

1. Interaction of electrons with matter
2. Interaction of photons with matter
3. Interaction of neutrons with matter
4. Interaction of protons with matter

1. Interaction of electrons with 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 matter

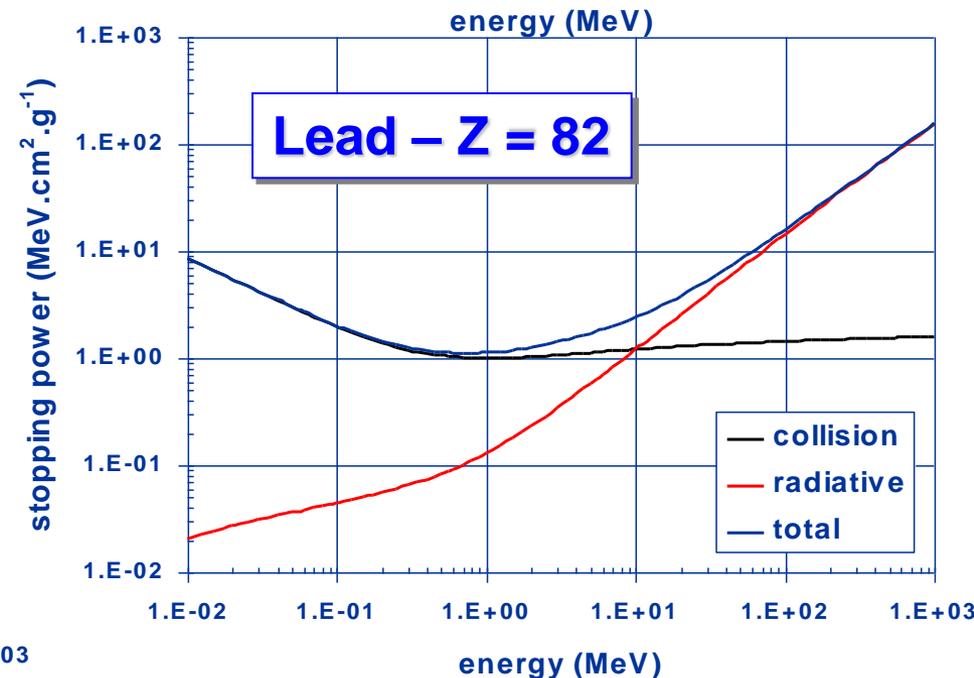
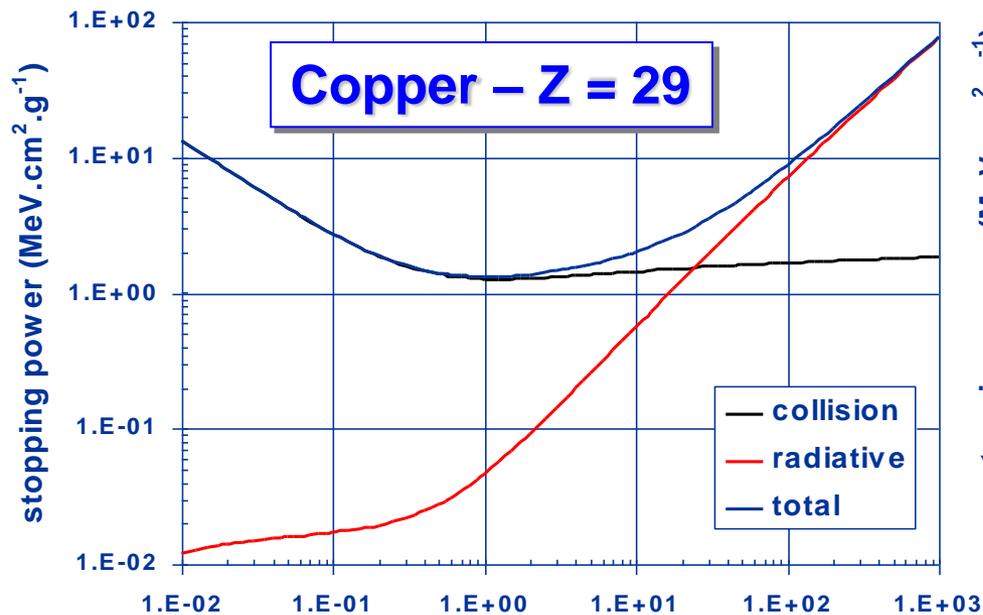
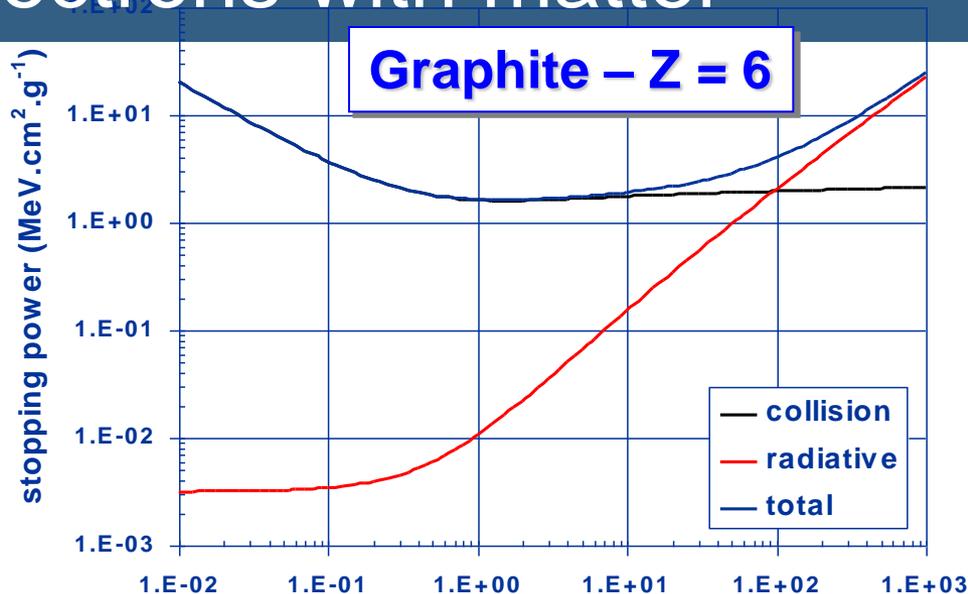
Electrons – stopping power

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

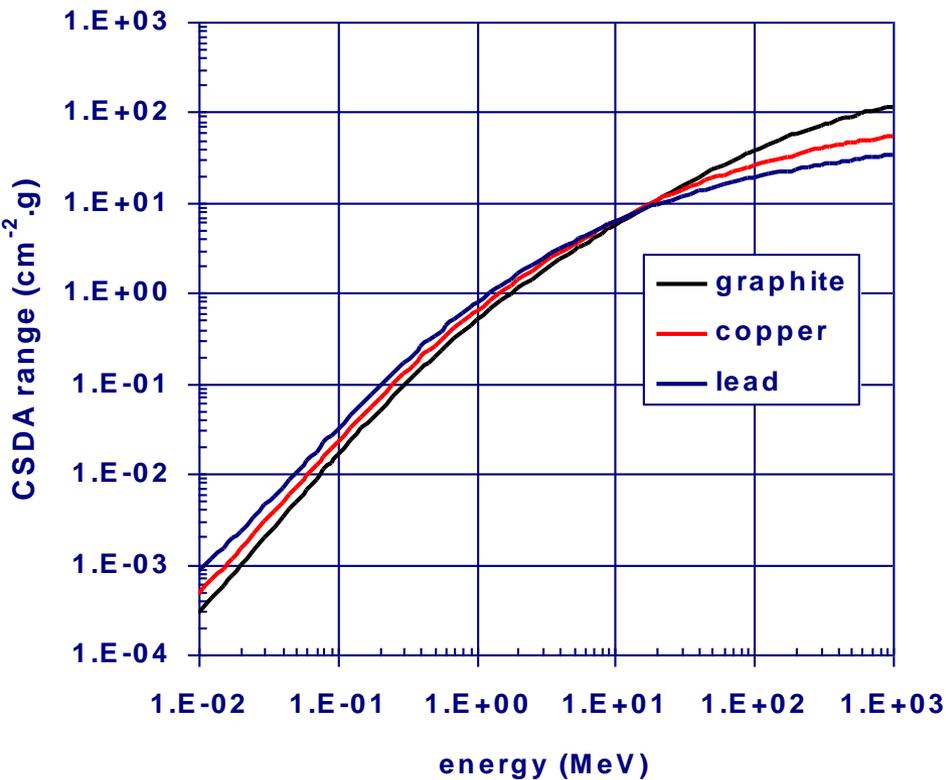
$$\frac{S}{\rho} = \frac{1}{\rho} \left(\frac{dE}{dl} \right)_{\text{coll}} + \frac{1}{\rho} \left(\frac{dE}{dl} \right)_{\text{rad}}$$

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

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

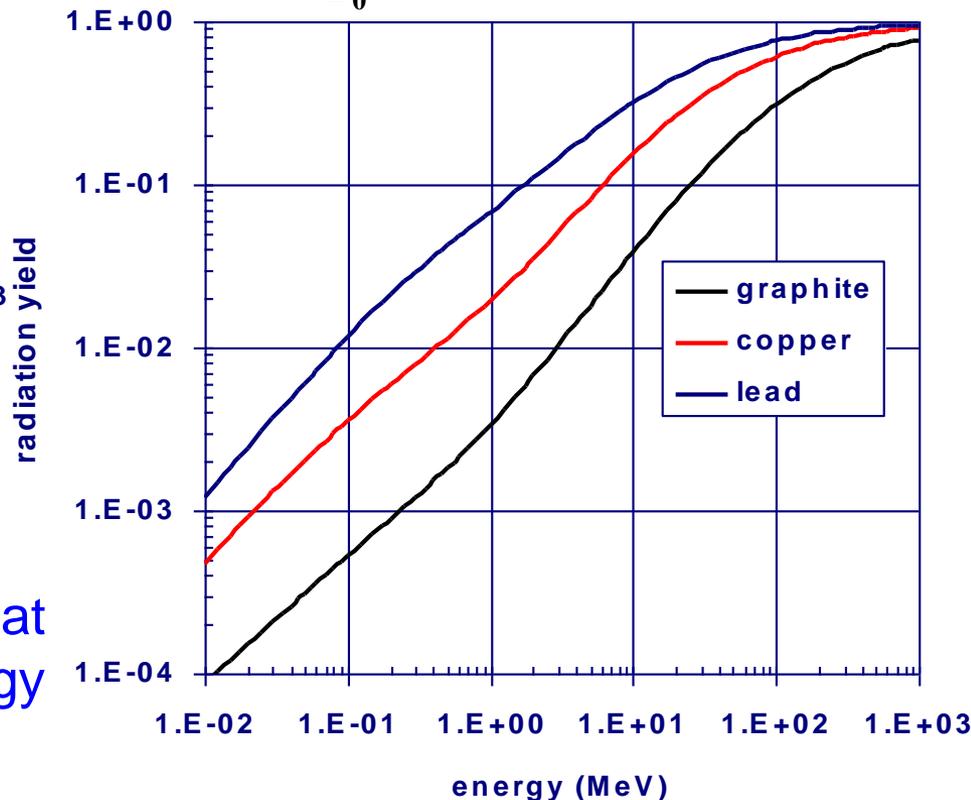


1. Interaction of electrons with matter



Continuous Slowing Down Approximation range:

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



Radiation yield:

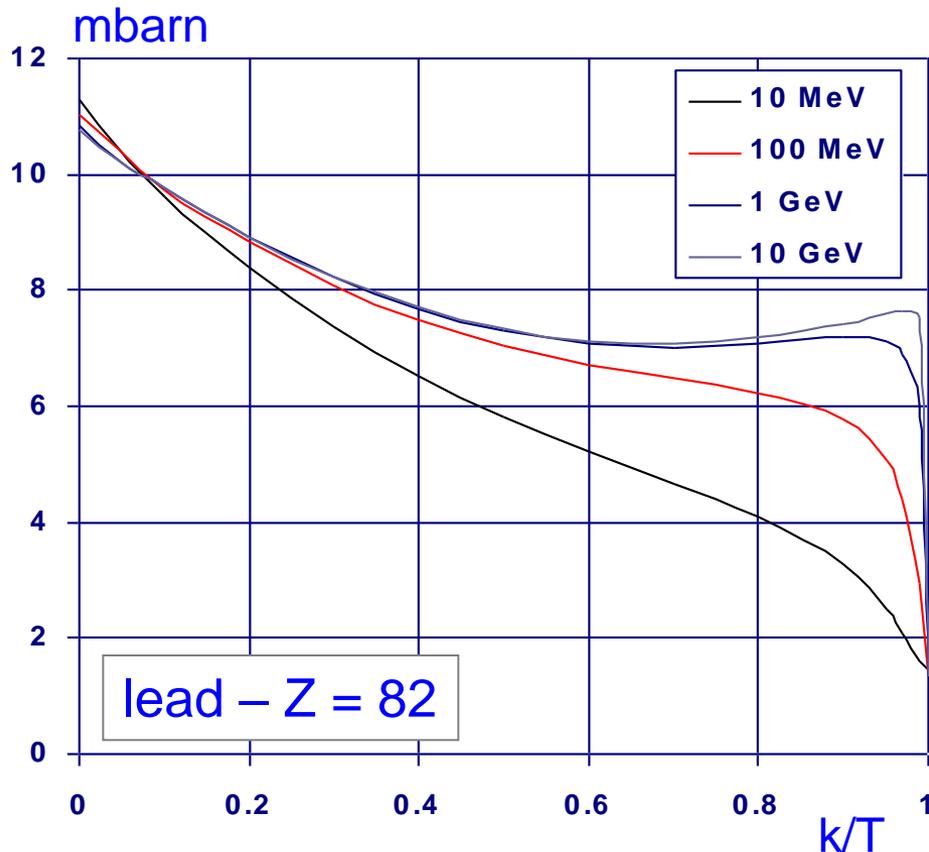
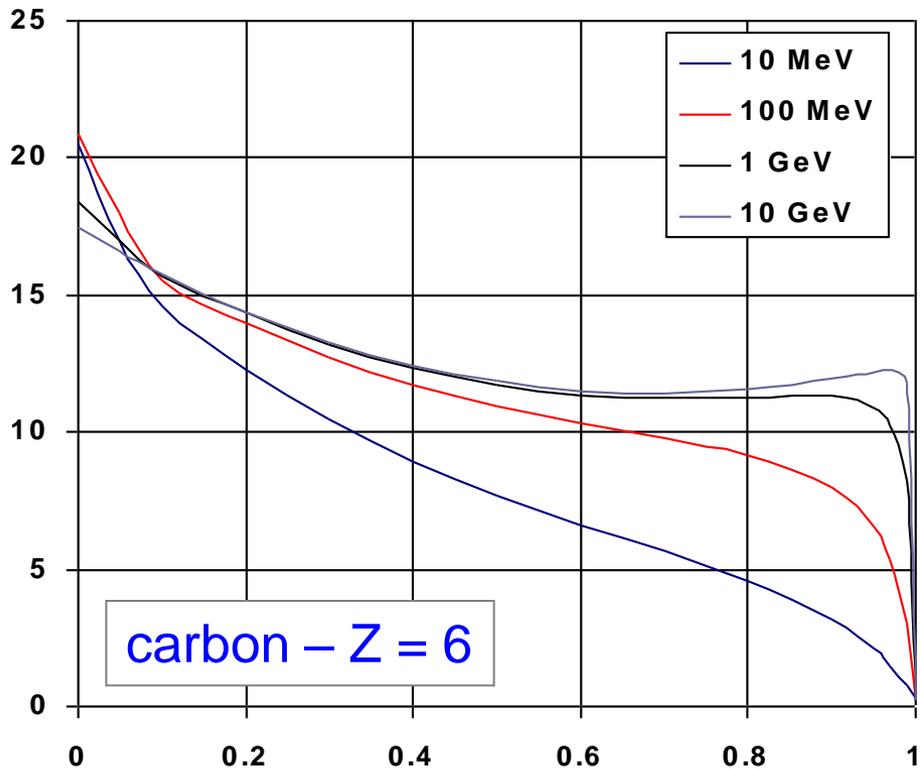
Fraction of the initial kinetic energy that is converted to Bremsstrahlung energy as the electron slows down to rest.

1. Interaction of electrons with matter

Differential Bremsstrahlung cross section:

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

mbarn



k: photon energy
T: electron kinetic energy

1. Interaction of electrons with 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}

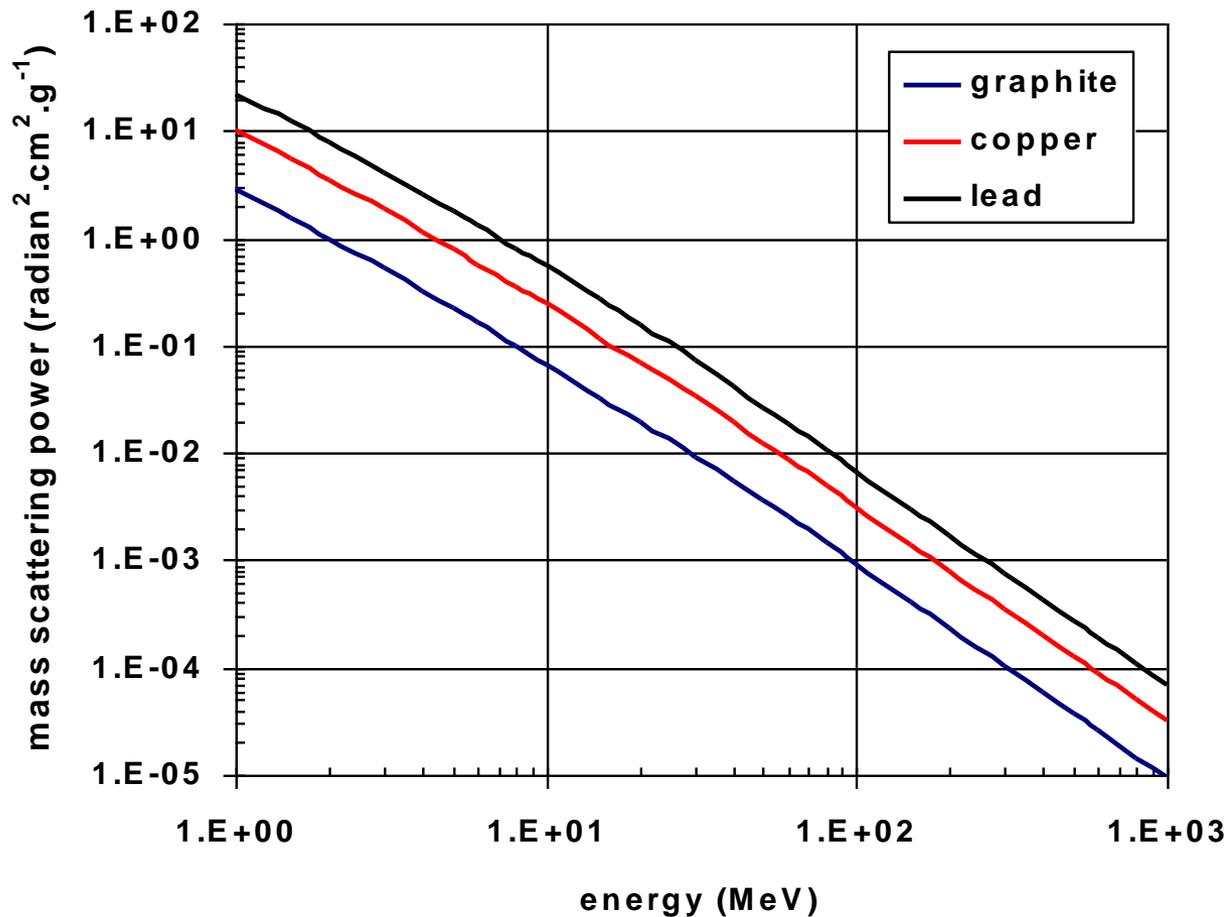
$$S_{sc} = \frac{1}{\rho} \frac{d\langle \theta^2 \rangle}{dx} \longrightarrow$$

$E_s = 21.2 \text{ MeV}$

X_0 : radiation length

β : v/c

p : momentum

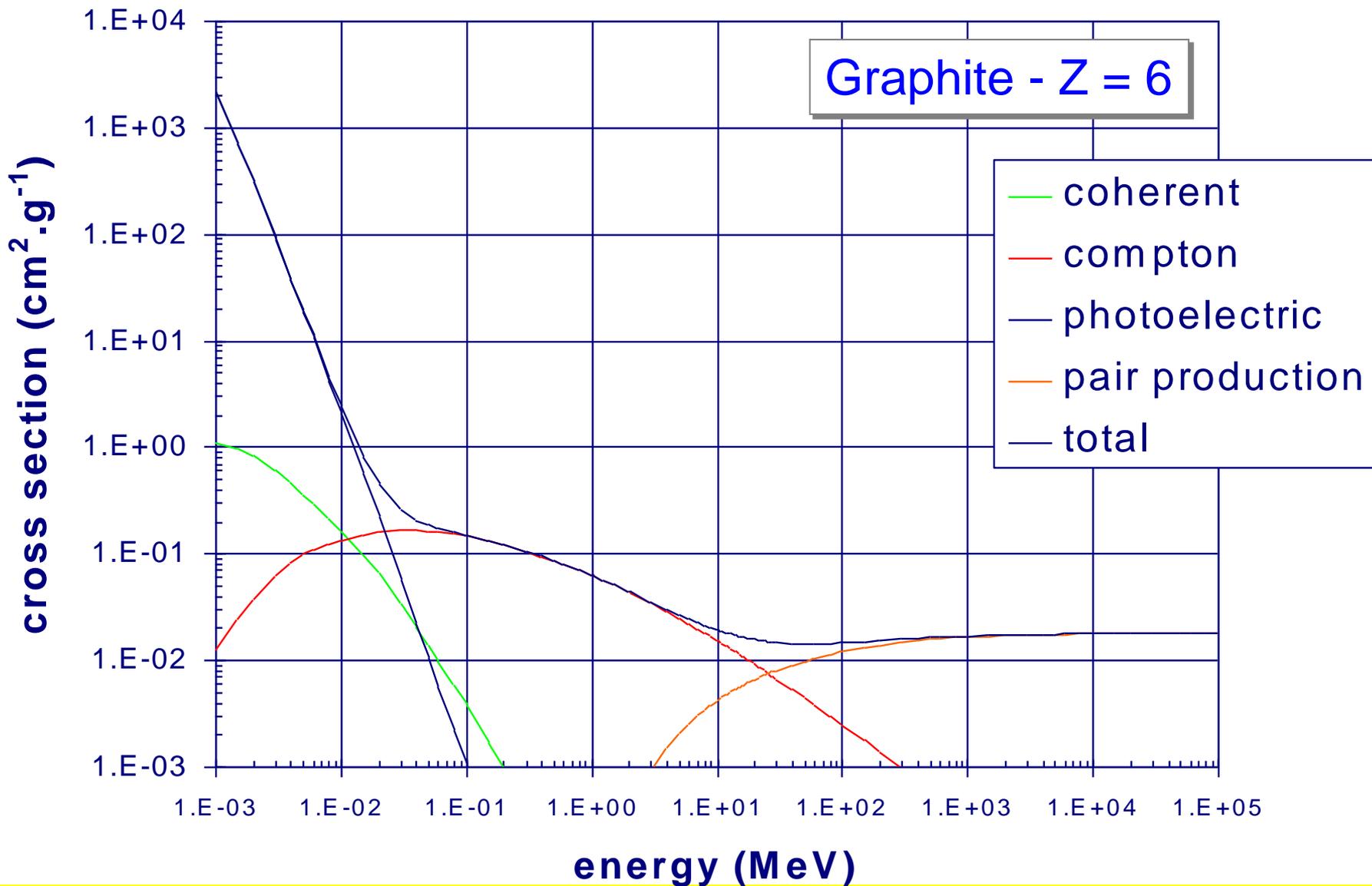


The physical processes:

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

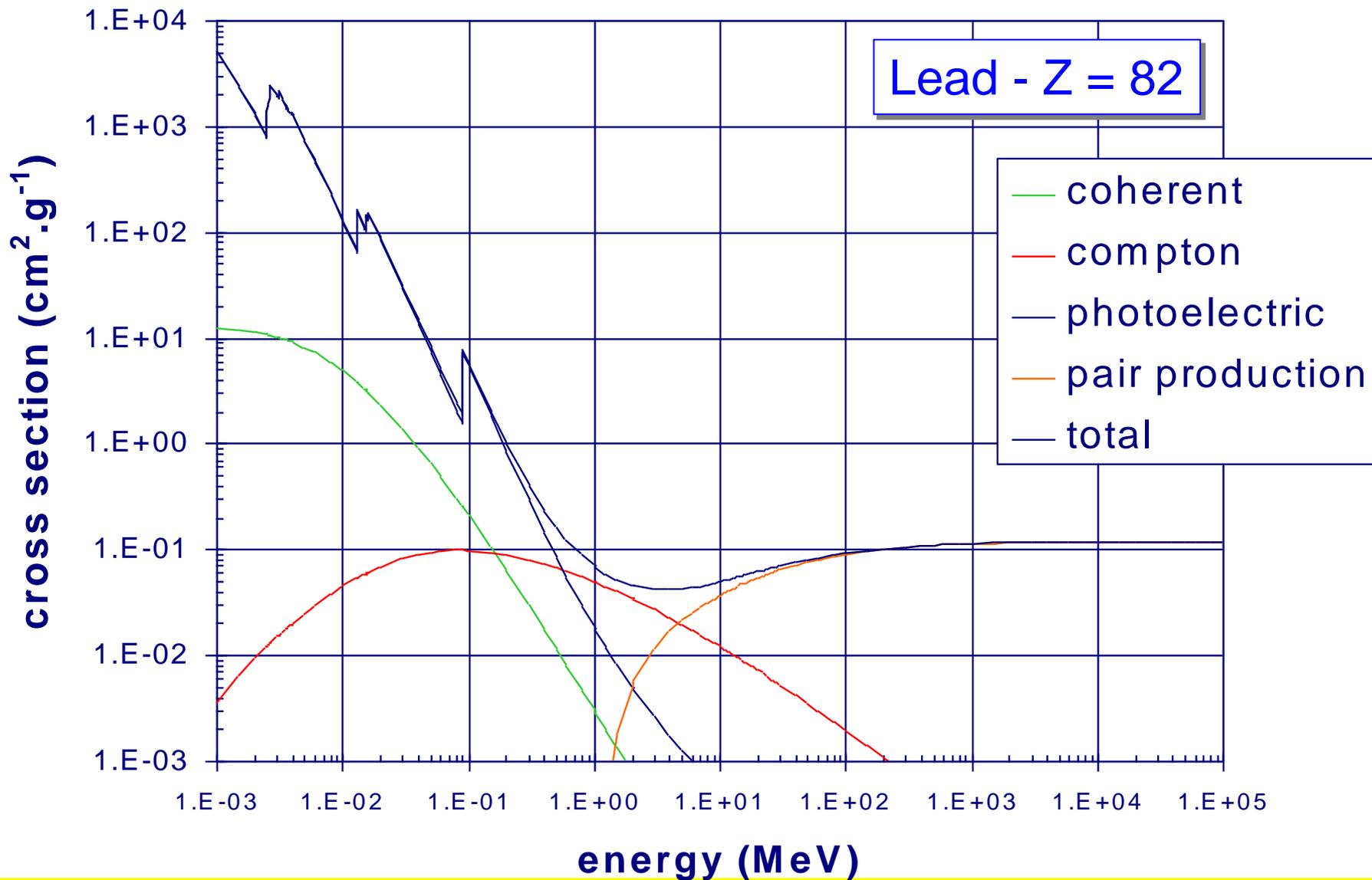
2. Interaction of photons with matter

Photon cross sections



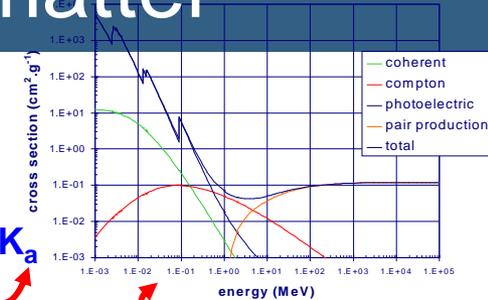
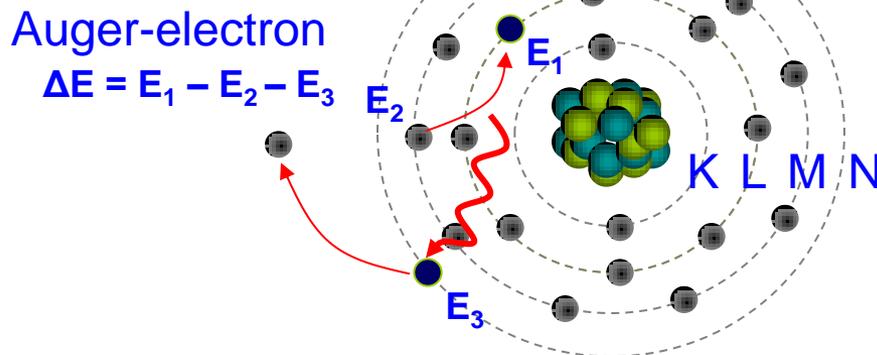
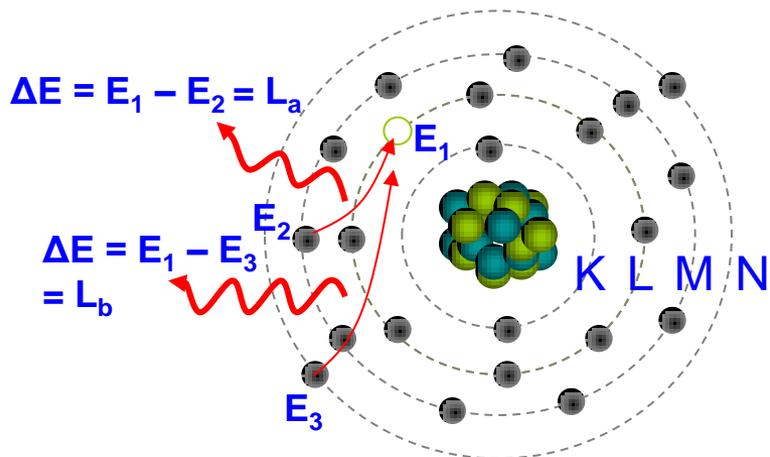
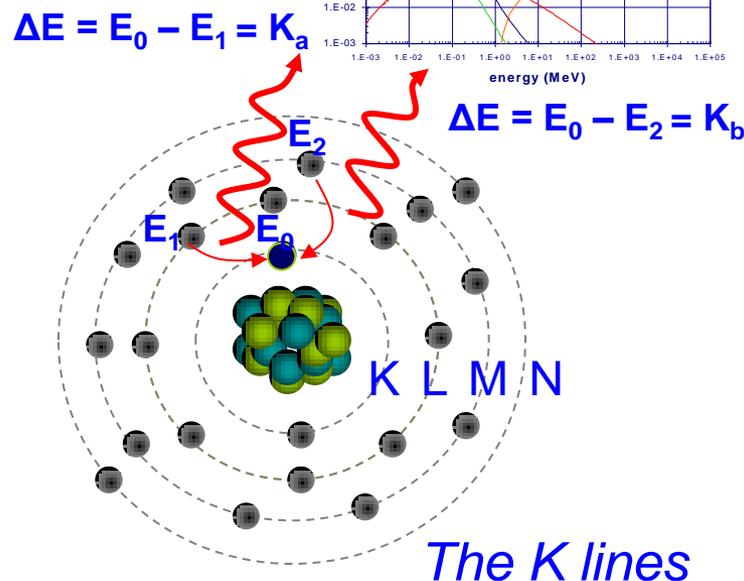
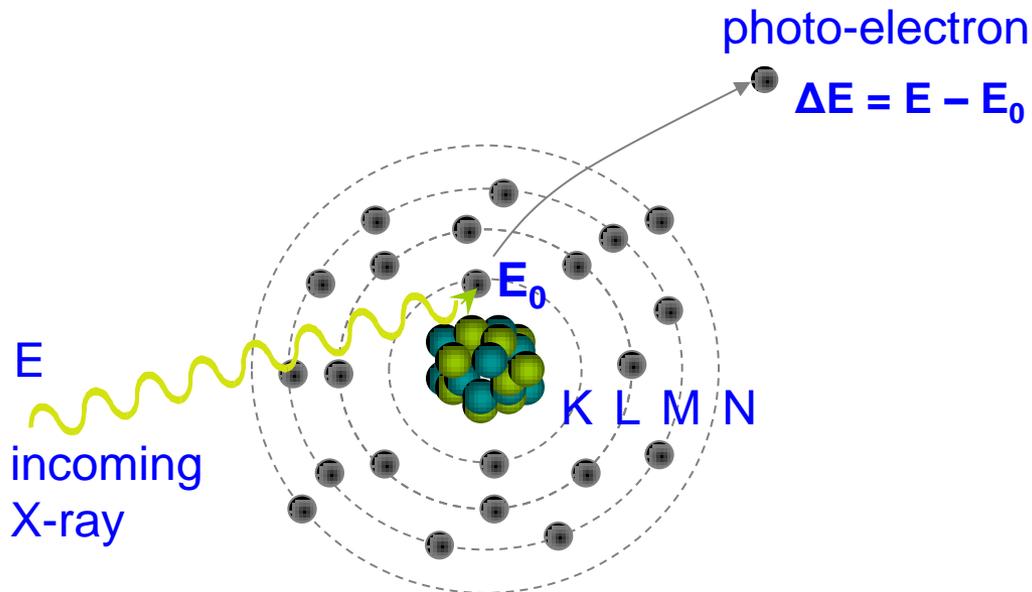
2. Interaction of photons with matter

Photon cross sections



2. Interaction of photons with matter

Photo-electric effect:

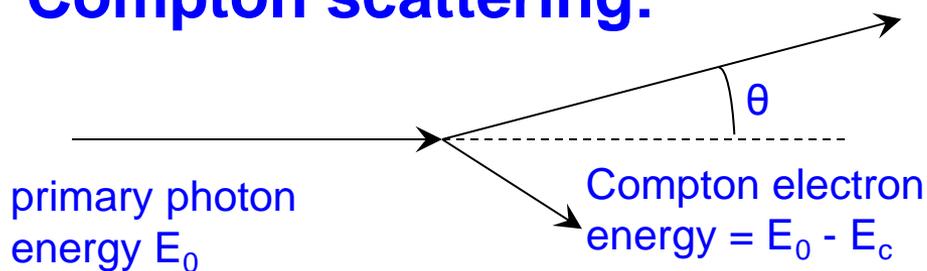


The L lines

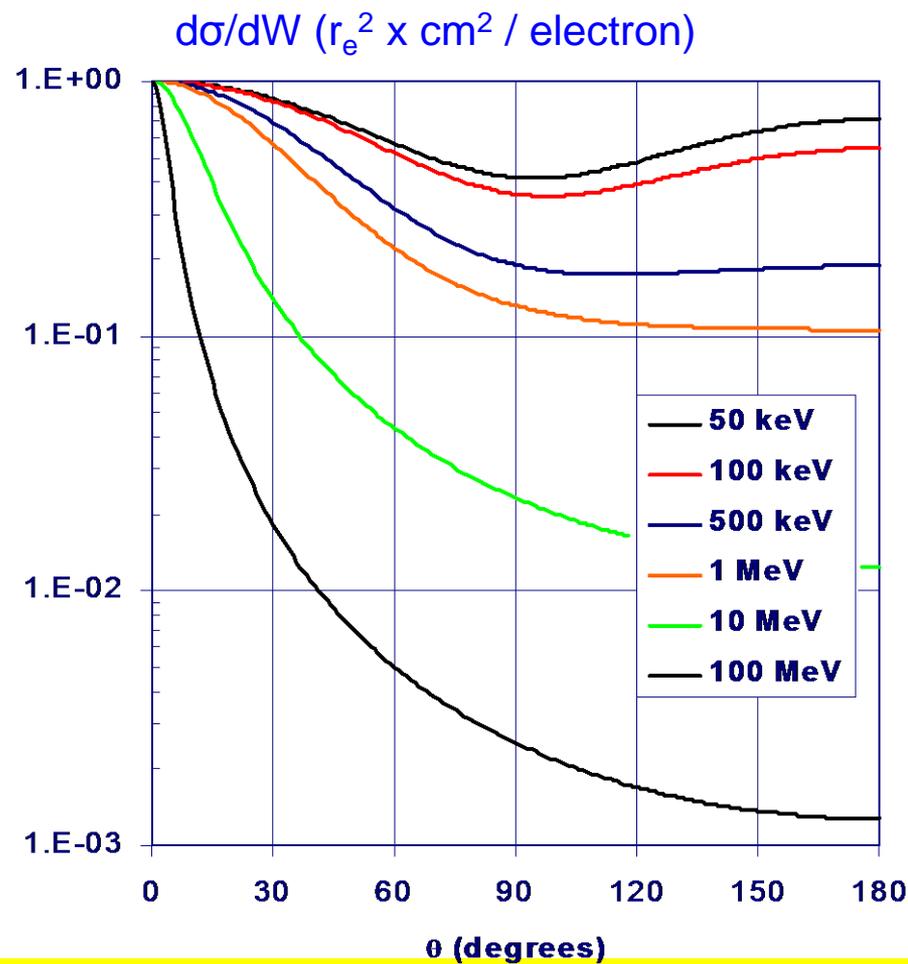
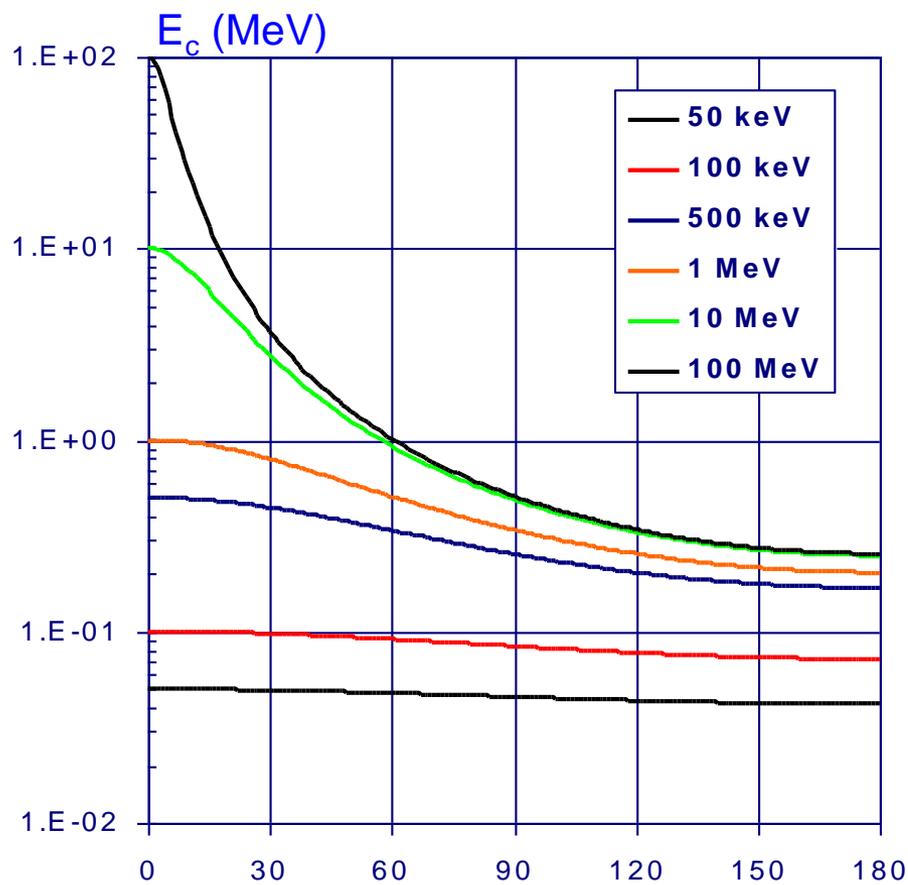
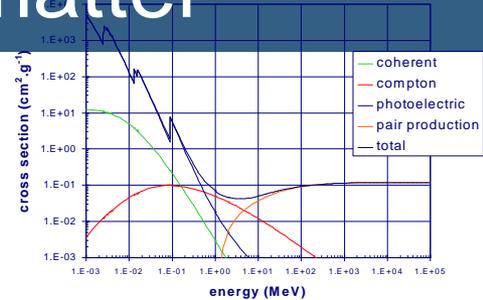
Auger electron

2. Interaction of photons with matter

Compton scattering:



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



2. Interaction of photons with matter

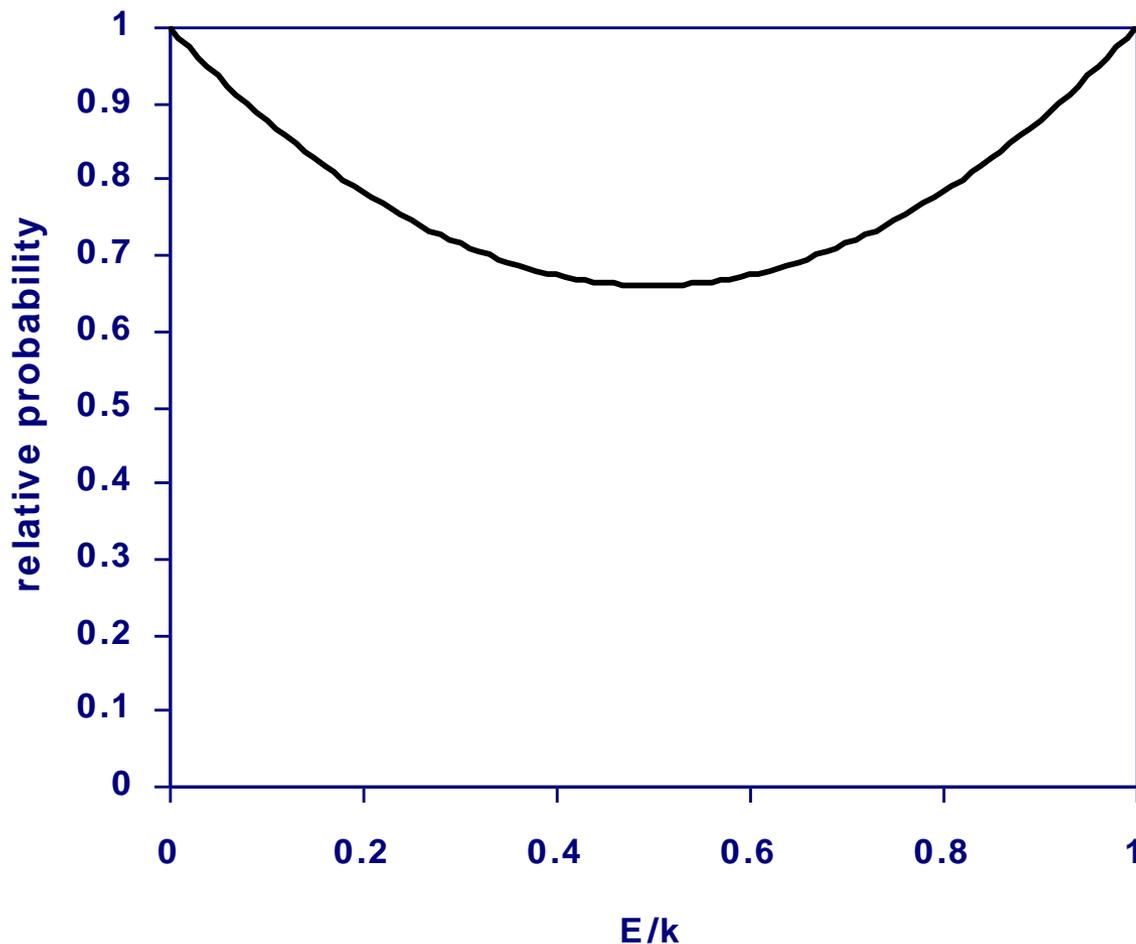
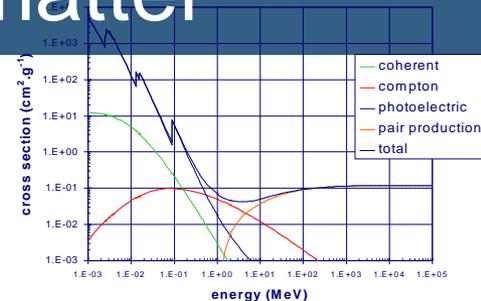
Pair production:

$$\sigma_{\text{nucleus}} \propto Z^2$$

threshold: 1.022 MeV

$$\sigma_{\text{electron}} \propto Z$$

threshold: 2.044 MeV



2. Interaction of photons with 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: $\text{cm}^2 \cdot \text{g}^{-1}$

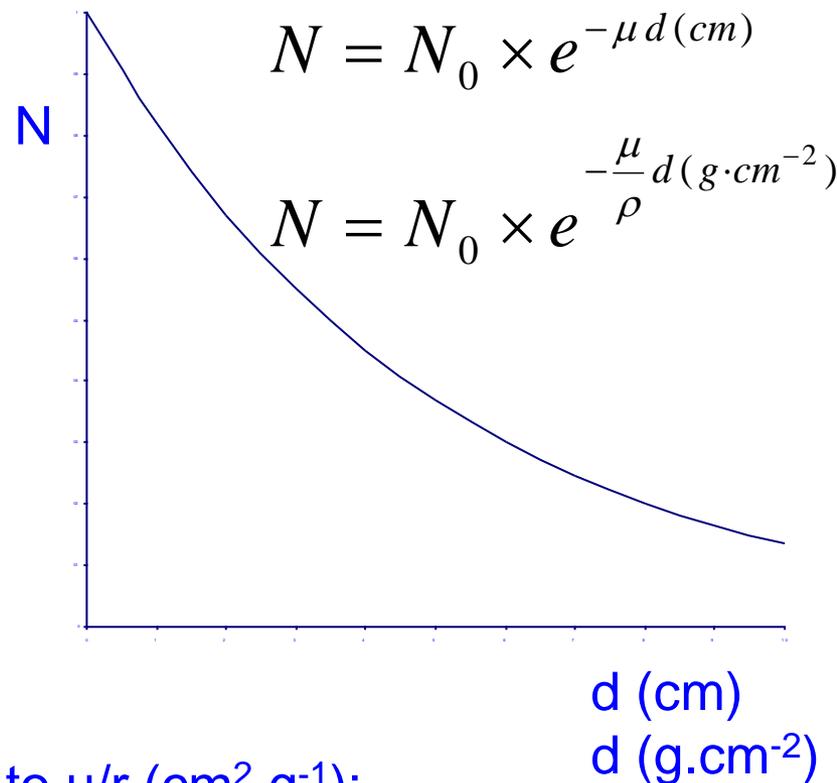
The linear attenuation coefficient μ :

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

units: cm^{-1}

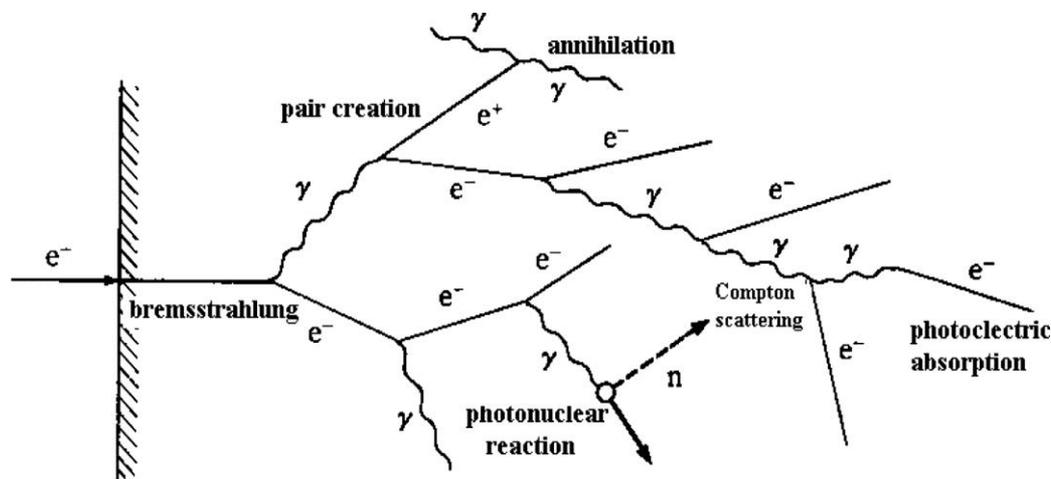
The conversion factor from σ (barns. atom^{-1}) to μ/r ($\text{cm}^2 \cdot \text{g}^{-1}$):

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



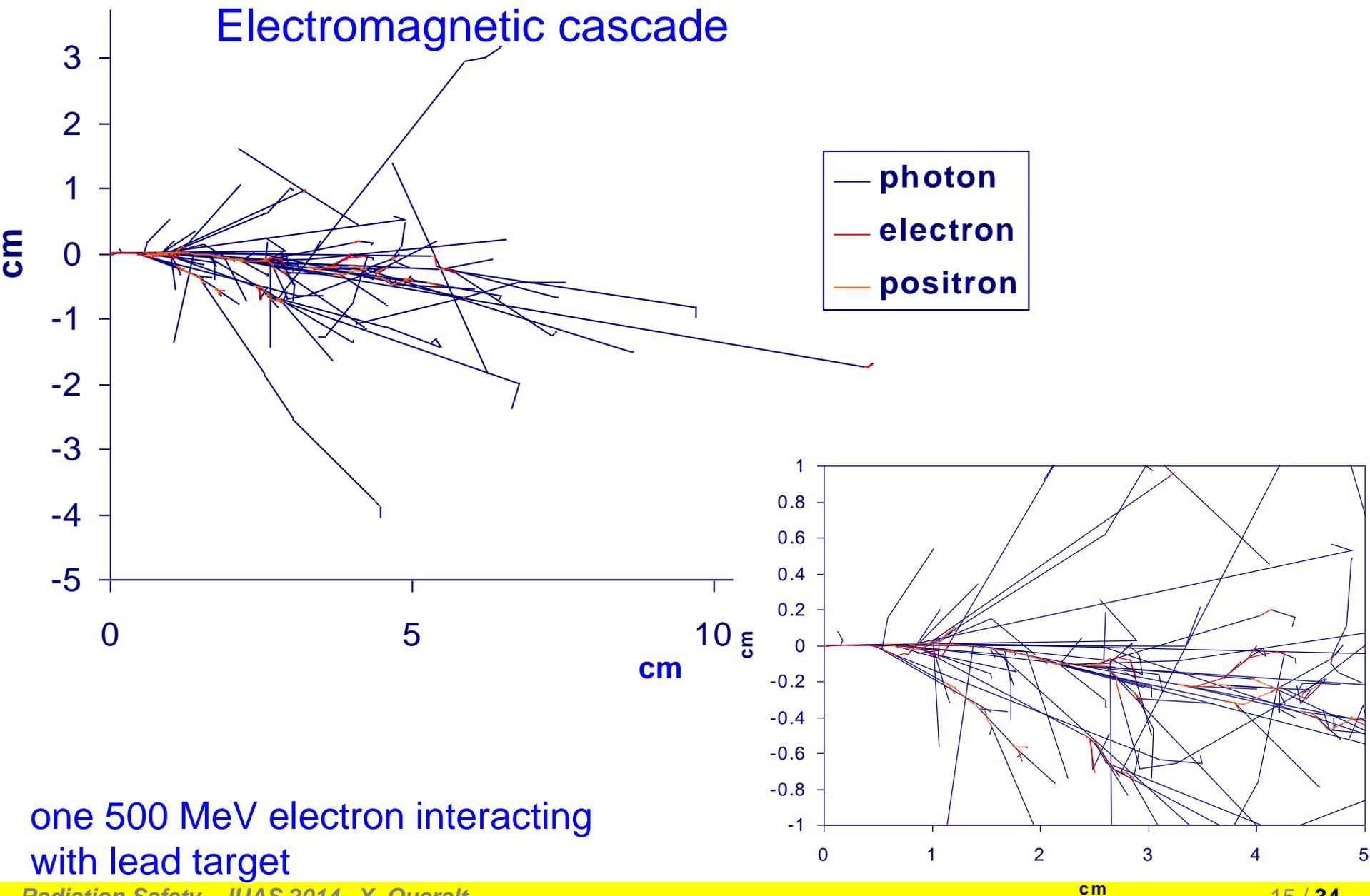
2. Interaction of photons with matter

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



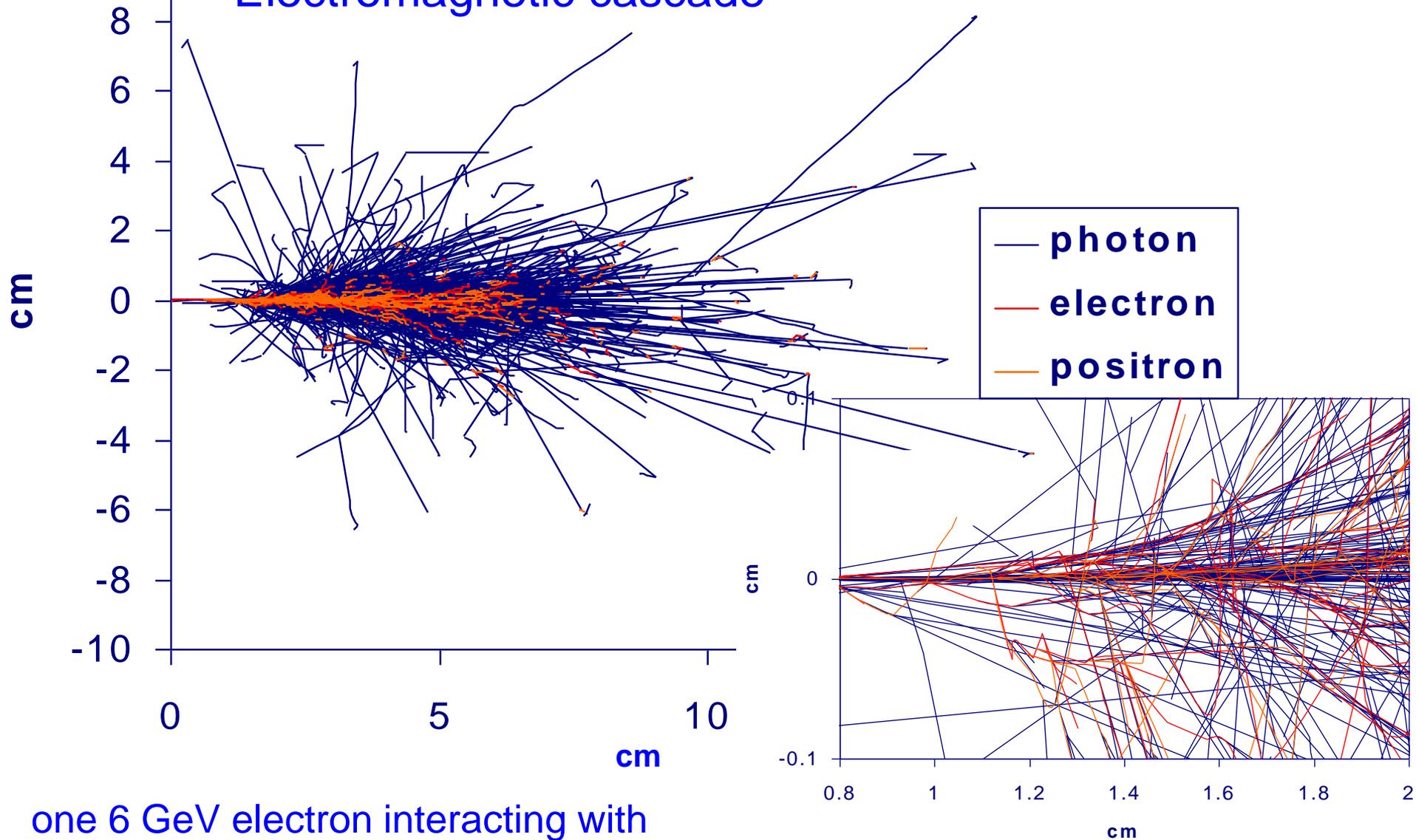
2. Interaction of photons with matter

Electromagnetic cascade



2. Interaction of photons with matter

Electromagnetic cascade

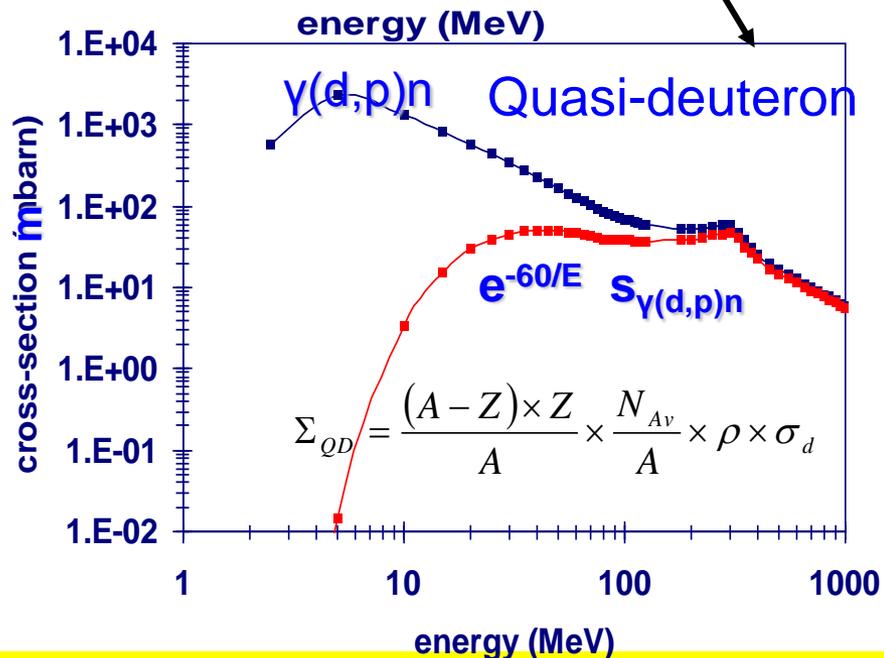
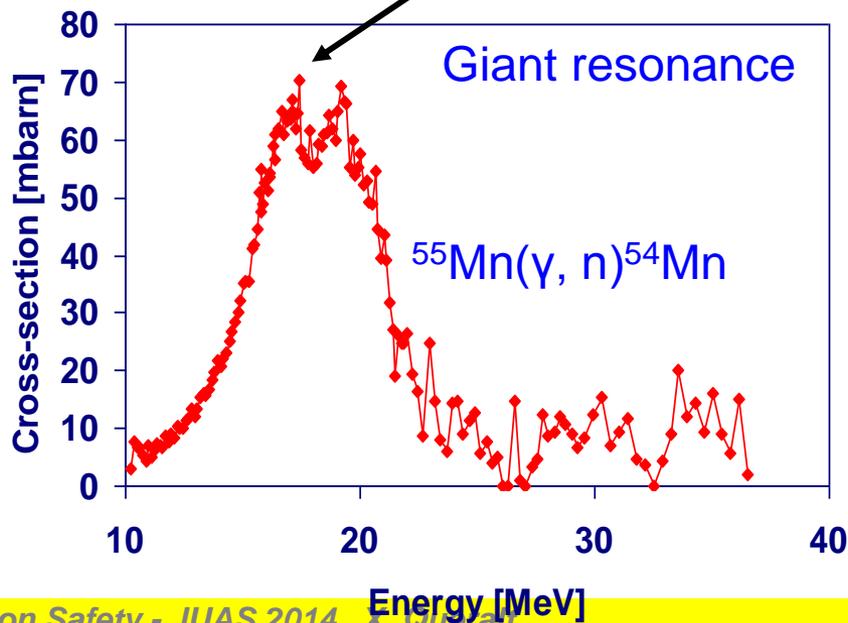
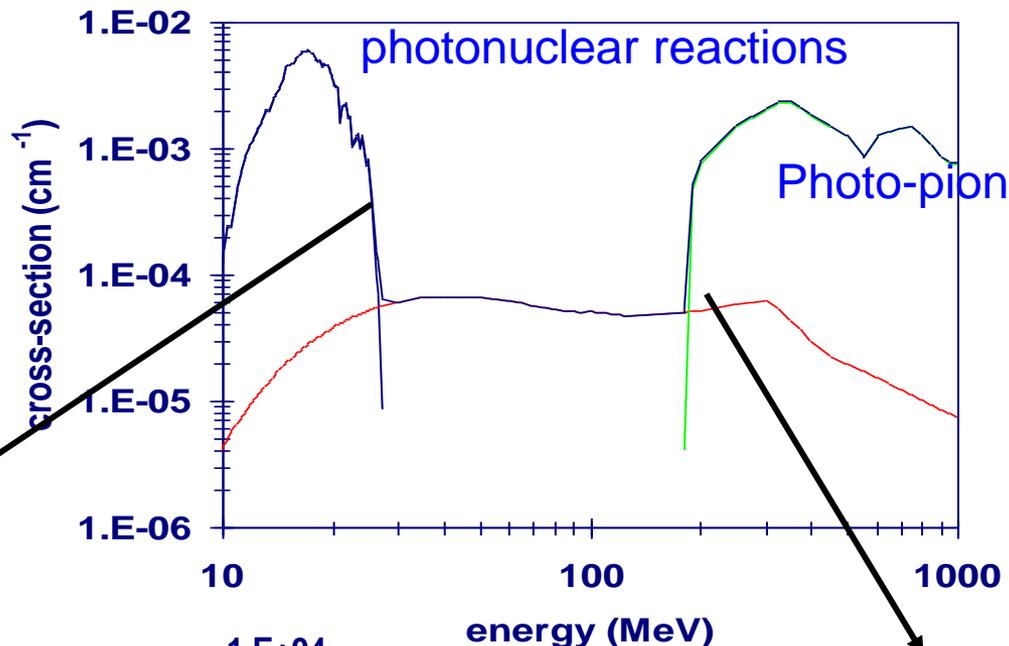


one 6 GeV electron interacting with lead target

2. Interaction of photons with matter

Photonuclear reactions:

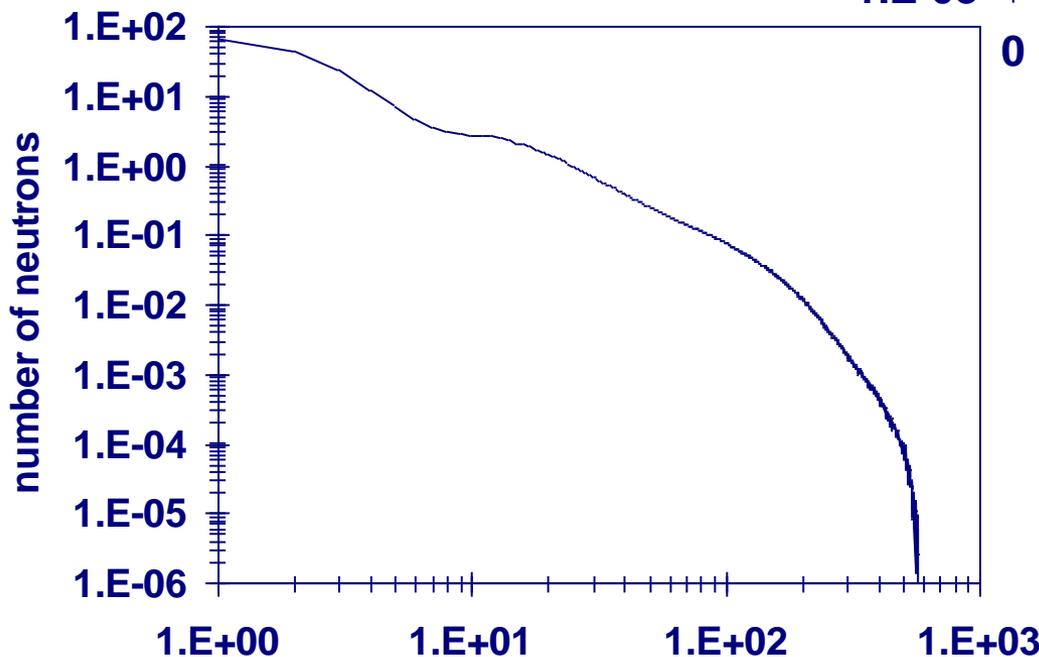
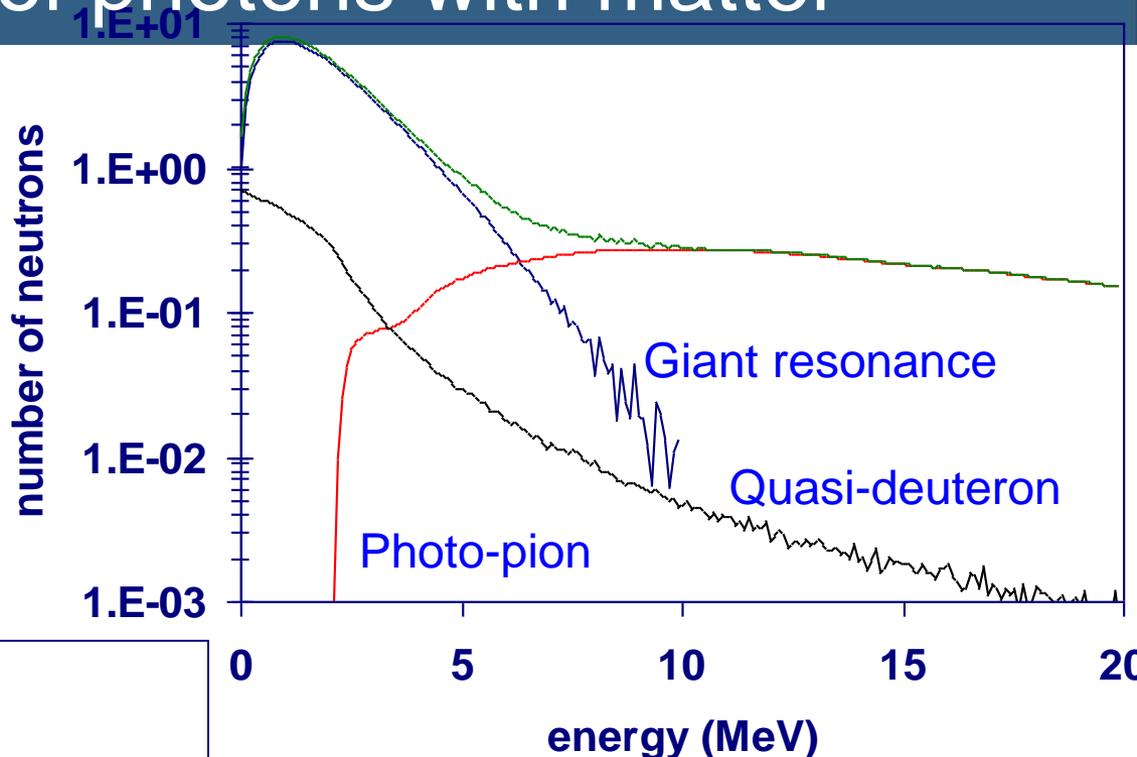
Neutron production



2. Interaction of photons with matter

Photonuclear reactions:

Neutron production



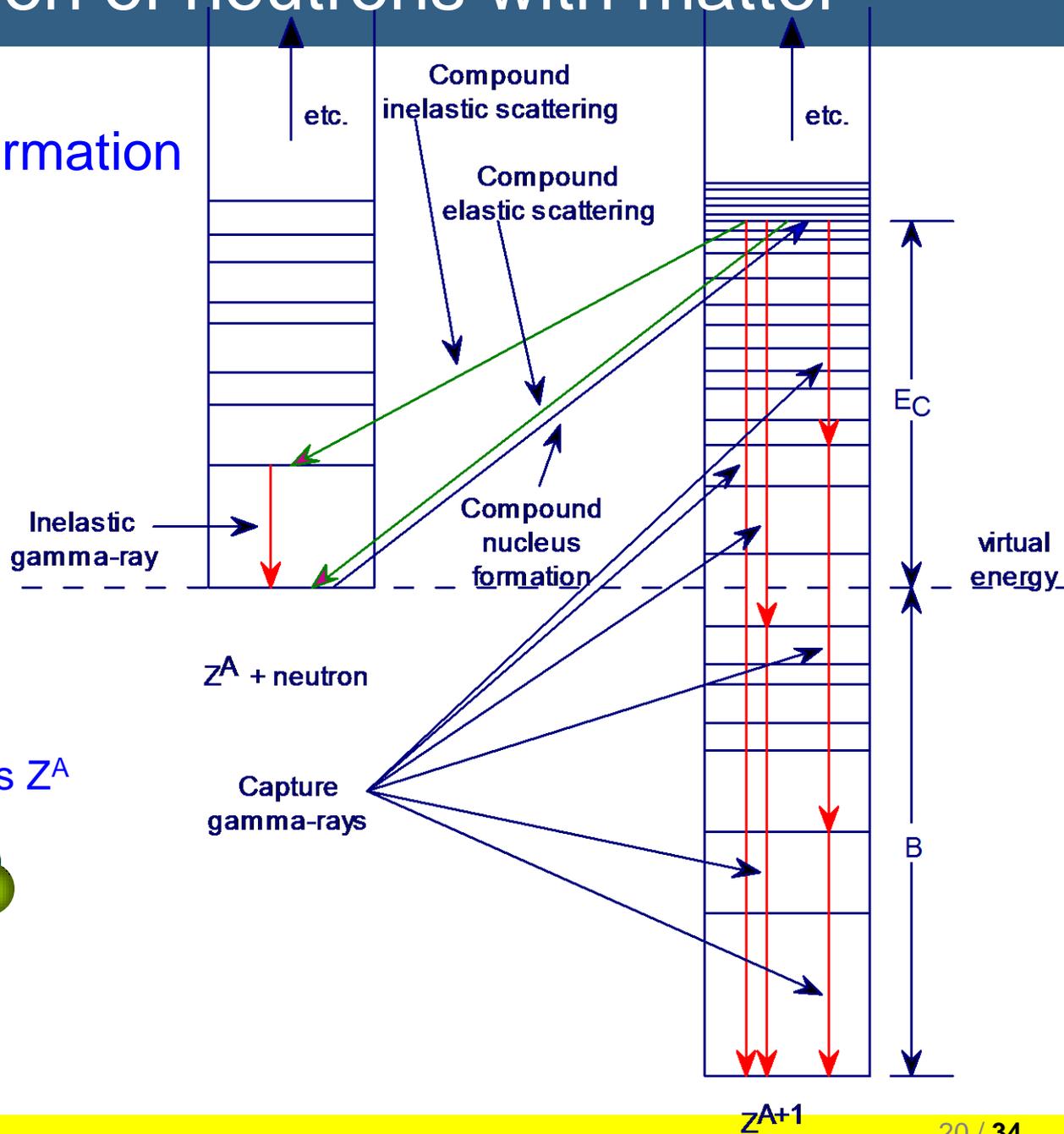
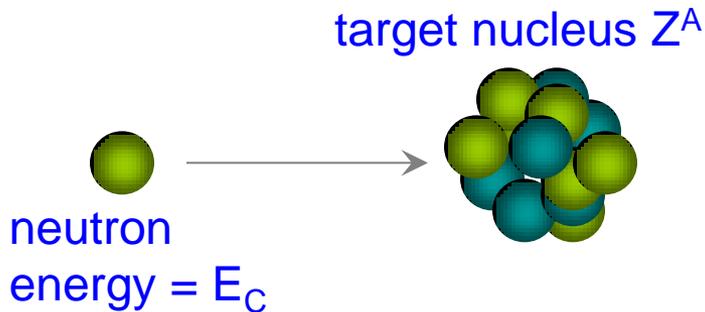
Example: neutron spectrum produced by 600 MeV electrons on Cu target

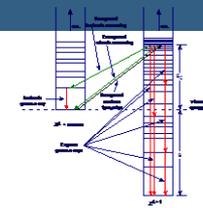
The physical processes:

1. Elastic scattering
 - compound elastic scattering
 - potential scattering
2. Inelastic scattering (n,n')
3. Other inelastic reactions: (n,p), (n,a), ...
4. Absorption reactions
 - radioactive capture
 - charged particle reactions
5. Direct reactions: spallation

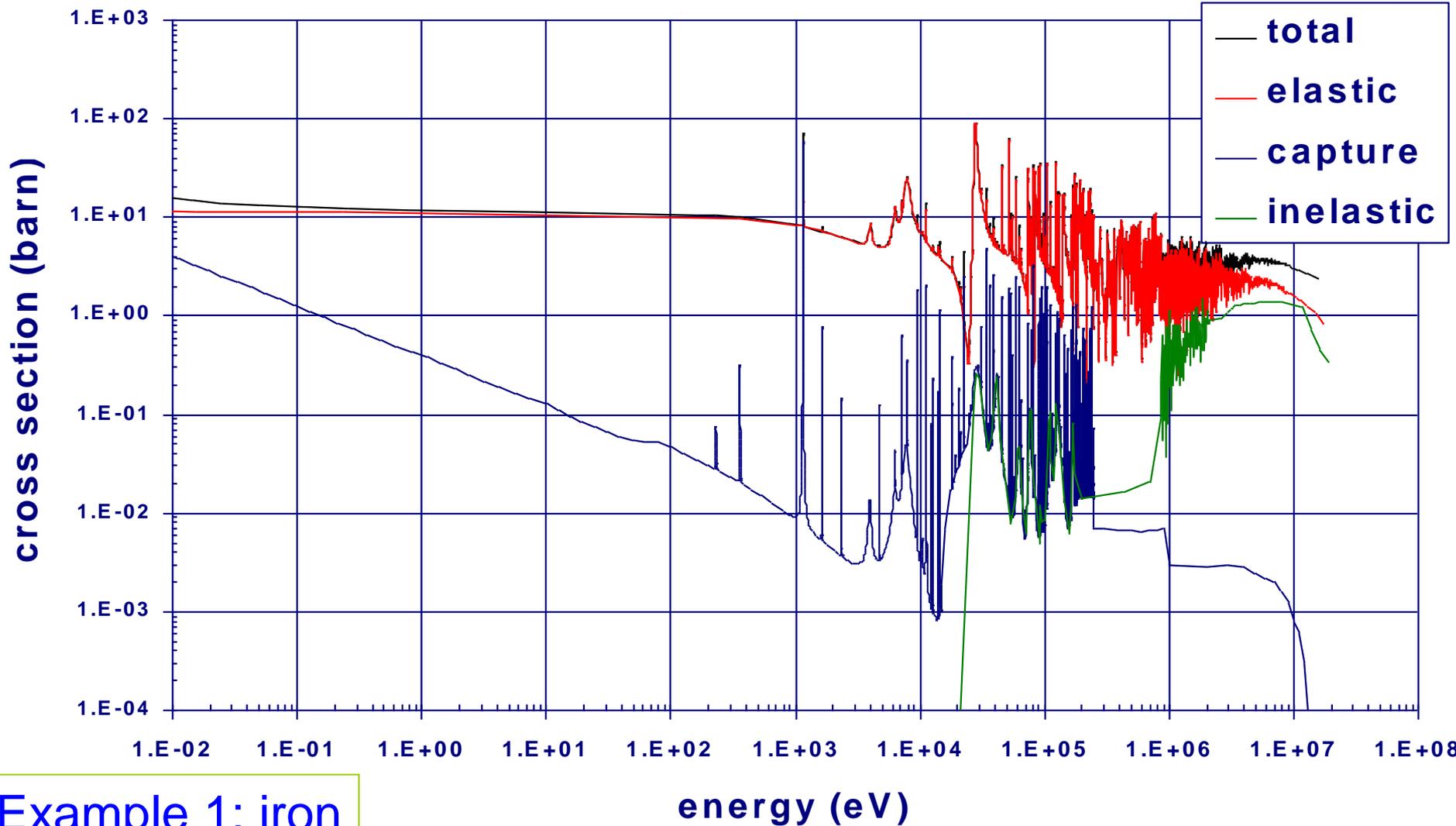
3. Interaction of neutrons with matter

Compound nucleus formation

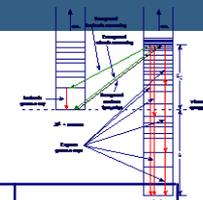




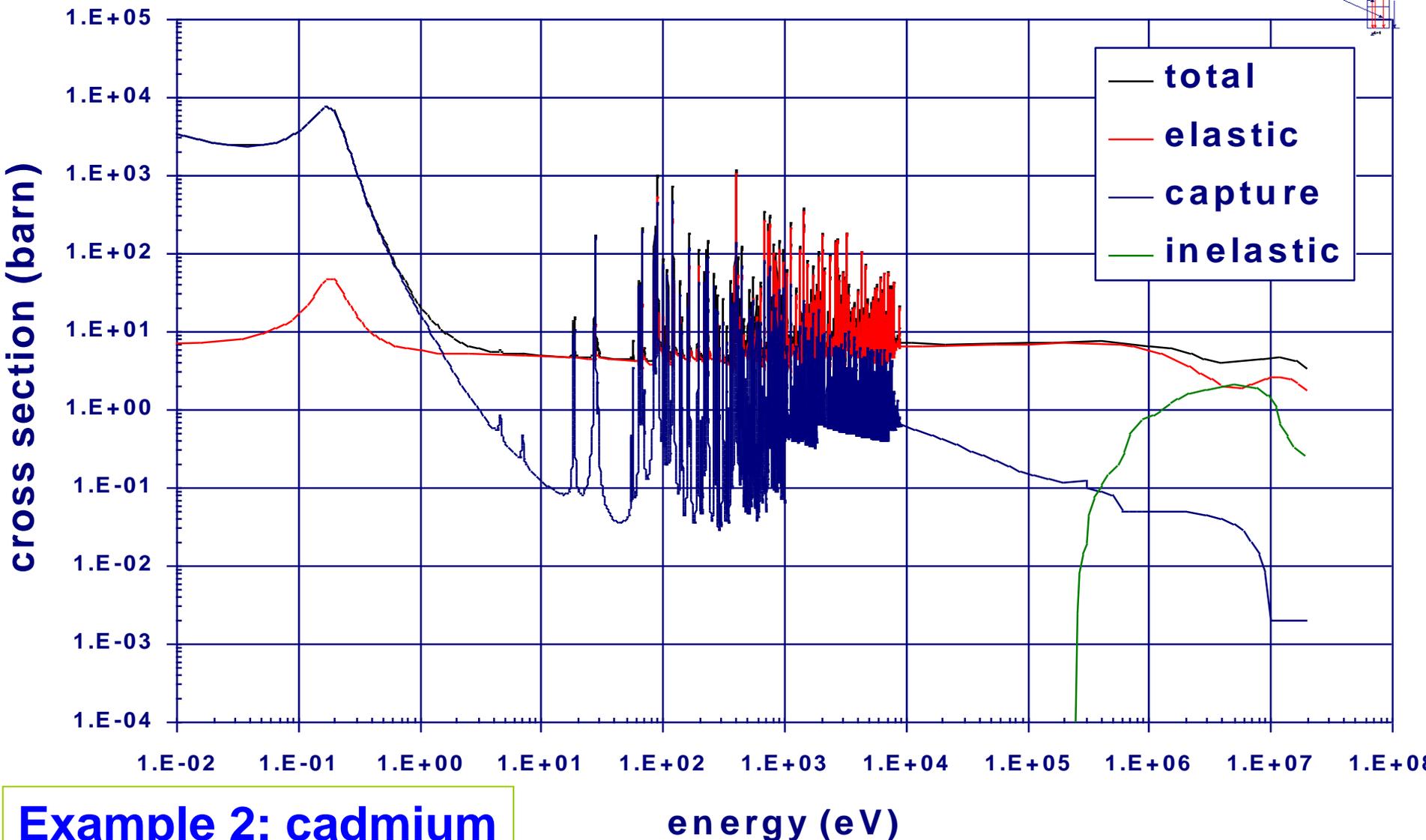
Neutron cross sections



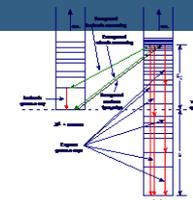
Example 1: iron



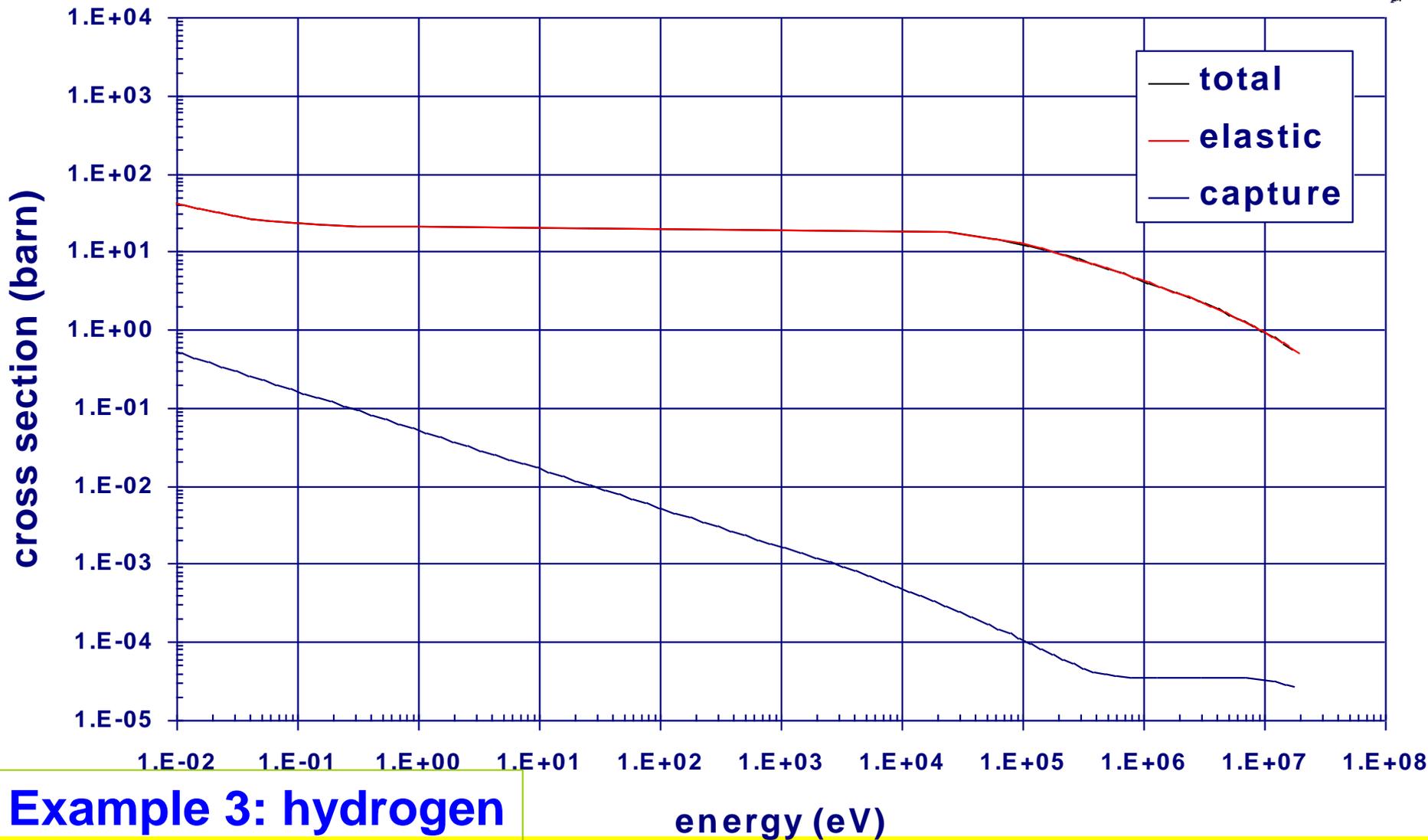
Neutron cross sections



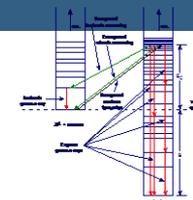
Example 2: cadmium



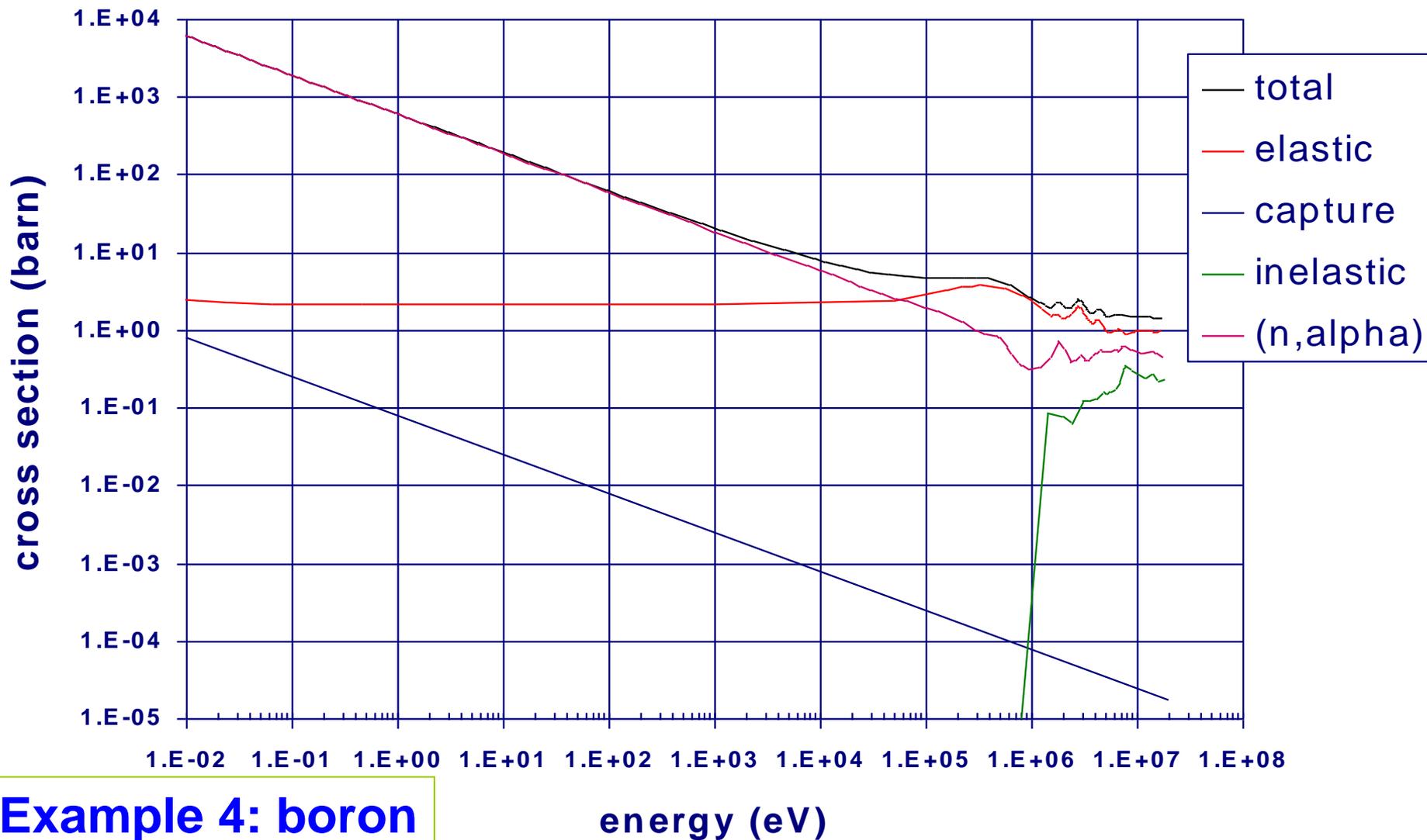
Neutron cross sections



Example 3: hydrogen

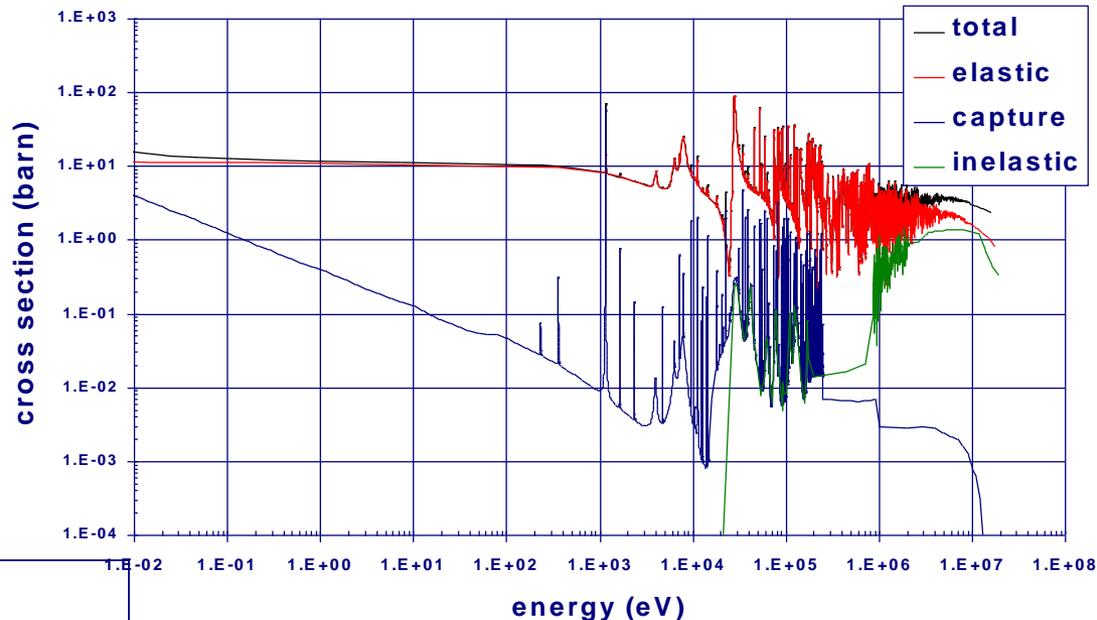


Neutron cross sections

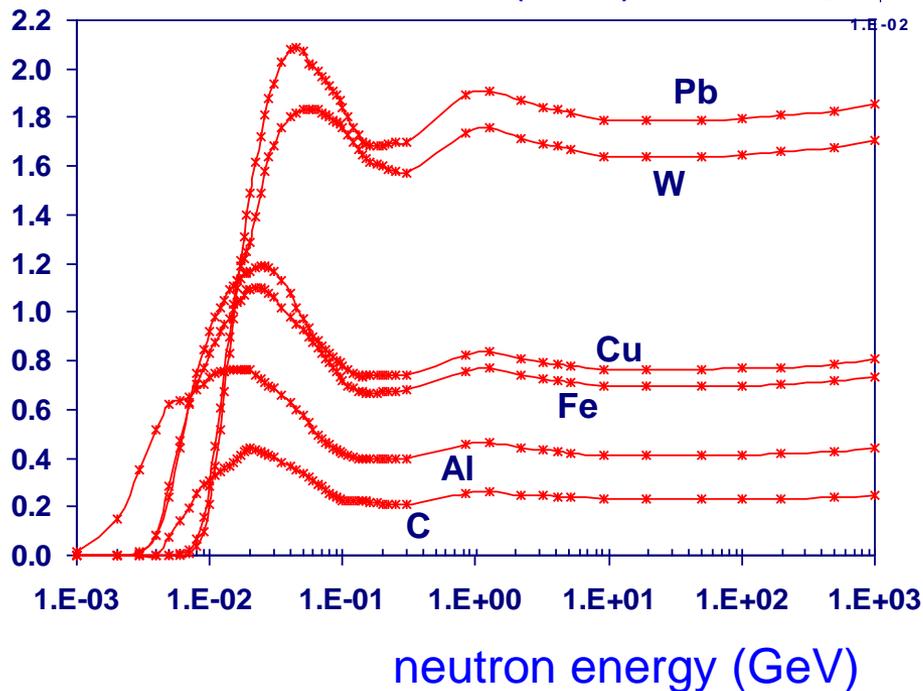


3. Interaction of neutrons with matter

Neutron cross sections



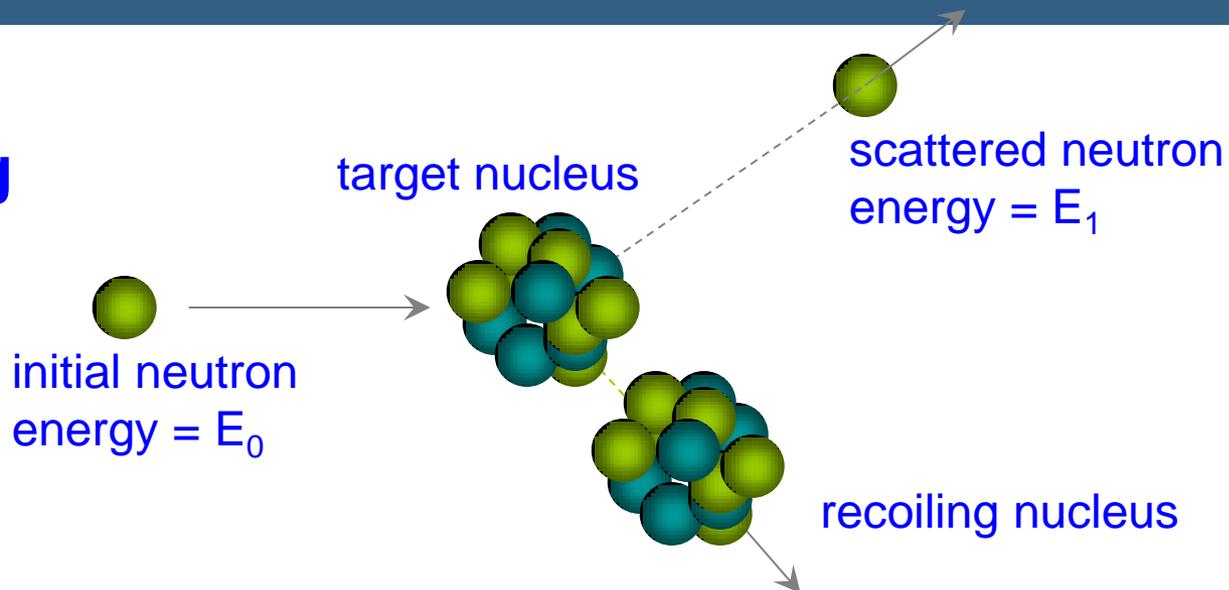
inelastic cross section (barn)



Example: iron

3. Interaction of neutrons with 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)	$0.98 E_0$	$0.0096 E_0$

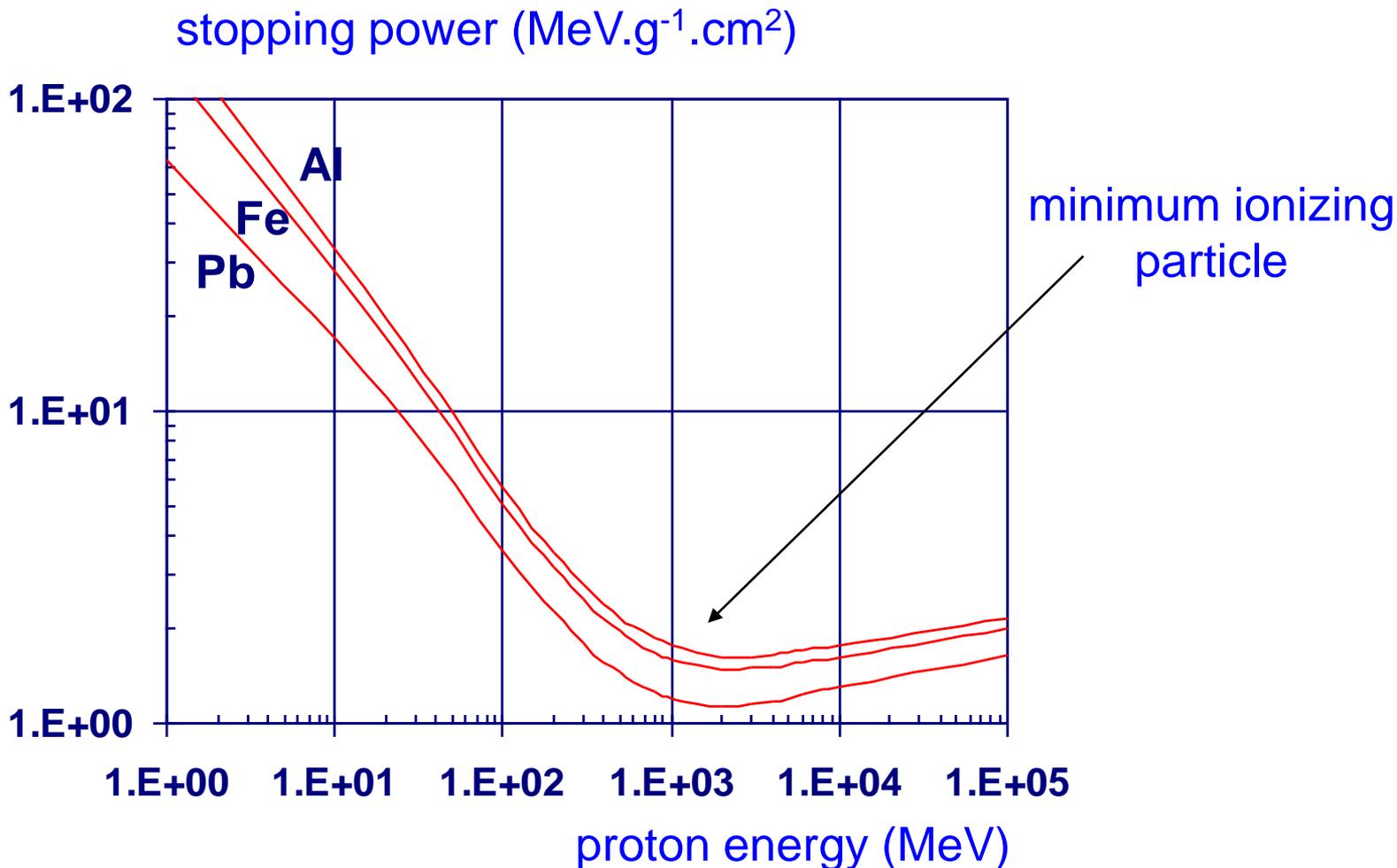
4. Interaction of protons with matter

The physical processes:

1. ionization
2. inelastic proton-nucleus scattering
spallation

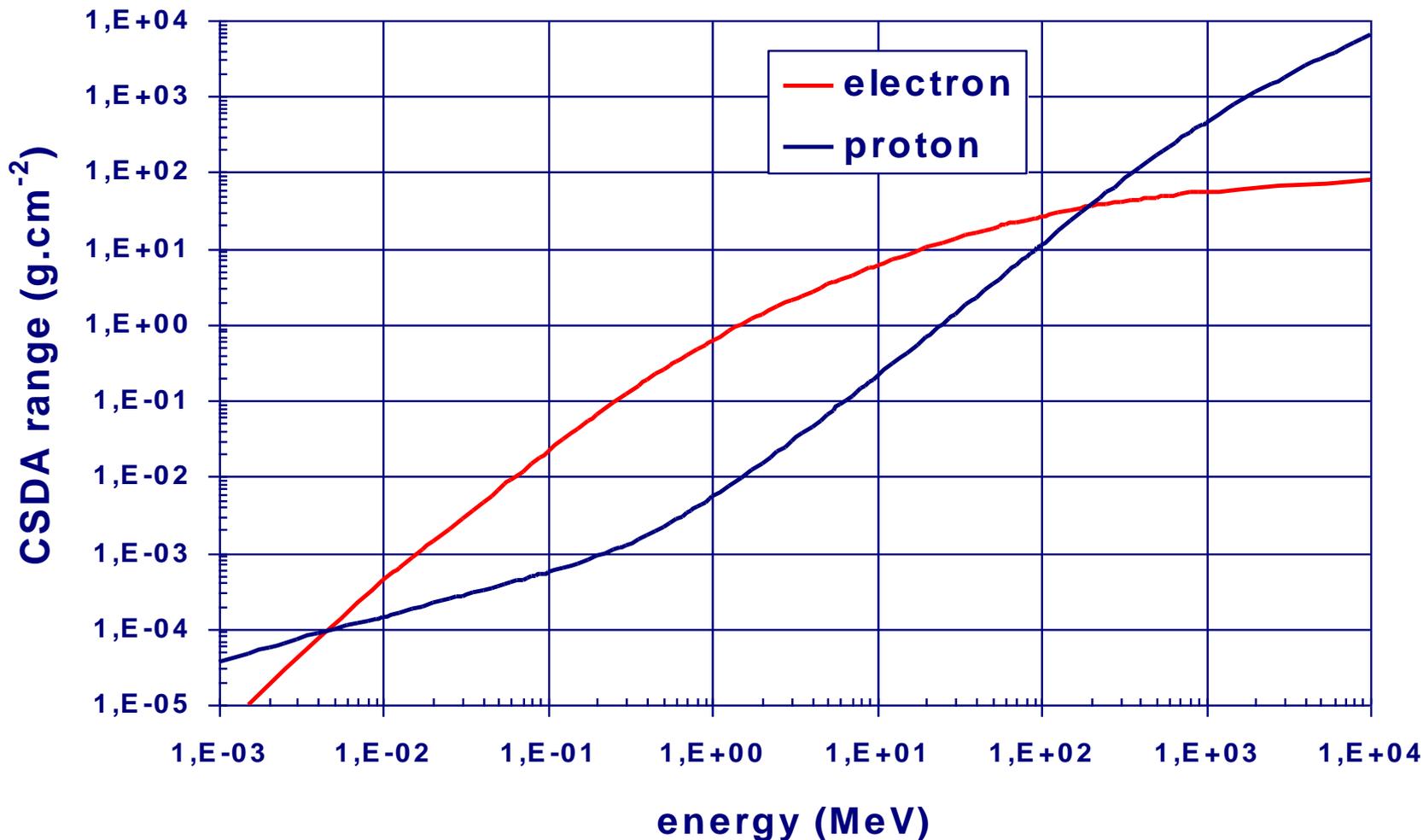
4. Interaction of protons with matter

Proton ionization loss – Stopping power



4. Interaction of protons with matter

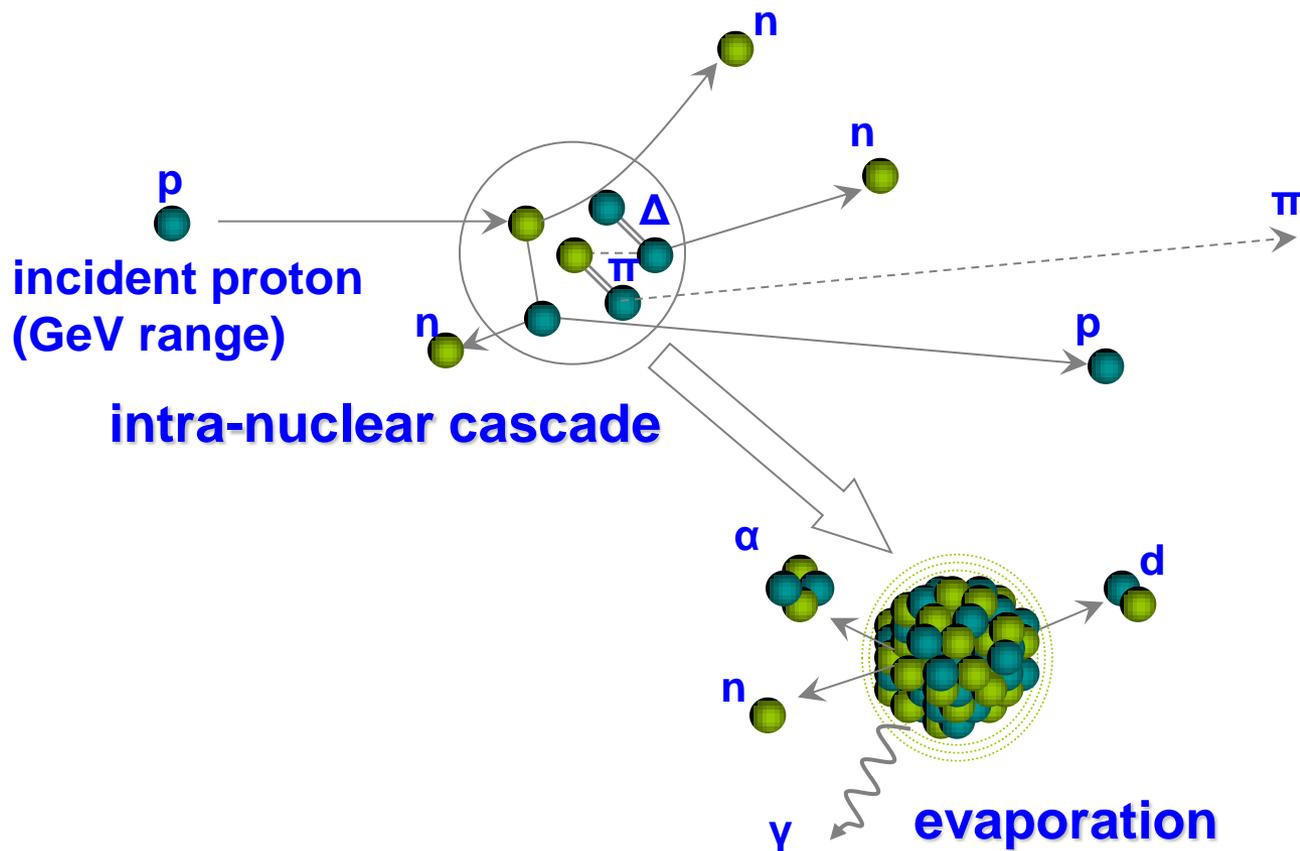
Comparison CSDA range of protons and electrons in iron



4. Interaction of protons with matter

Inelastic proton – nucleus scattering:

Spallation reaction

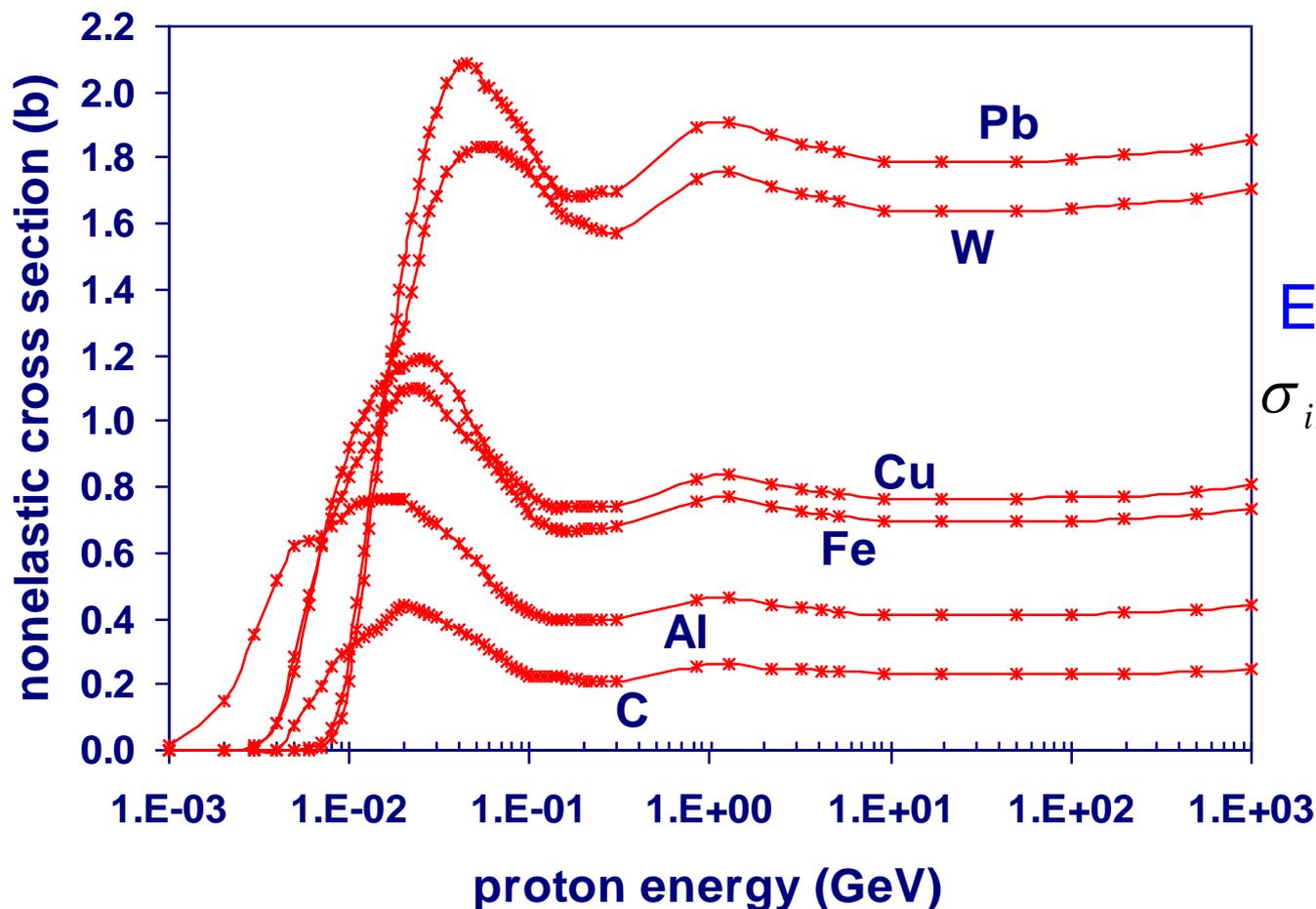


4. Interaction of protons with matter

Inelastic proton – nucleus scattering

Spallation reaction

Inelastic cross section



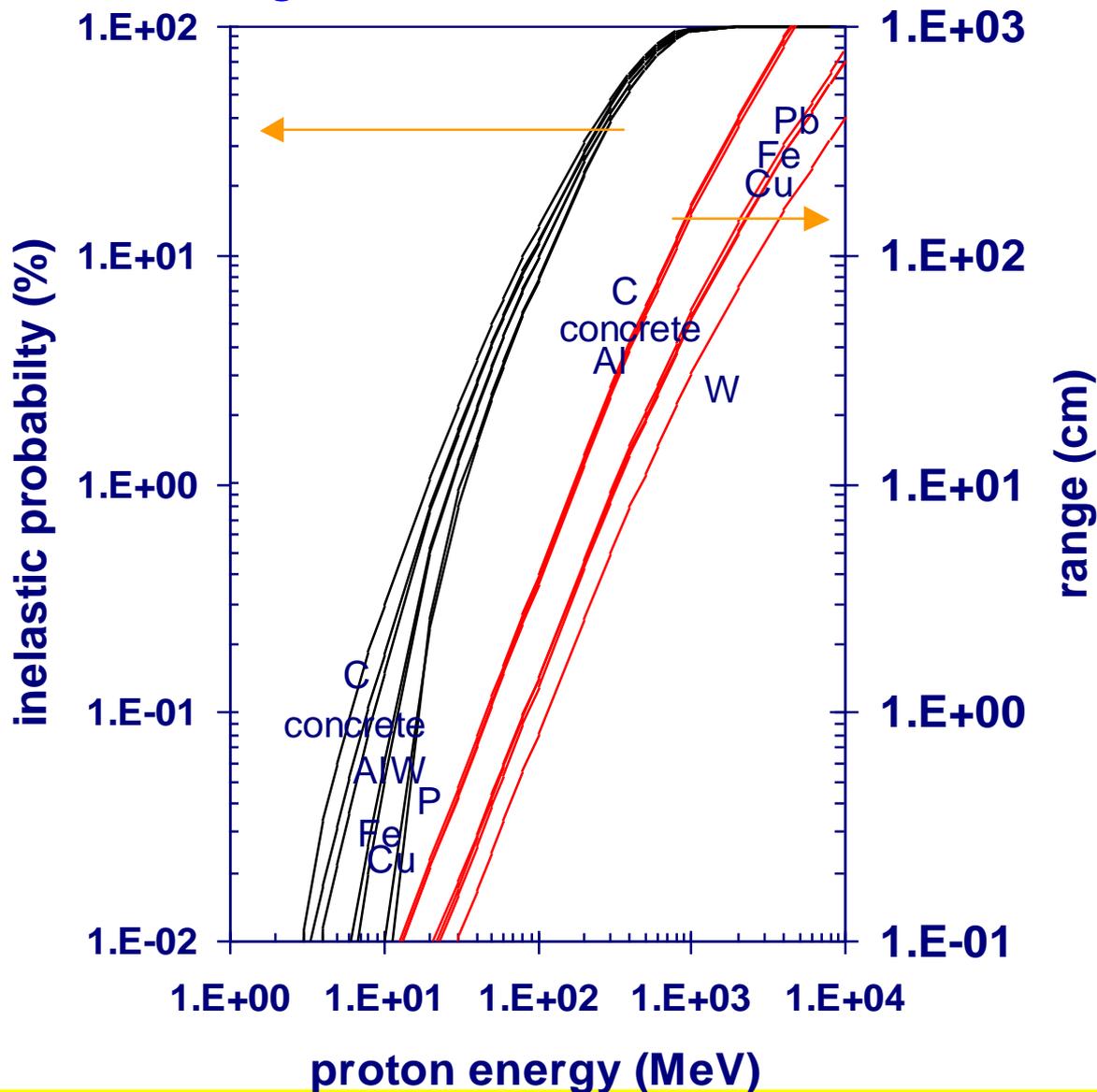
$E > 1 \text{ GeV}$

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

4. Interaction of protons with matter

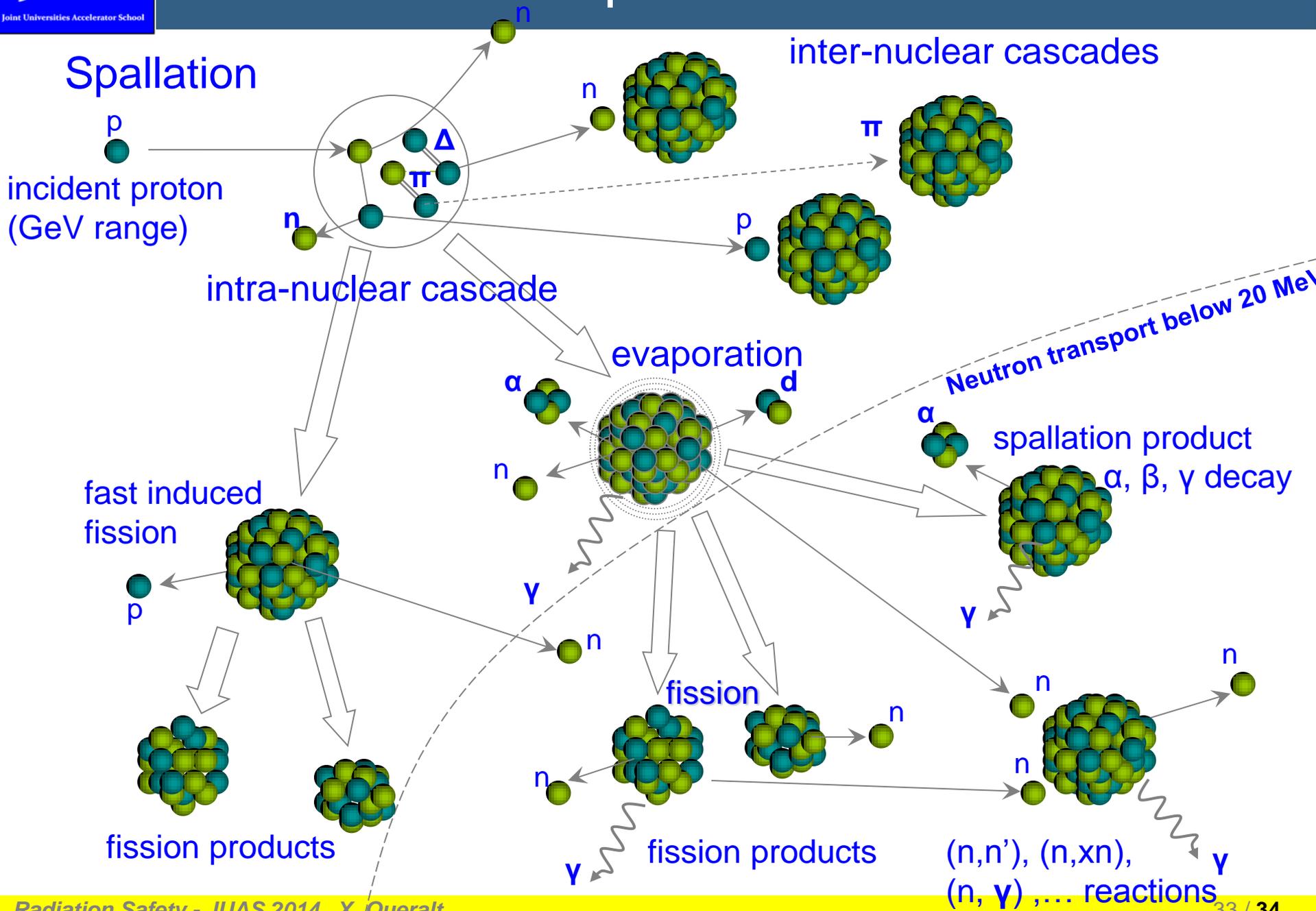
Inelastic proton – nucleus scattering

Comparison ionization energy loss and inelastic scattering



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

4. Interaction of protons with matter



Spallation

