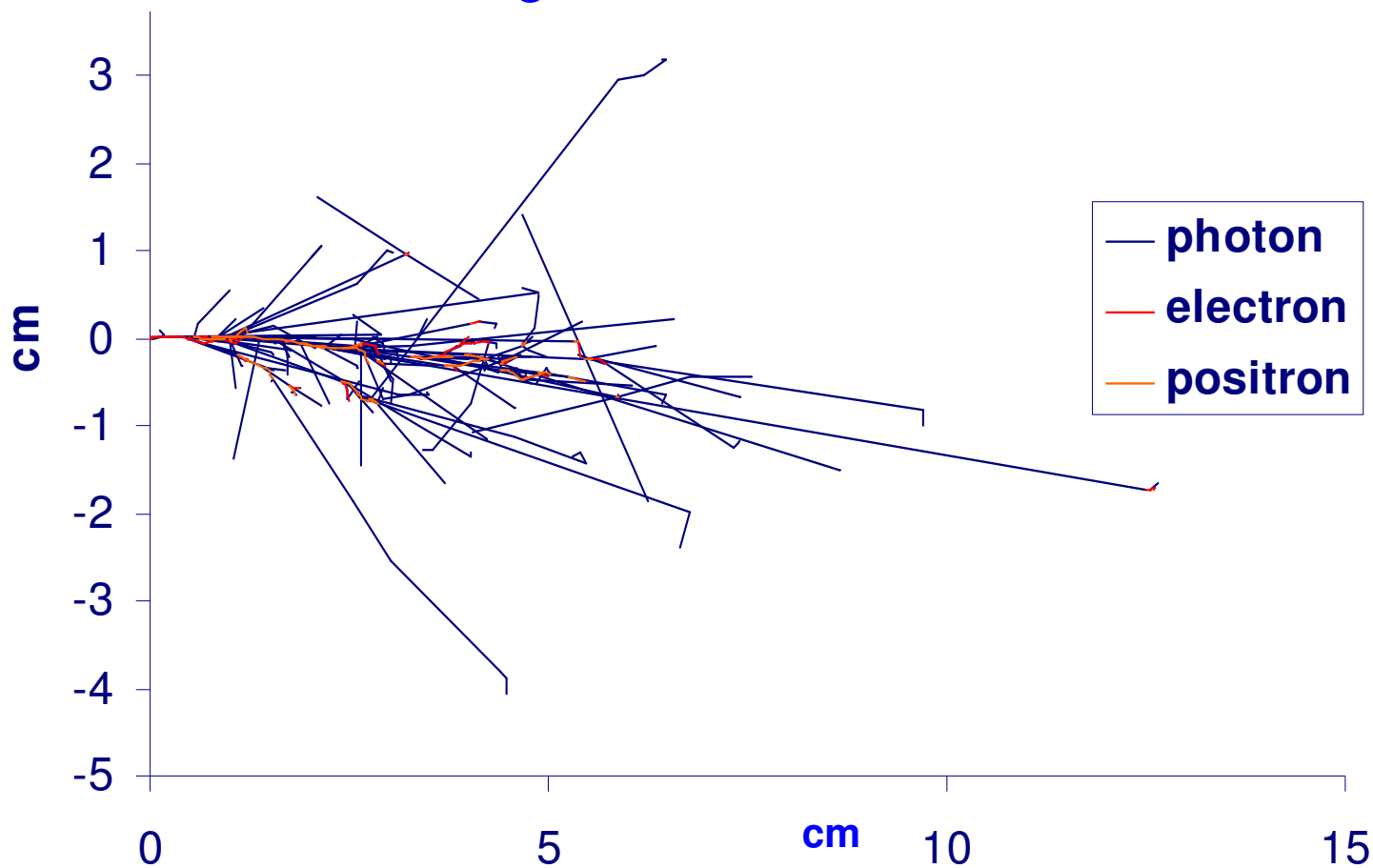
2. Interaction of photons with the matter

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



2. Interaction of photons with the matter

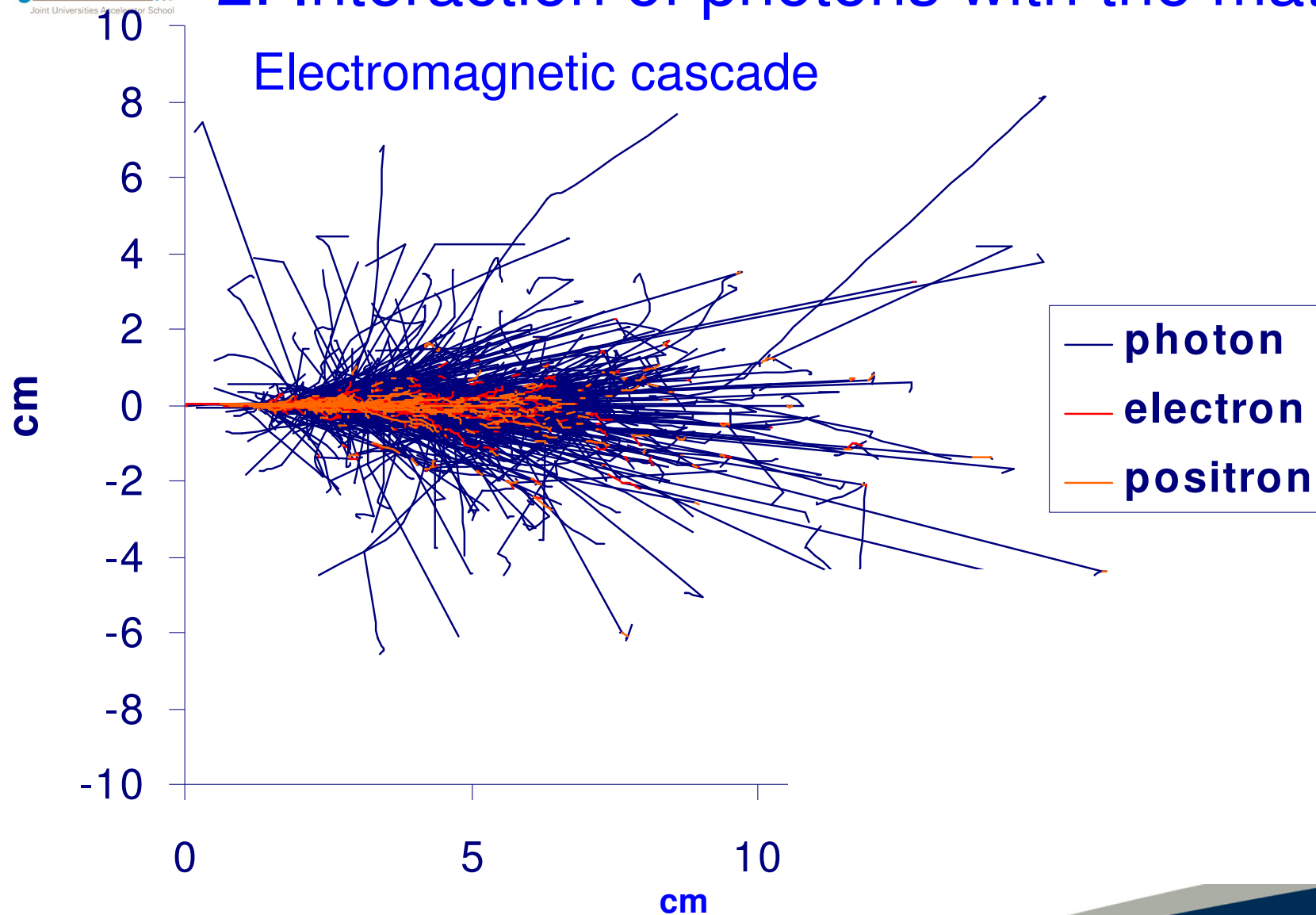
Electromagnetic cascade



one 500 MeV electron interacting
with lead target



2. Interaction of photons with the matter

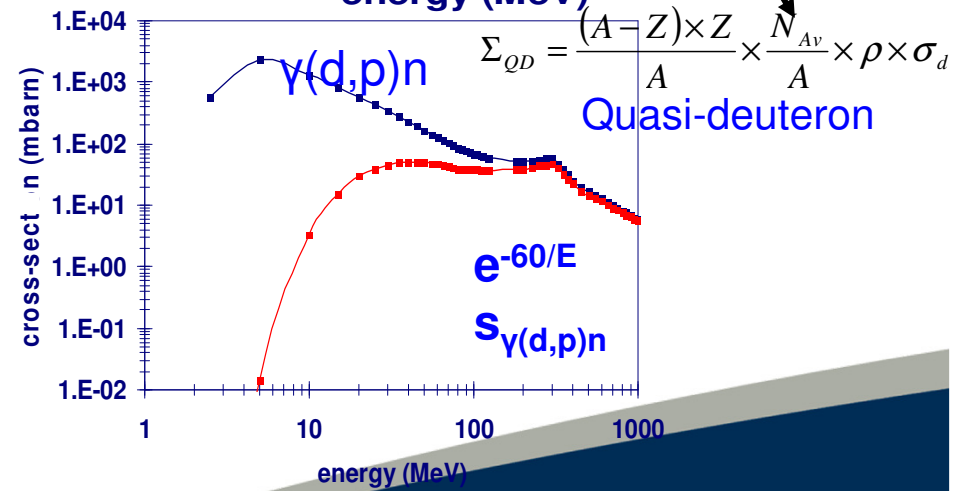
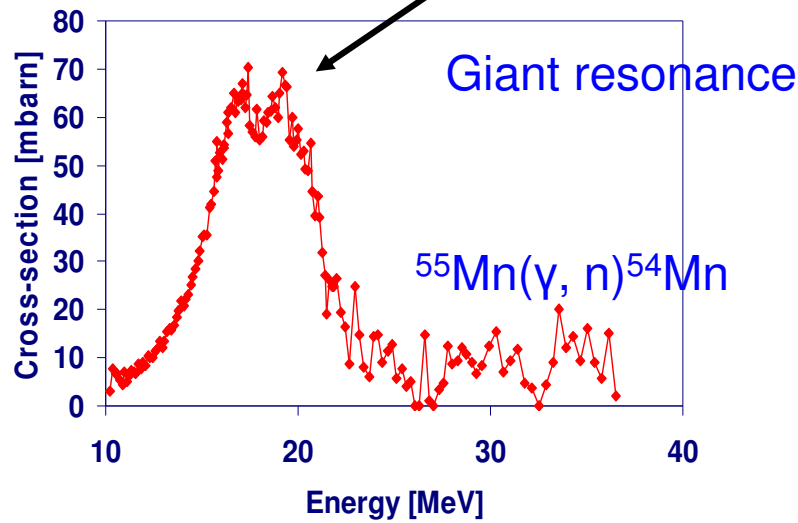
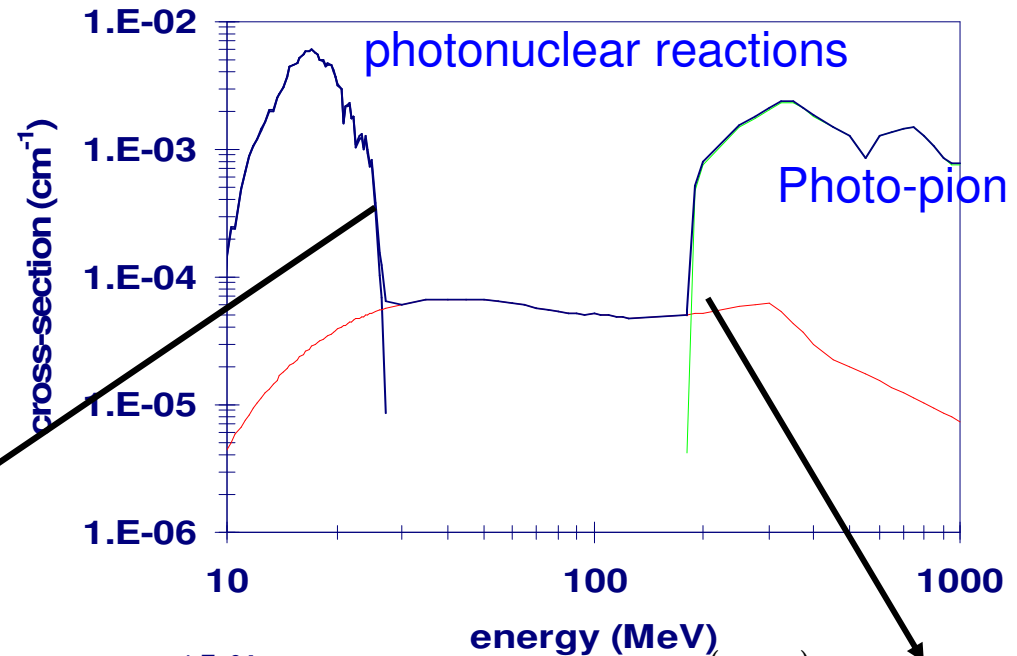


one 6 GeV electron interacting with
lead target



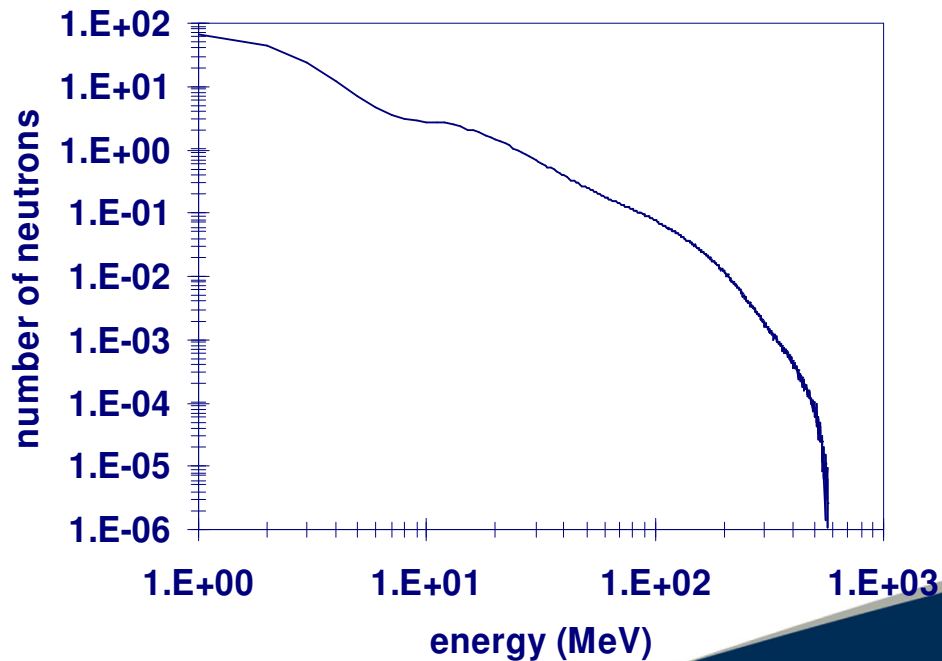
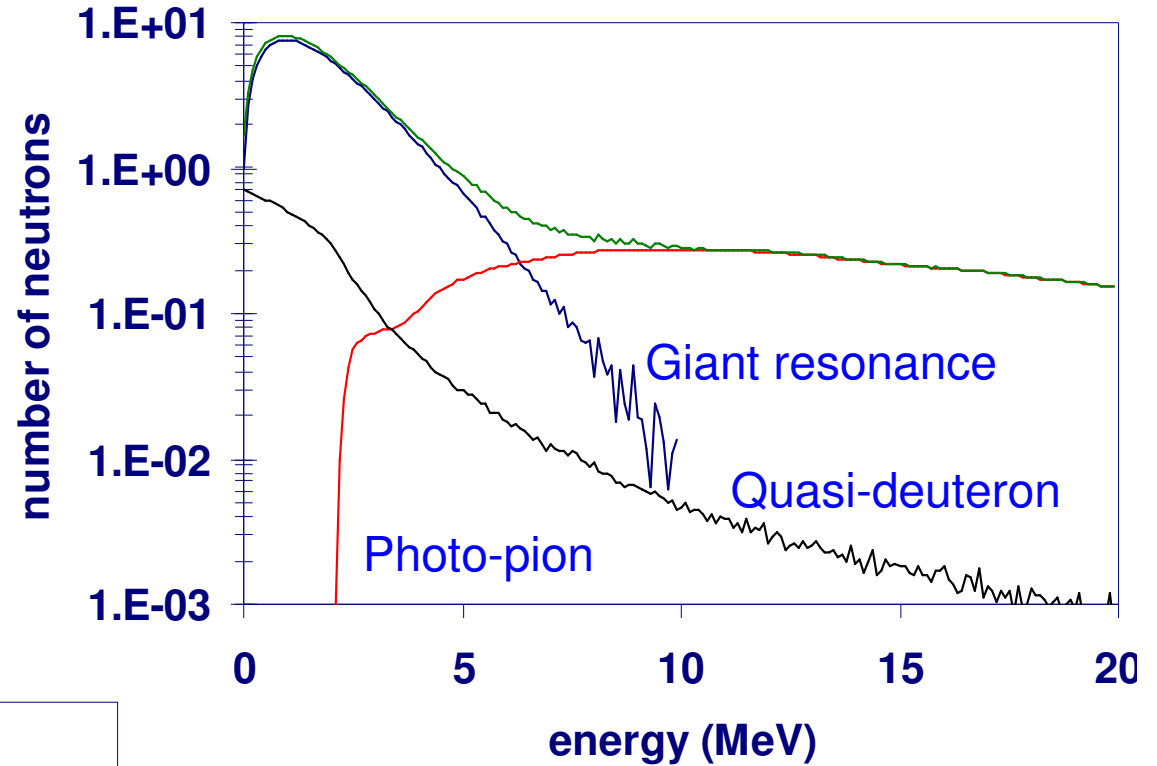
2. Interaction of photons with the matter

Photonuclear reactions:
Neutron production



2. Interaction of photons with the matter

Photonuclear reactions: Neutron production



Example: neutron spectrum
produced by 600 MeV electrons
on Cu target



3. Interaction of neutrons with the matter

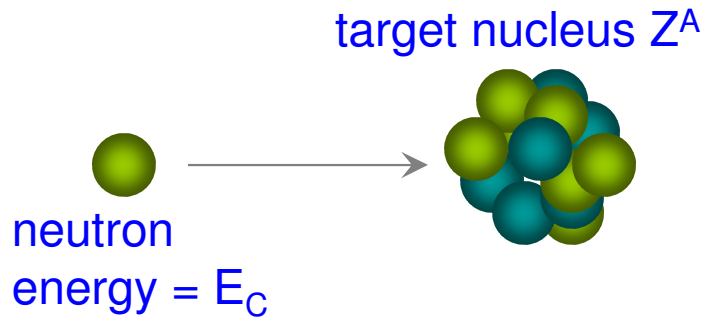
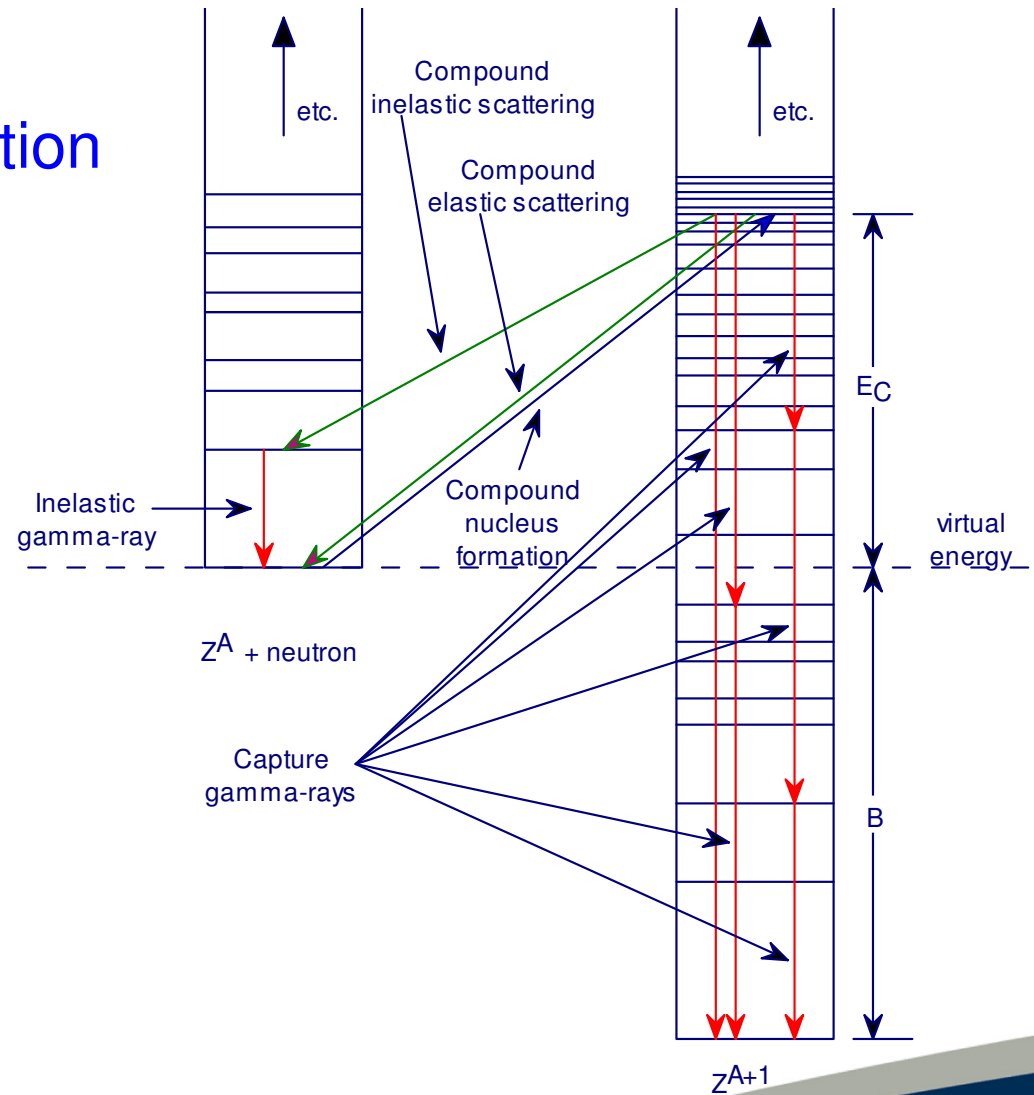
The physical processes:

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



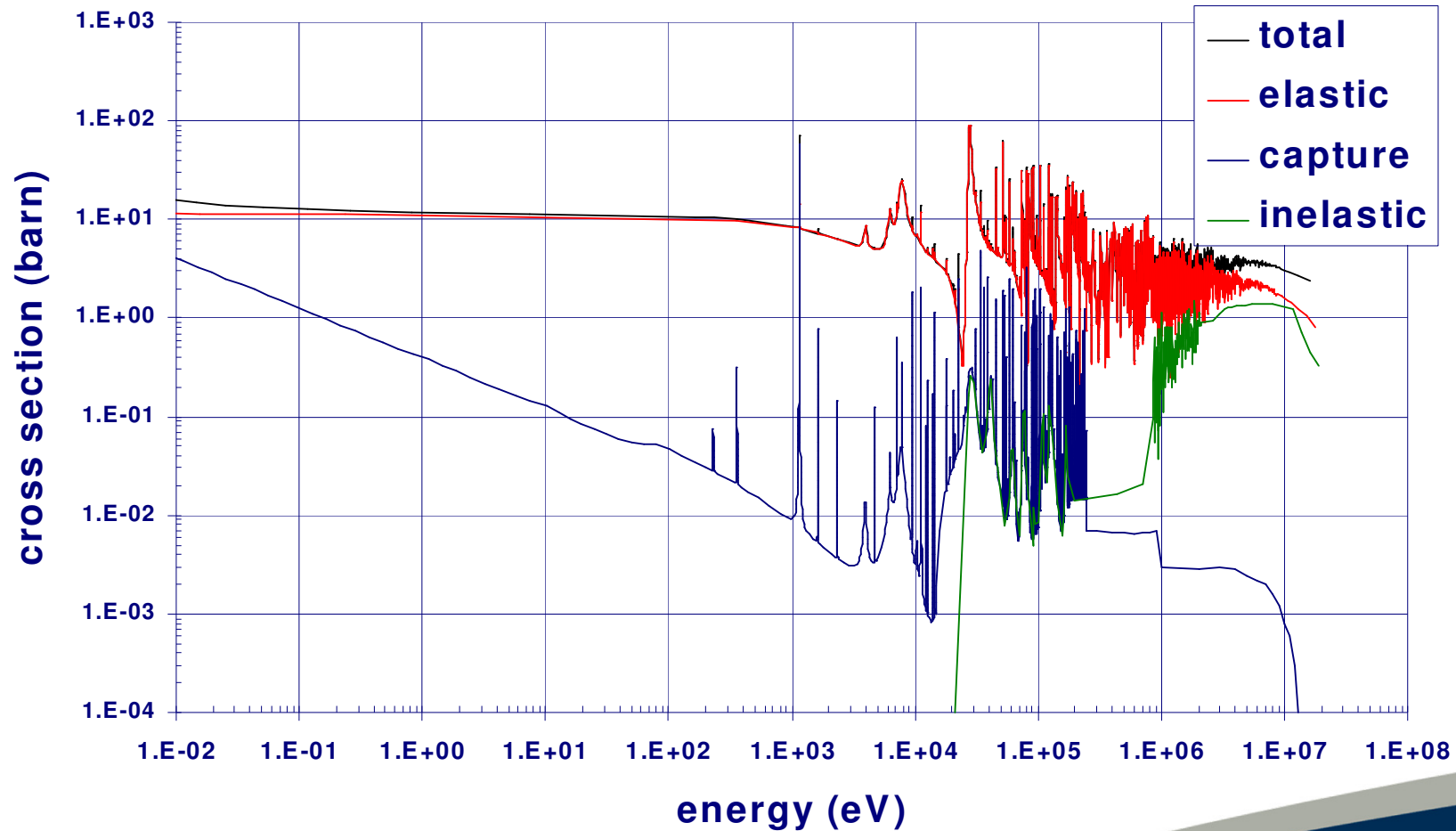
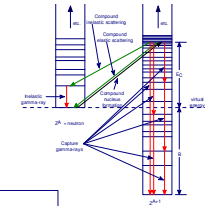
3. Interaction of neutrons with the matter

Compound nucleus formation



3. Interaction of neutrons with the matter

Neutron cross sections

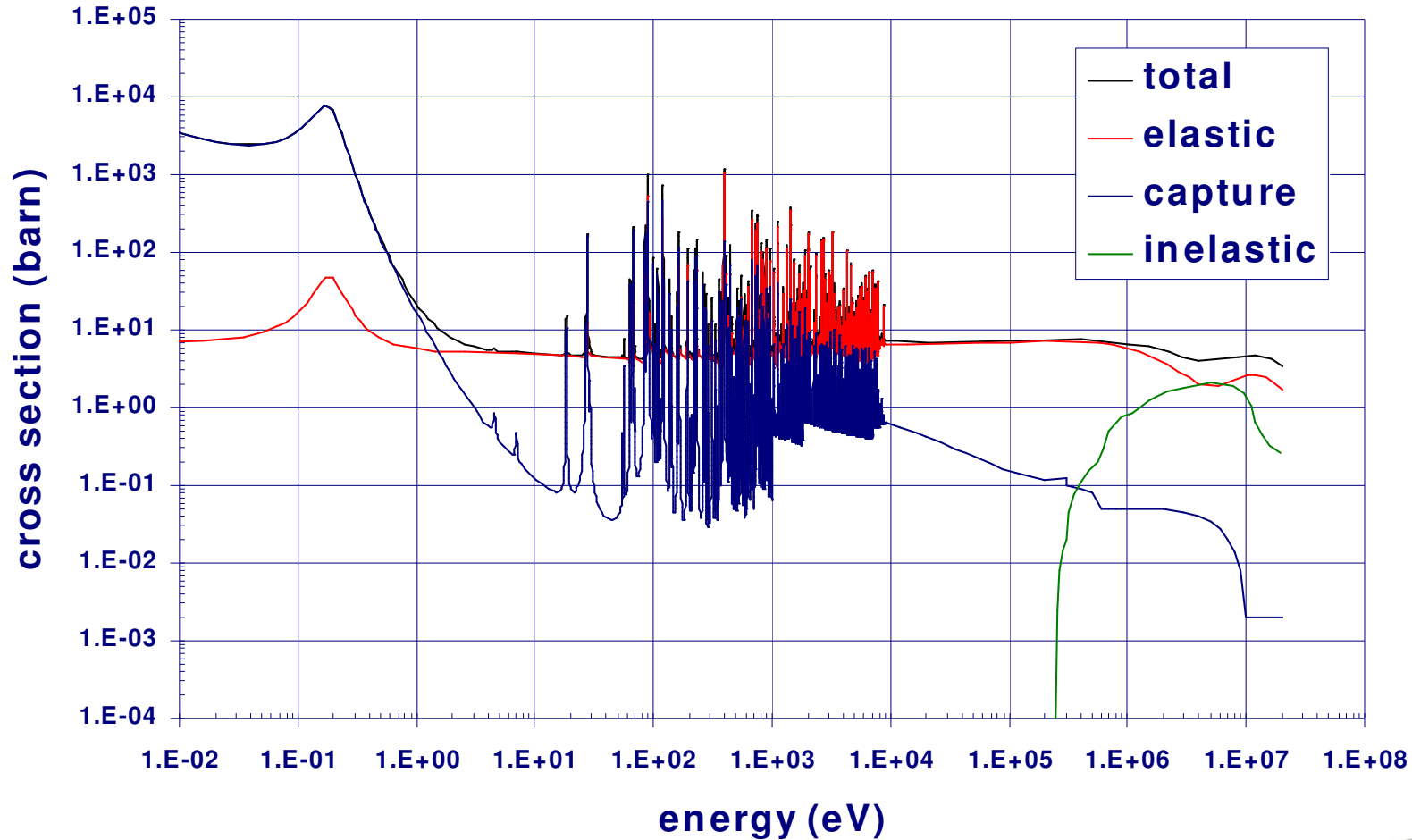
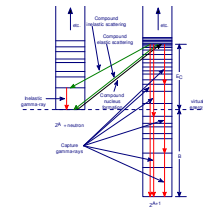


Example 1: iron



3. Interaction of neutrons with the matter

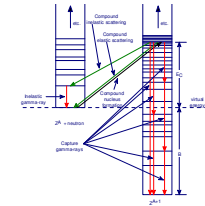
Neutron cross sections



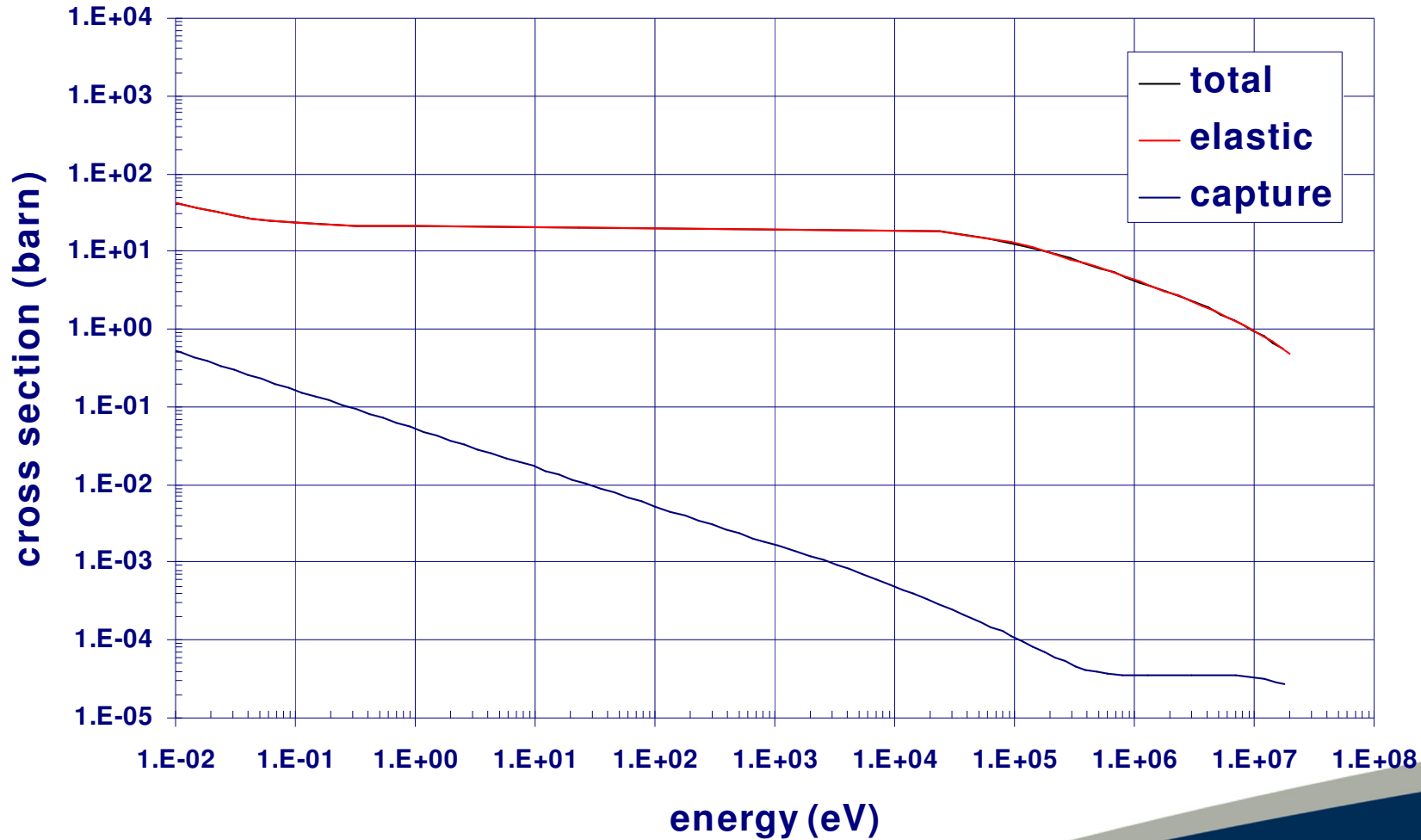
Example 2: cadmium



3. Interaction of neutrons with the matter



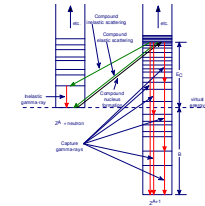
Neutron cross sections



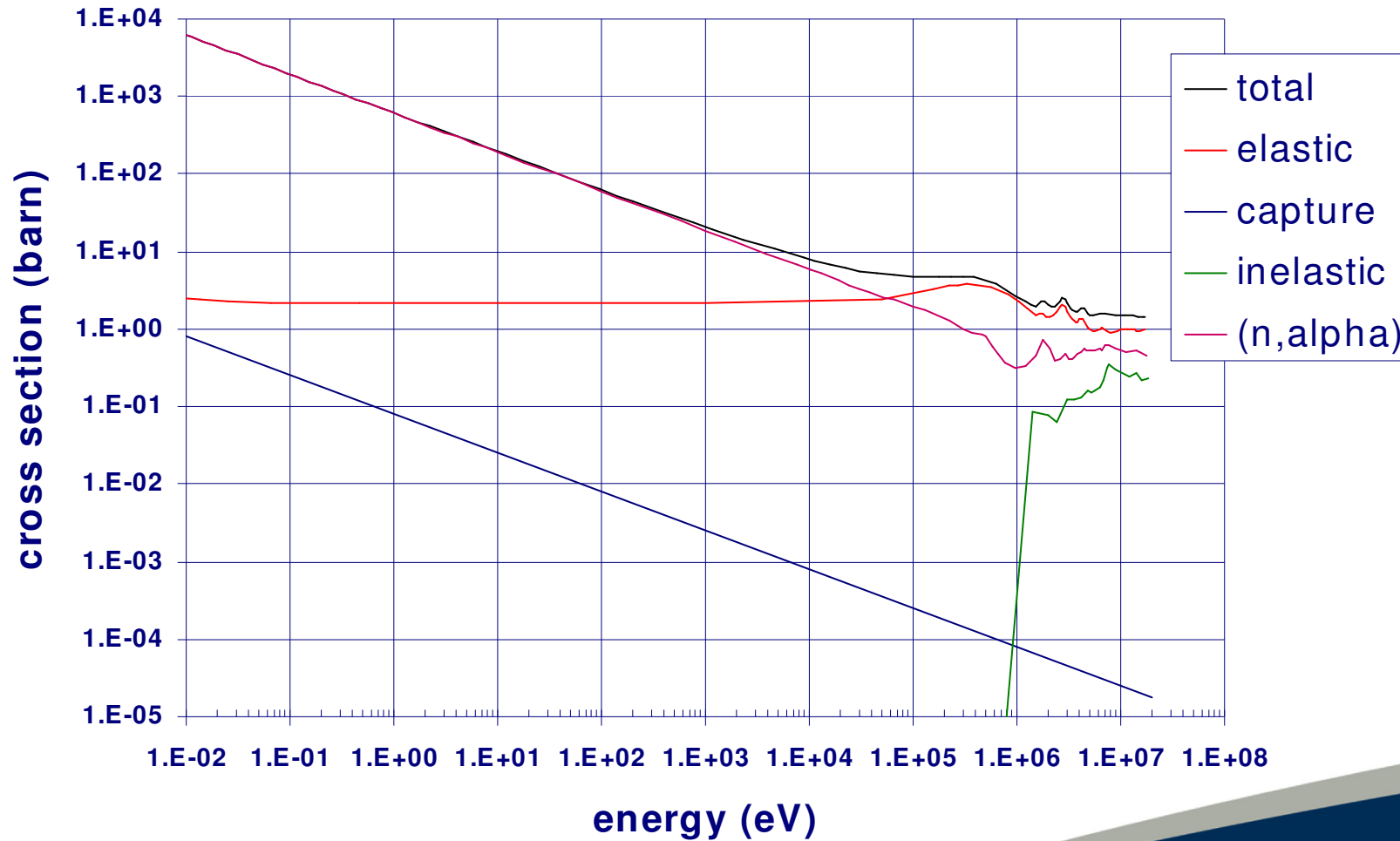
Example 3: hydrogen



3. Interaction of neutrons with the matter



Neutron cross sections

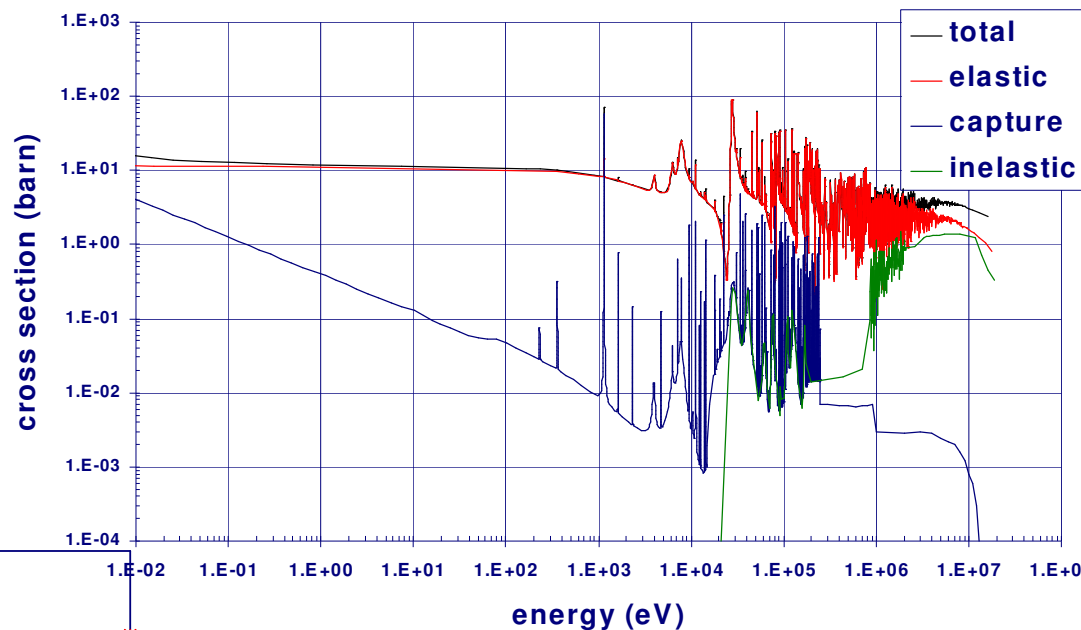


Example 4: boron

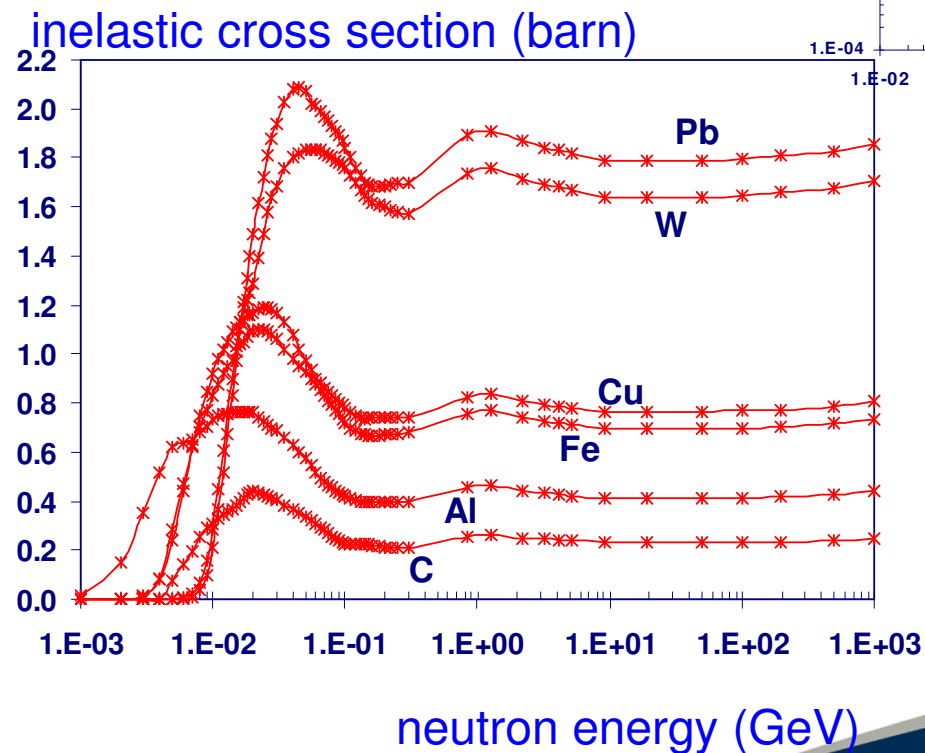


3. Interaction of neutrons with the matter

Neutron cross sections

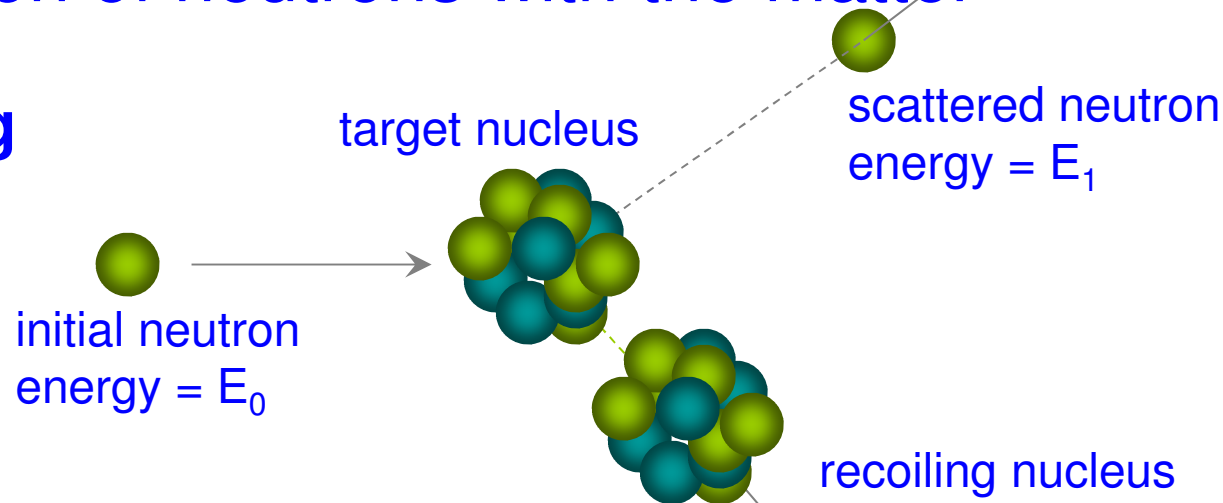


Example: iron



3. Interaction of neutrons with the matter

Elastic scattering



Minimum energy of scattered neutron:

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

Average energy loss per collision:

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

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

4. Interaction of protons with the matter

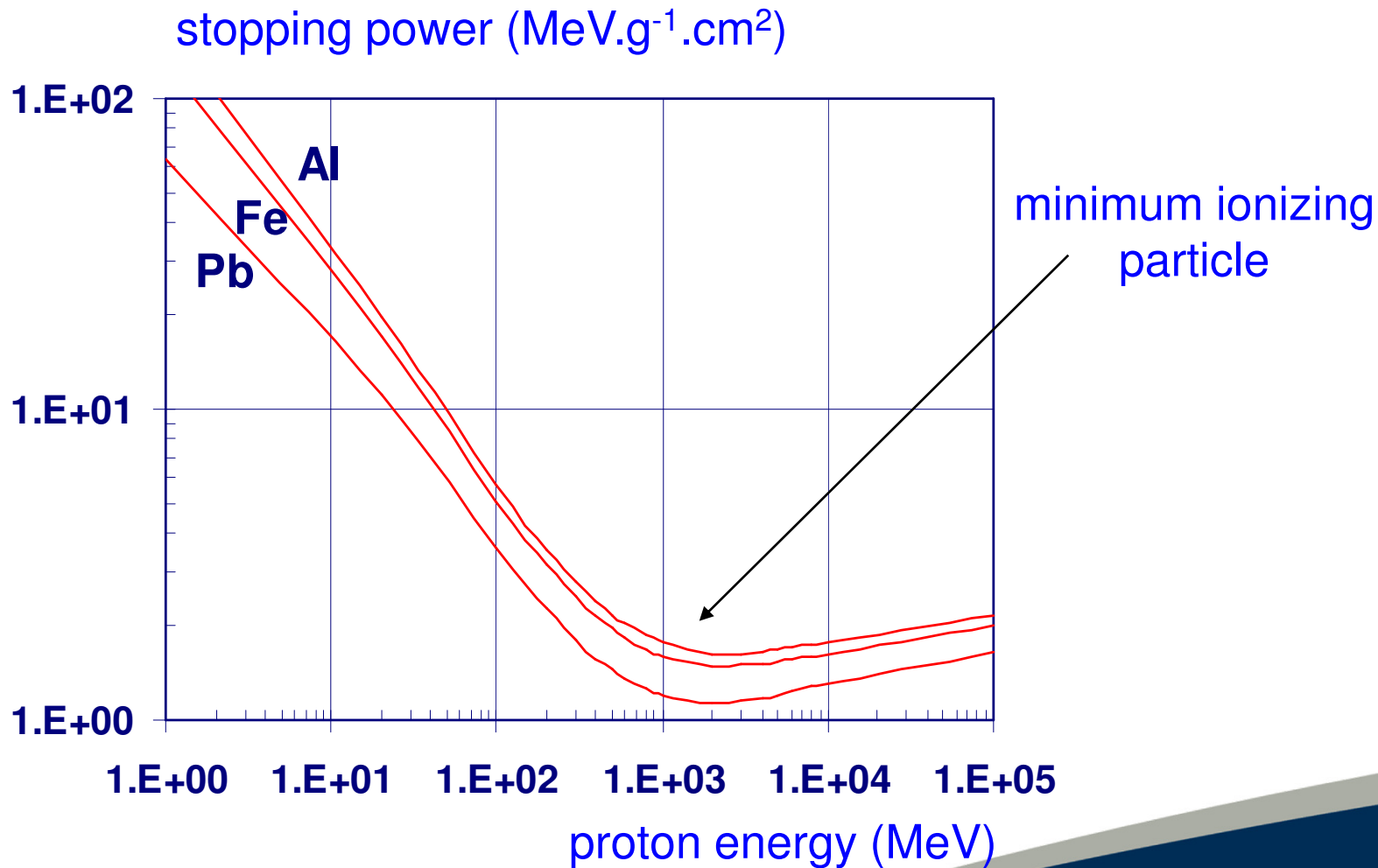
The physical processes:

1. ionization
2. inelastic proton-nucleus scattering
spallation



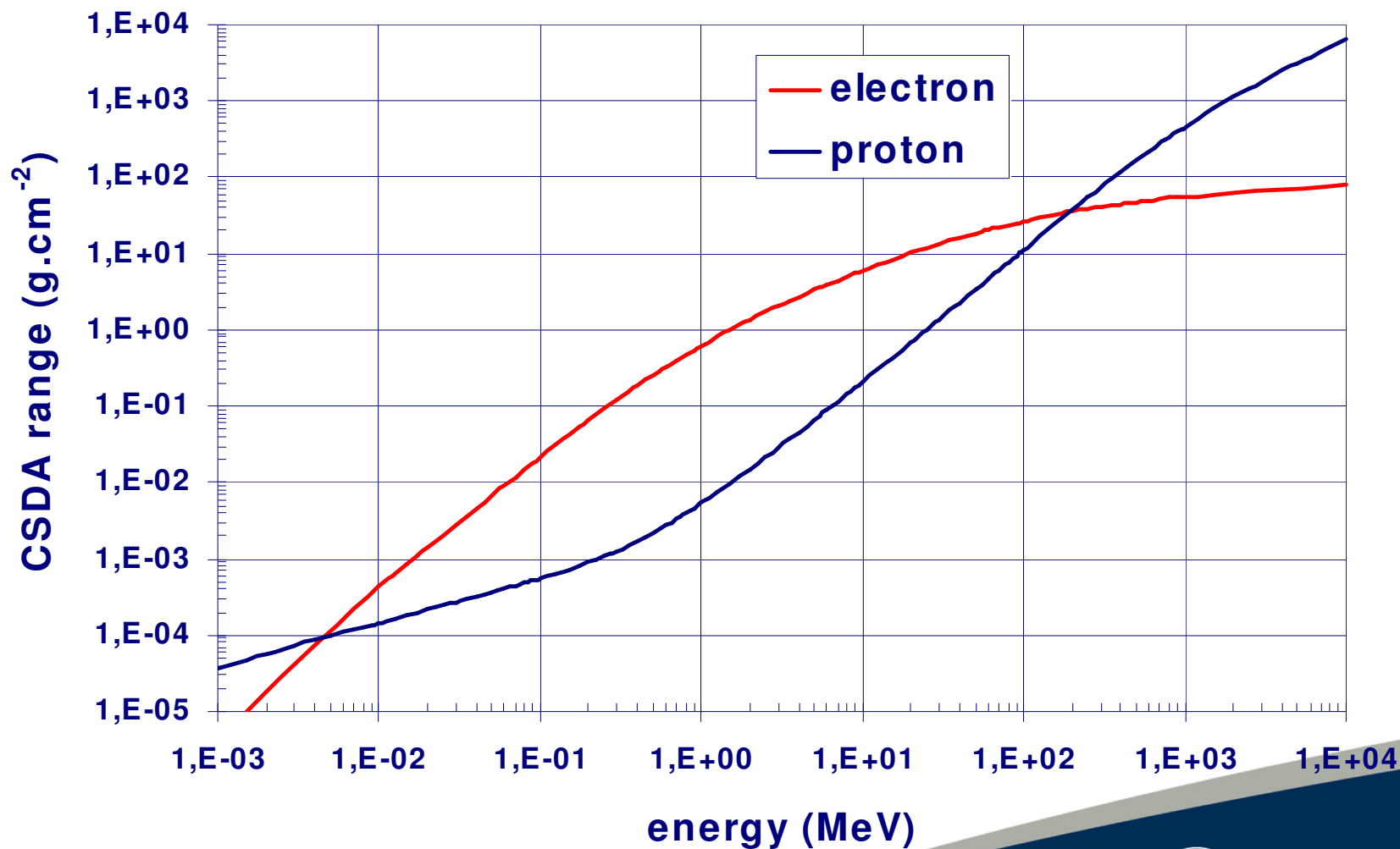
4. Interaction of protons with the matter

Proton ionization loss – Stopping power



4. Interaction of protons with the matter

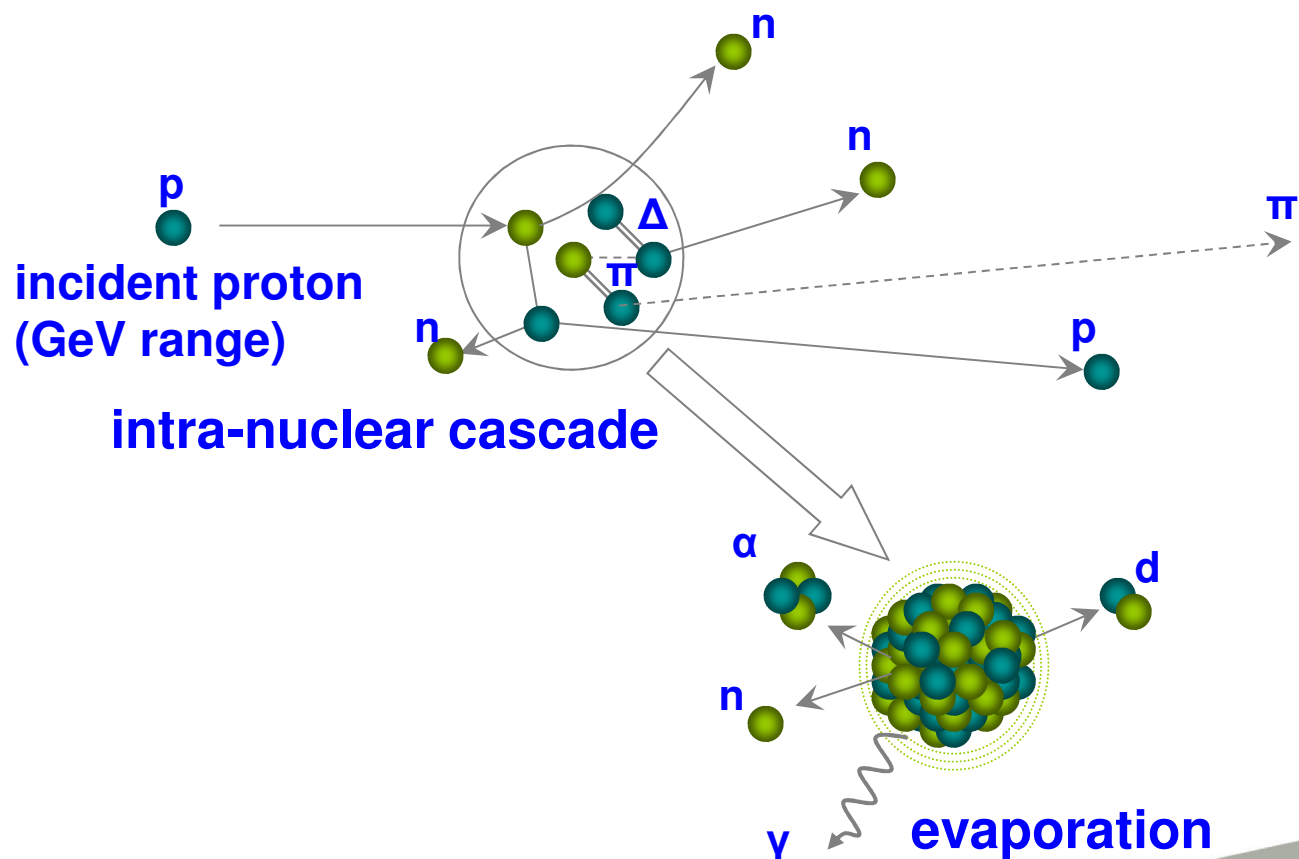
Comparison CSDA range of protons and electrons in iron



4. Interaction of protons with the matter

Inelastic proton – nucleus scattering:

Spallation reaction

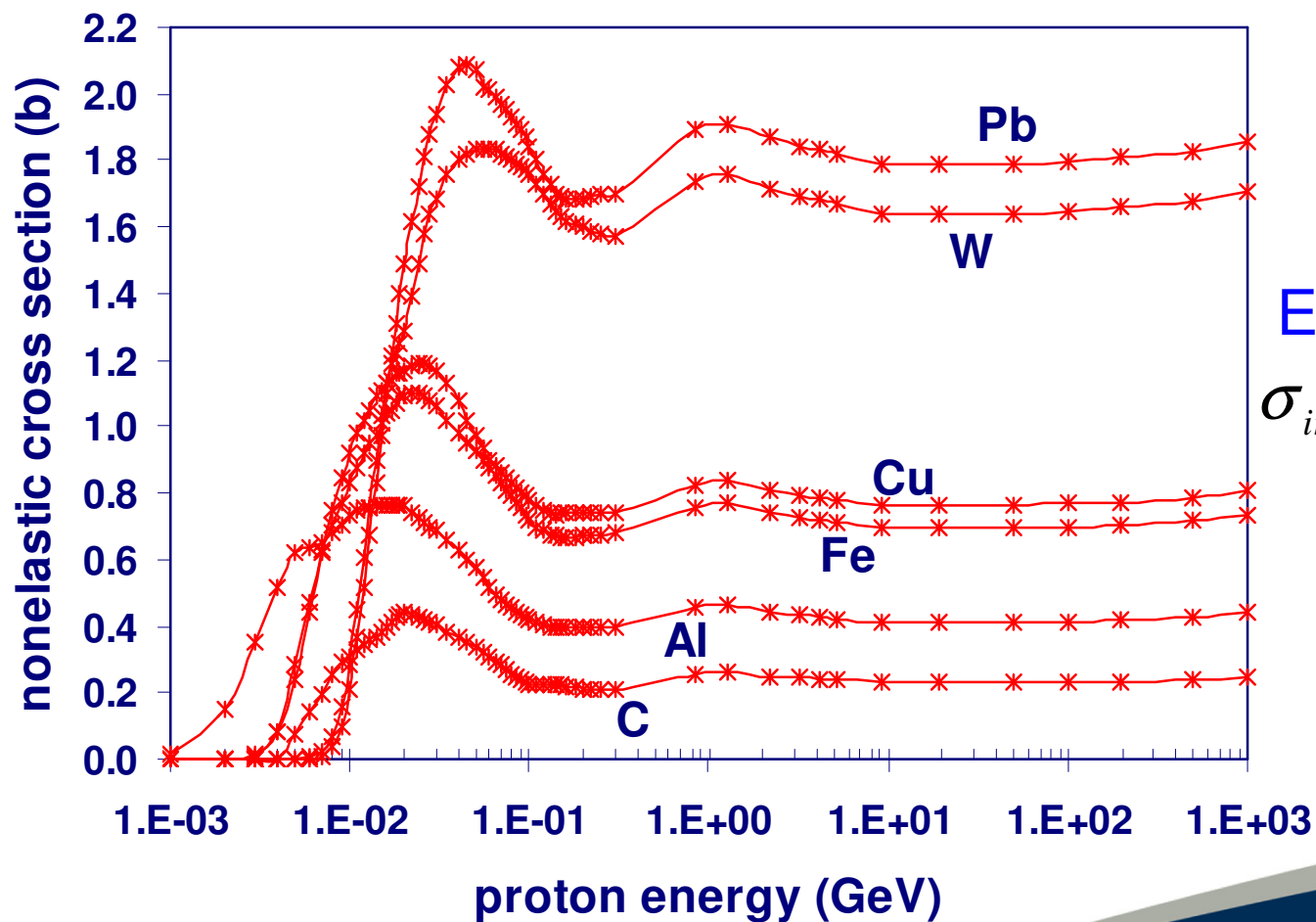


4. Interaction of protons with the matter

Inelastic proton – nucleus scattering

Spallation reaction

Inelastic cross section



$E > 1 \text{ GeV}$

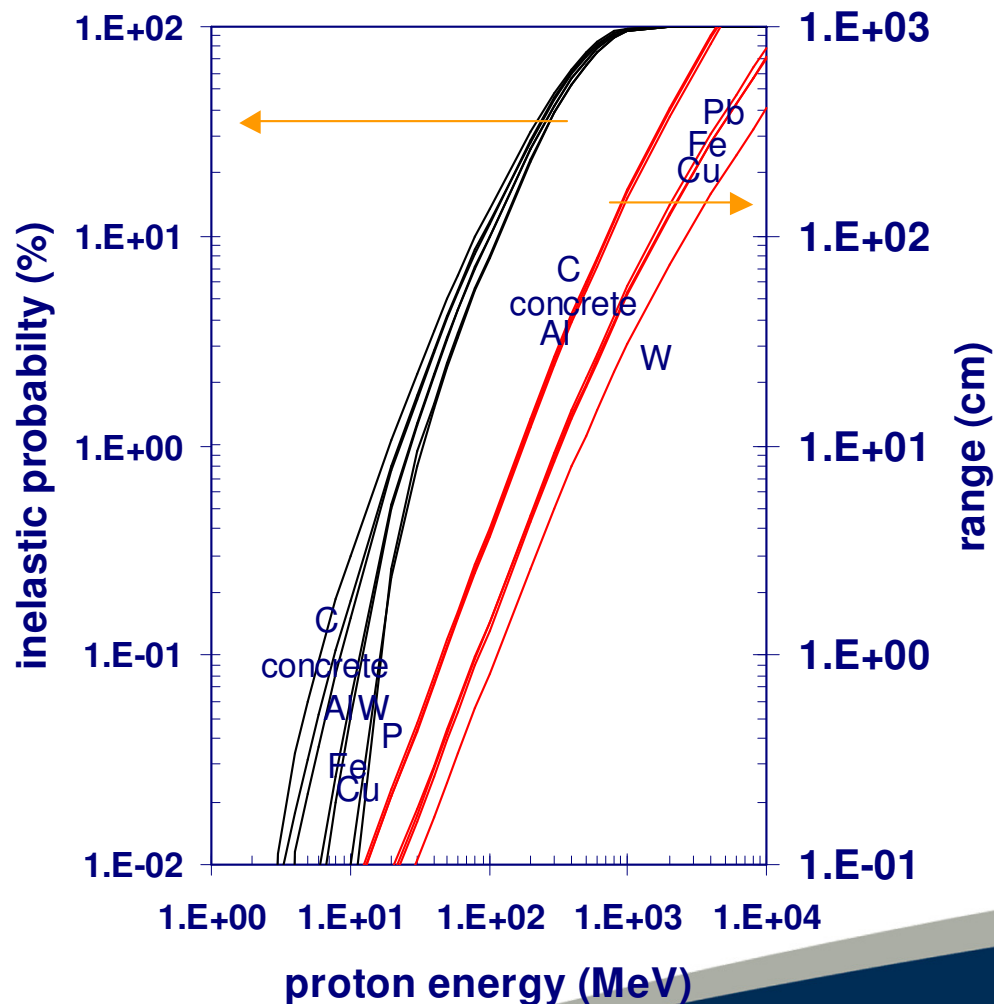
$$\sigma_{inel} = 0.042 \times A^{0.7} \text{ barn.}$$



4. Interaction of protons with the matter

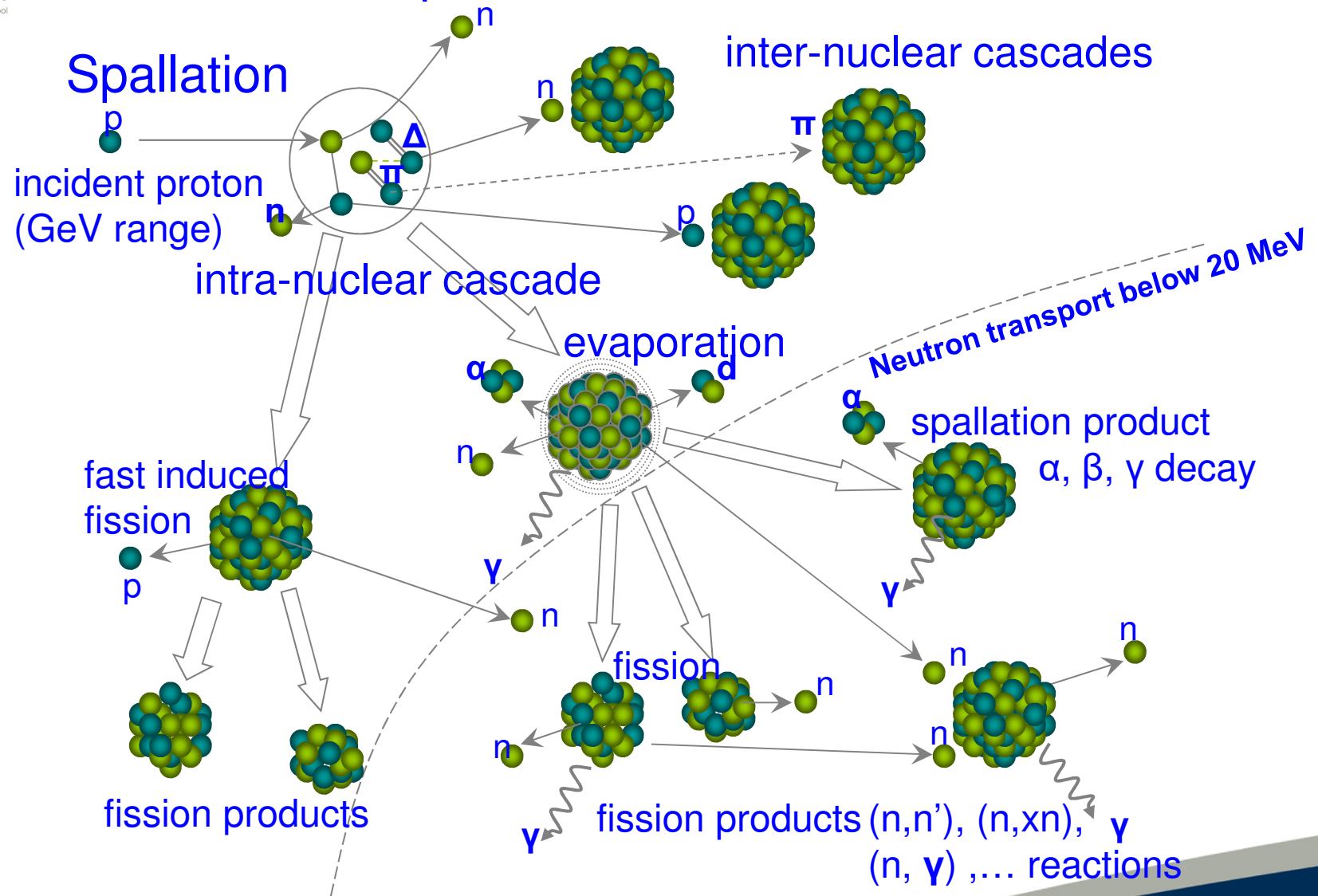
Inelastic proton – nucleus scattering

Comparison ionization energy loss and inelastic scattering

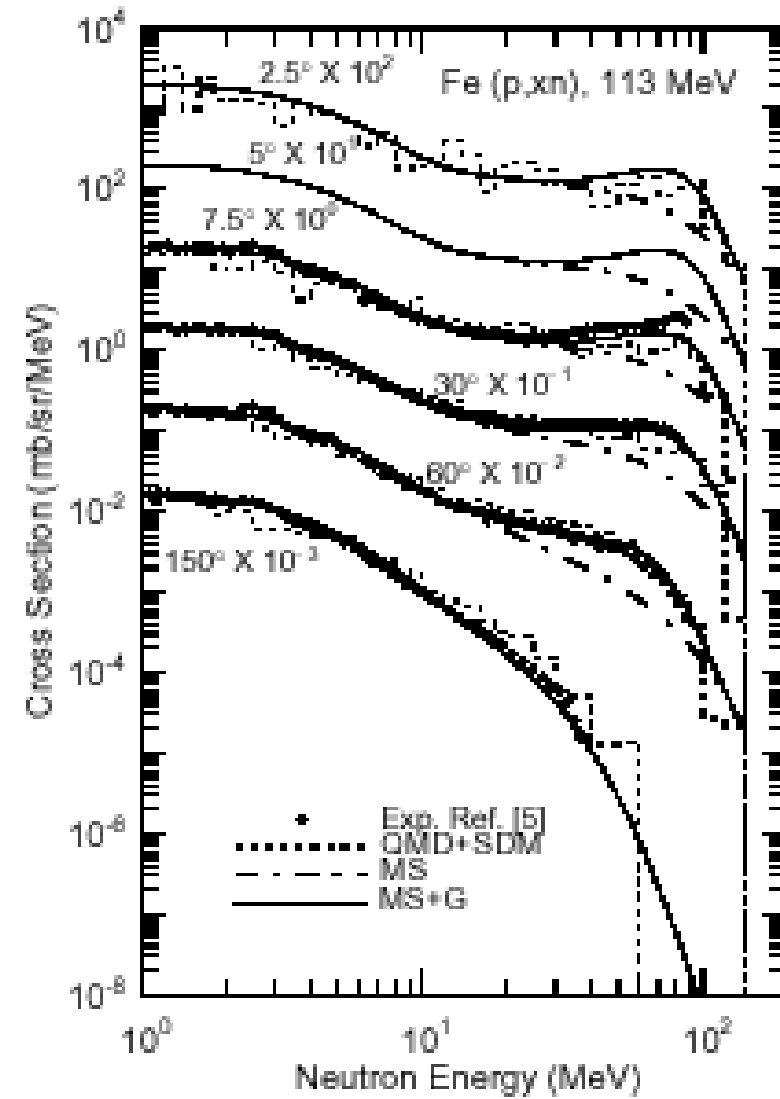
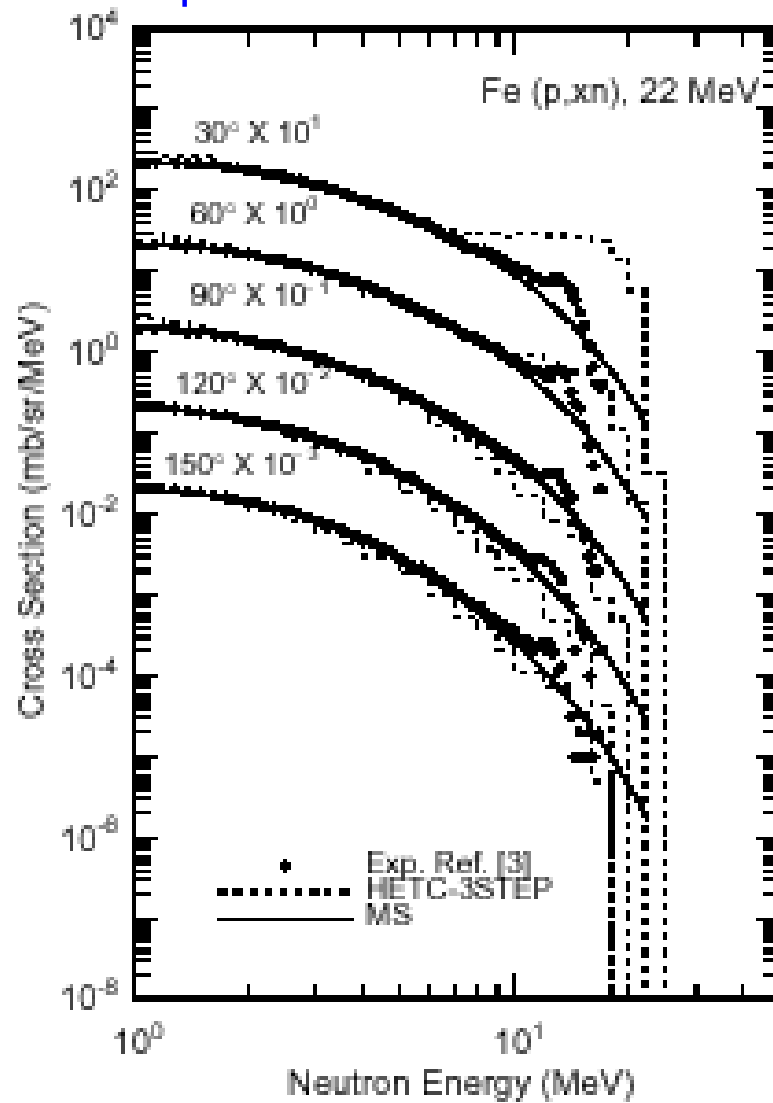


→ $E > 1$ GeV:
100 % probability
for spallation reaction

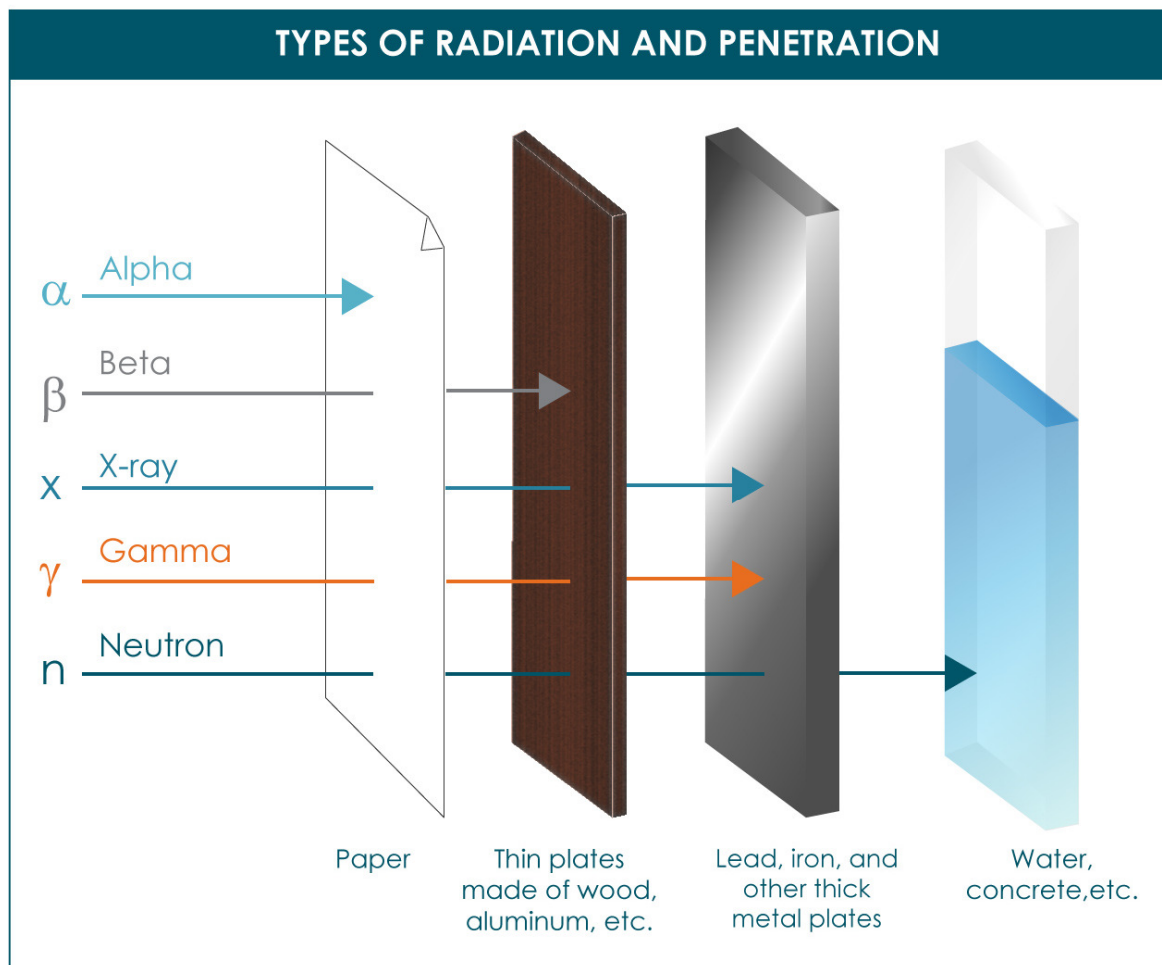
4. Interaction of protons with the matter



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/>