3. Interaction of Neutral Particles with Matter

3.1 The interaction of photons with matter

- Photoelectric effect
- Compton effect
- Pair production
- Total photon absorption coefficients

3.2 Detection of neutrons

3.3 Detection of neutrinos

3.1 Interactions of photons with matter

- Photons are electrically neutral particles;
  In order to be detected, they must transfer their energy to charged particles

- Interaction with detector material via three discrete processes:

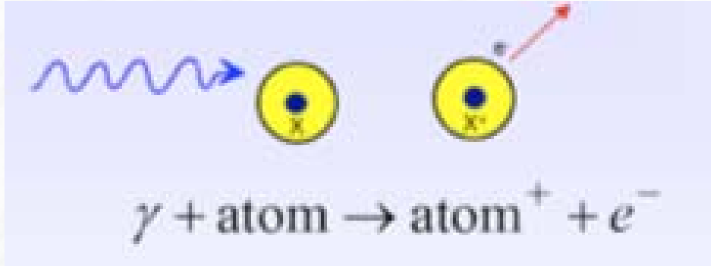
  - Photoelectric effect
  - Compton scattering
  - Pair creation

- Photons "disappear" via these reactions (photoelectric effect and pair creation) or are "scattered" and loose energy
  → The Intensity of a photon beam is exponentially attenuated in matter (see later):

$$I(x) = I_0 \cdot e^{-\mu \cdot x}$$

where: x represents the path length in the material,
$I(x)$ is the intensity of the photon beam, with $I_0 = I\,(x=0)$, and
μ := attenuation coefficient.

Photoelectric effect:



- Absorption of the photon by electrons
  → ionisation, for high energies, electrons are released from the inner shells (K, L, ..) of the atoms

- The energy of the electrons is fixed: $E_e = E\gamma - E_B$ (e)

- Theoretically, the photoelectric effect is difficult to treat rigorously, due to the complexity of the Dirac wave-functions for the atomic electrons

- It shows a strong modulation if $E_\gamma \approx E_B$ (binding energy); For regions away from absorption edges one finds in leading order for the K-shell absorption cross section for an atom:

$$\sigma^{K}_{Photo} = \sqrt{\frac{32}{\varepsilon^7}}\,\alpha^4 \cdot Z^5 \cdot \sigma^{e}_{Th} \qquad [\mathrm{cm}^2 / \mathrm{Atom}]$$

where σ_{Th}^{e} represents the Thomson cross section for elastic scattering of photons on electrons, which is given by:

$$\sigma^{e}_{Th} = \frac{8}{3} \cdot \pi \cdot r_e^2 \qquad = 6.65\ 10^{-25}\ \mathrm{cm}^2 = 0.665\ \mathrm{b} \quad (\mathrm{barn})$$

Compared to the ionisation cross sections discussed in Section 2, these cross sections

- For high photon energies ($\varepsilon >> 1$) the cross section can be approximated by:

$$\sigma^K_{Photo} = 4\pi r_e^2 \alpha^4 \cdot Z^5 \cdot \frac{1}{\varepsilon} \qquad \text{where} \quad \varepsilon = \frac{E_\gamma}{m_e c^2} \quad \text{(reduced photon energy)}$$

- The cross section shows a very strong Z dependence:

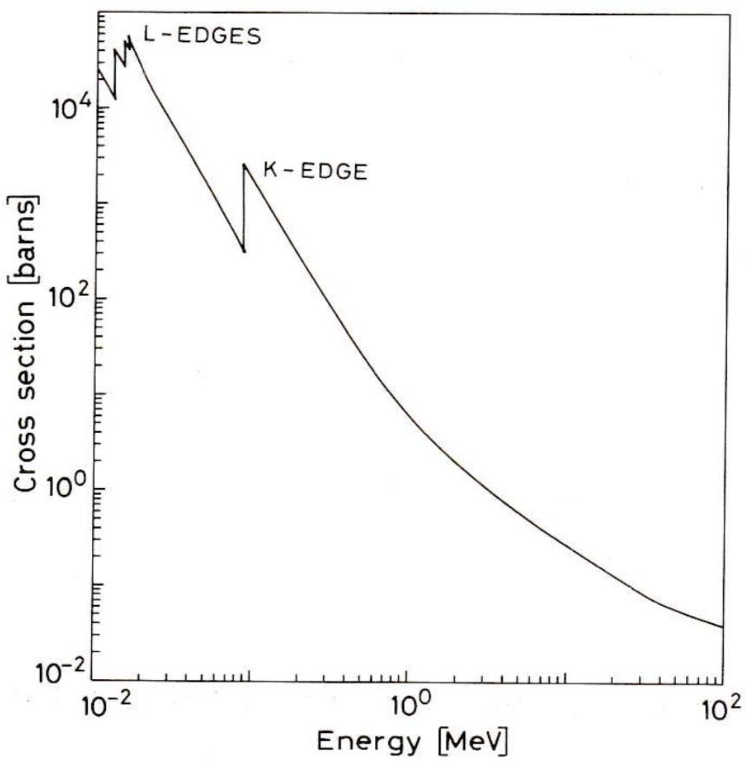
$$\sigma^K_{Photo} \propto Z^5$$

→ large absorption via photoelectric effect in high-Z materials

(in the range 0.1 MeV < E_γ < 5 MeV, the exponent is found to vary between 4 and 5)

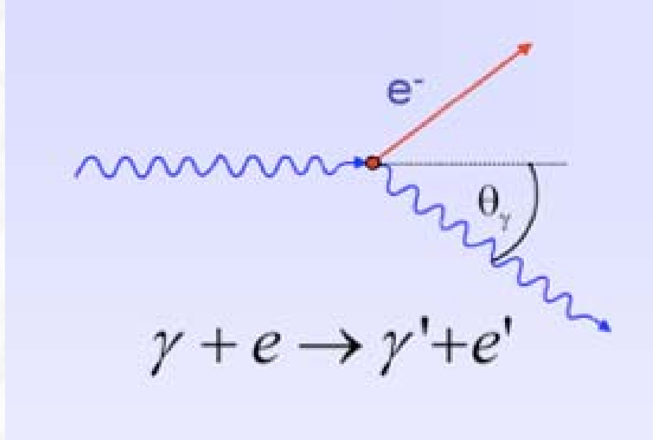
- For photons with energies above the K-shell binding energy, the energy is mainly transferred to K-shell electrons

- Photo electric effect is accompanied by the emission of X-rays or Auger electrons (de-excitation of atom)



Photoelectric cross section for lead (from Ref. [2])

Compton scattering:



- Describes the elastic scattering of a photon on a quasi-free electron

  (i.e. binding energy can be neglected compared to the photon energy)

- Applying energy and momentum conservation, the following relations can be obtained:

$$E_{\gamma'} = E_\gamma \frac{1}{1+\varepsilon(1-\cos\theta_\gamma)}$$

where $\varepsilon = \frac{E_\gamma}{m_e c^2}$

- This can also be expressed as a change of the photon wave length:

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c}(1-\cos\theta)$$

where $\frac{h}{m_e c}$ = 2.426 10^{-12} m is called the Compton wave length

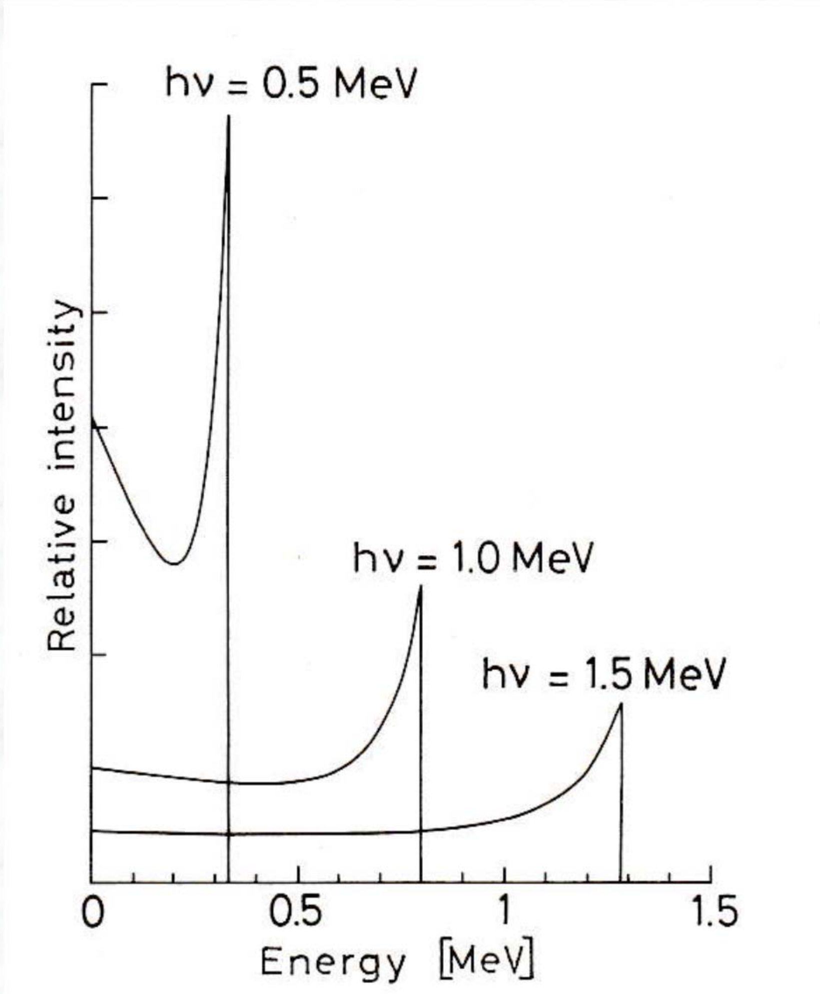
•Maximal energy transfer to the electron for $\theta = \pi$

→ $$E_{\gamma'}^{min} = E_\gamma \frac{1}{1+2\varepsilon}$$

This corresponds to a maximal electron energy of:

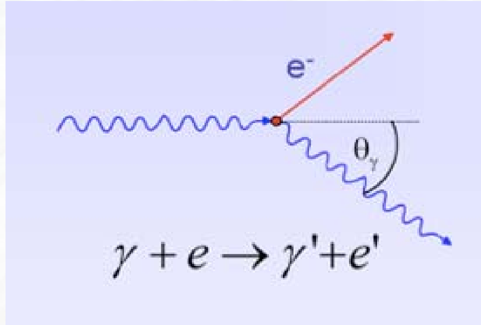
$$E_e^{max} = E_\gamma - E_{\gamma'}^{min} = E_\gamma \frac{2\varepsilon}{1+2\varepsilon}$$

Appears as **"Compton Edge"** in the electron energy spectrum



Energy distribution of the Compton recoil electrons. The sharp drop at the maximum recoil energy is known as *Compton edge* (from Ref. [2])

- The differential cross section can be calculated in QED and is given by the **Klein-Nishina formula:**

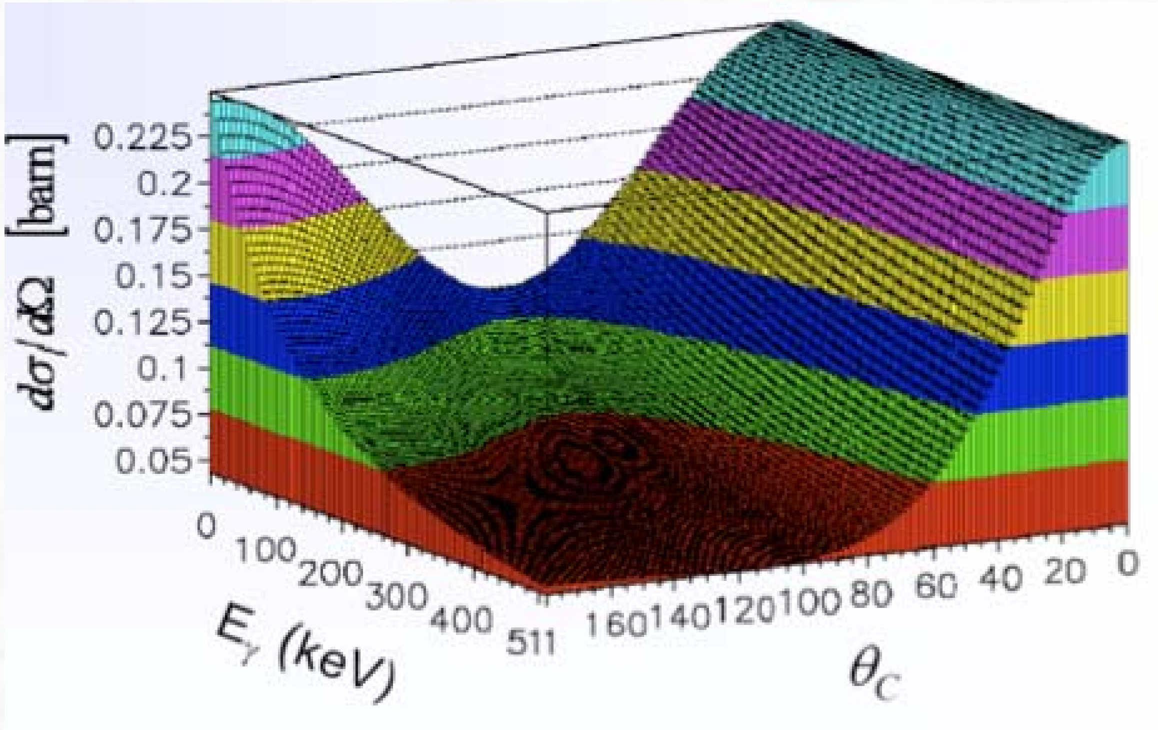


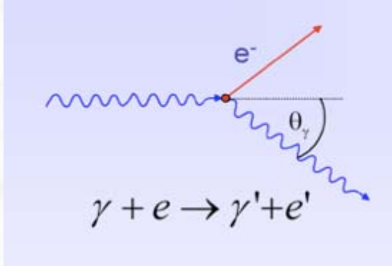
$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2} \frac{1}{[1+\varepsilon(1-\cos\theta_\gamma)]^2} \left(1 + \cos^2\theta_\gamma + \frac{\varepsilon^2 (1-\cos\theta_\gamma)^2}{1+\varepsilon(1-\cos\theta_\gamma)} \right)$$

[cm² / electron]

$$\varepsilon = \frac{E_\gamma}{m_e c^2}$$

$$\frac{d\sigma}{d\Omega}(\theta, \varepsilon)$$





- Integration over $d\Omega$ gives the total cross section per electron for Compton scattering

$$\sigma_c^e = 2\pi r_e^2 \left[\left(\frac{1+\varepsilon}{\varepsilon^2}\right) \left\{ \frac{2(1+\varepsilon)}{1+2\varepsilon} - \frac{1}{\varepsilon}\ln(1+2\varepsilon) \right\} + \frac{1}{2\varepsilon}\ln(1+2\varepsilon) - \frac{1+3\varepsilon}{(1+2\varepsilon)^2} \right]$$

[cm^2 / electron]

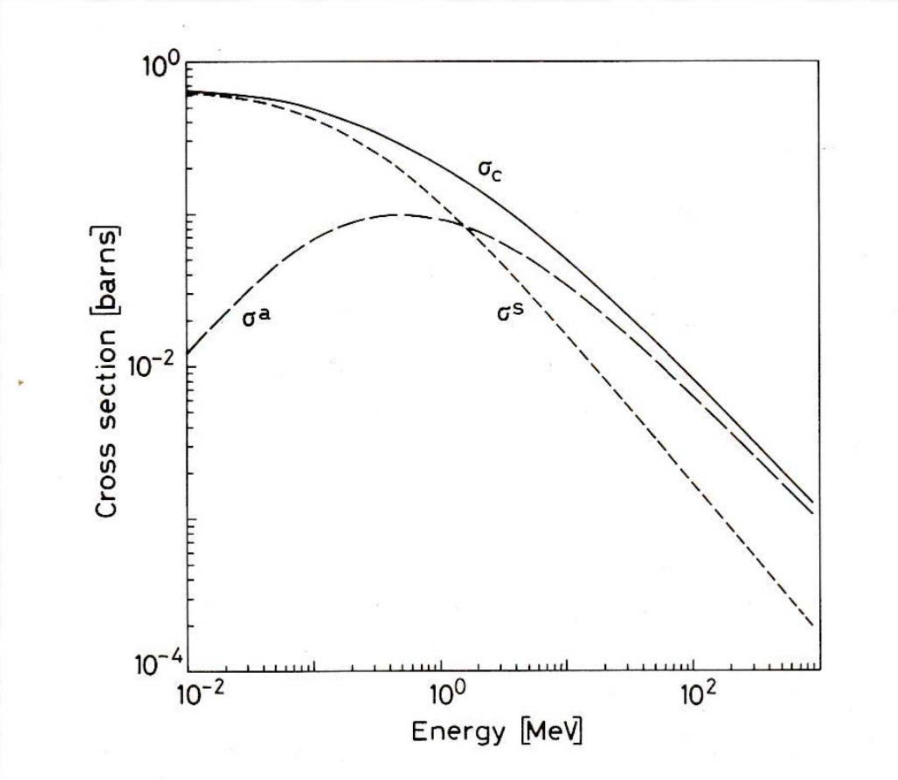
- For high energies $\varepsilon >> 1$ the Klein-Nishina formula can be approximated by:

$$\sigma_c^e \sim \frac{\ln \varepsilon}{\varepsilon}$$

- The scattering cross section per atom (Z electrons) is given by:

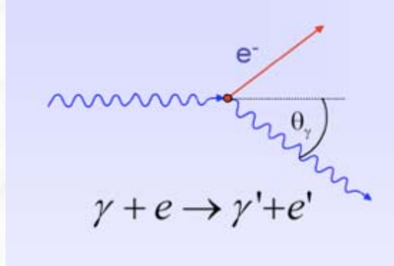
$$\sigma_c^{Atom} = Z\,\sigma_c^e$$

Absorber material dependence: ~ Z



Total Compton scattering cross section (from Ref. [2])

- In Compton scattering only part of the energy is transferred to the electron, i.e. photon is scattered and red-shifted, however, it does not disappear



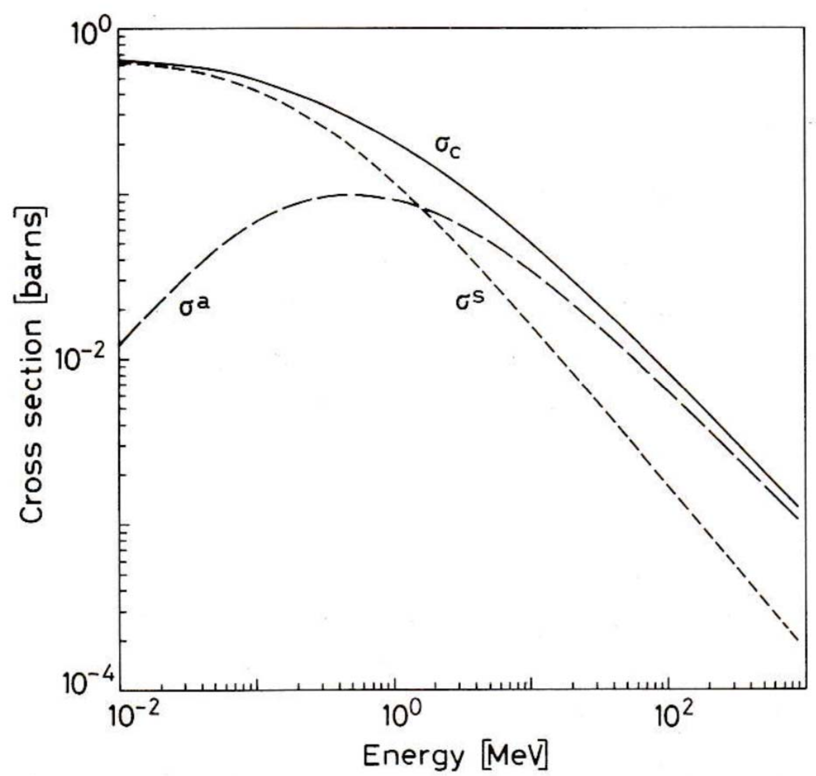
[cm^2 / electron]

- Therefore one defines a scattering and an absorption cross section for the atom as:

$$\sigma^S = \frac{E_{\gamma'}}{E_\gamma}\sigma_c^e$$

$$\sigma^A = \sigma_c^e - \sigma^S$$

- For these cross sections also different attenuation coefficients (μ_{CS} and μ_{CA}) are determined (see later)



Total Compton scattering cross section
(from Ref. [2])

Thomson and Rayleigh scattering:

Thomson scattering: elastic scattering of photons on free electrons in the low energy limit

for $\varepsilon \rightarrow 0$ the Klein-Nishina formula reduces to the Thomson cross section

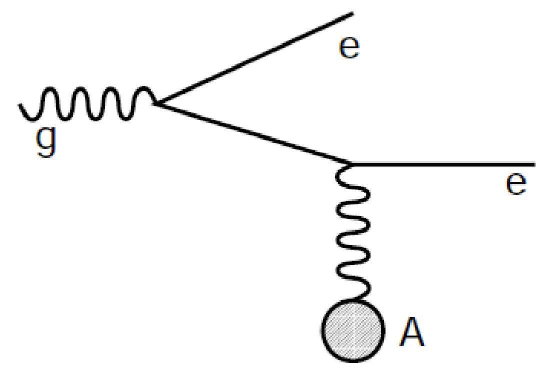
$$\sigma_{Th}^{e} = \frac{8}{3} \cdot \pi \cdot r_e^2$$

Rayleigh scattering: scattering of photons by atoms as a whole, all electrons participate in a coherent manner (→ also called coherent scattering)

In both processes no energy is transferred to the medium;
Atoms are neither excited nor ionized and only the direction of the photons is changed

For high $E\gamma$: Thomson and Rayleigh scattering are very small and can be neglected.

Pair production: $\gamma + (A) \rightarrow e^+ e^- + (A)$



- Only possible in the close neighbourhood of a collision partner (atomic nucleus)
- Threshold energy: $E_\gamma > 2\, m_e\, c^2 = 1.022$ MeV
- Cross section (high energy approximation):

$$\sigma_{pair} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

energy independent, asymptotic value, $\sim Z^2$

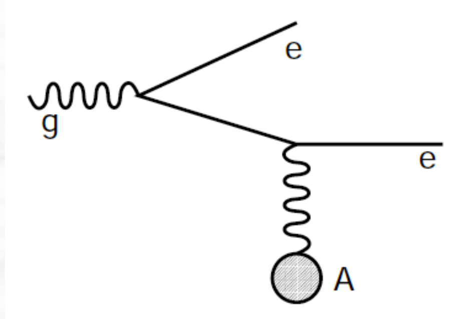
$$\Longrightarrow \quad \boxed{\mu_{pair} = \frac{7}{9} \frac{1}{X_0}}$$

- After traversing a material thickness of 9/7 X_0, the photon intensity –due to pair creation- is decreased by 1/e
  .or.
- For high photon energies, pair production occurs after traversing a material thickness corresponding to one radiation length with a probability of

$$p = 1 - e^{-7/9} = 0.54$$

- The energy distribution on the two electrons (e^+, e^-) is:

  - symmetric for low and medium energies
  - asymmetric for high energies

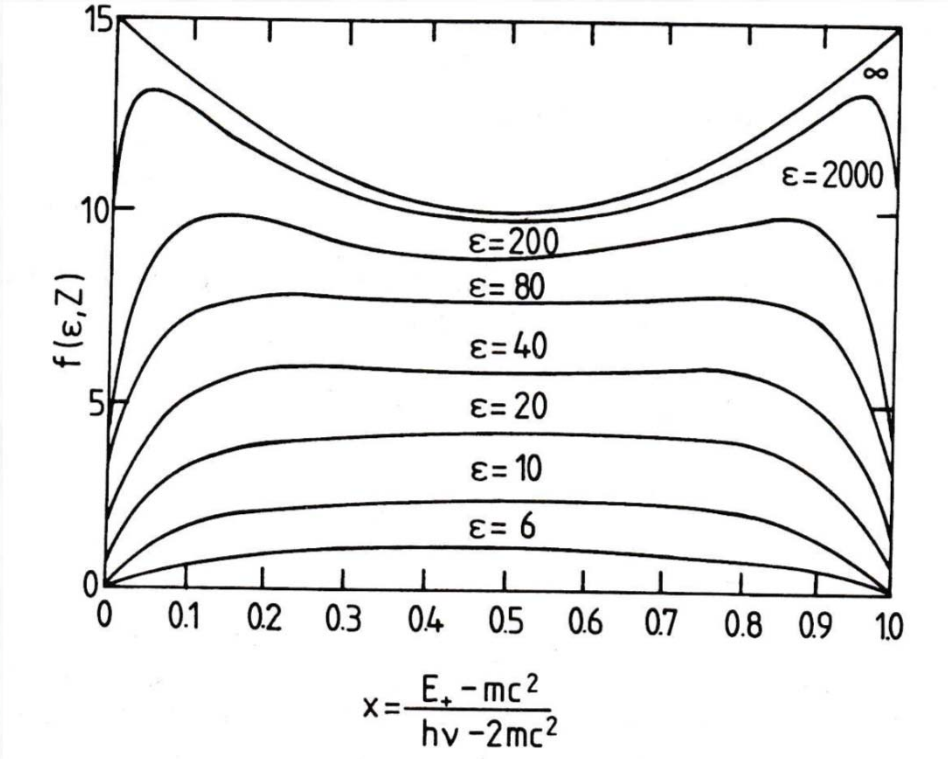


- Define the ratio x of the kinetic energy of the positron to the total kinetic energy of the pair:

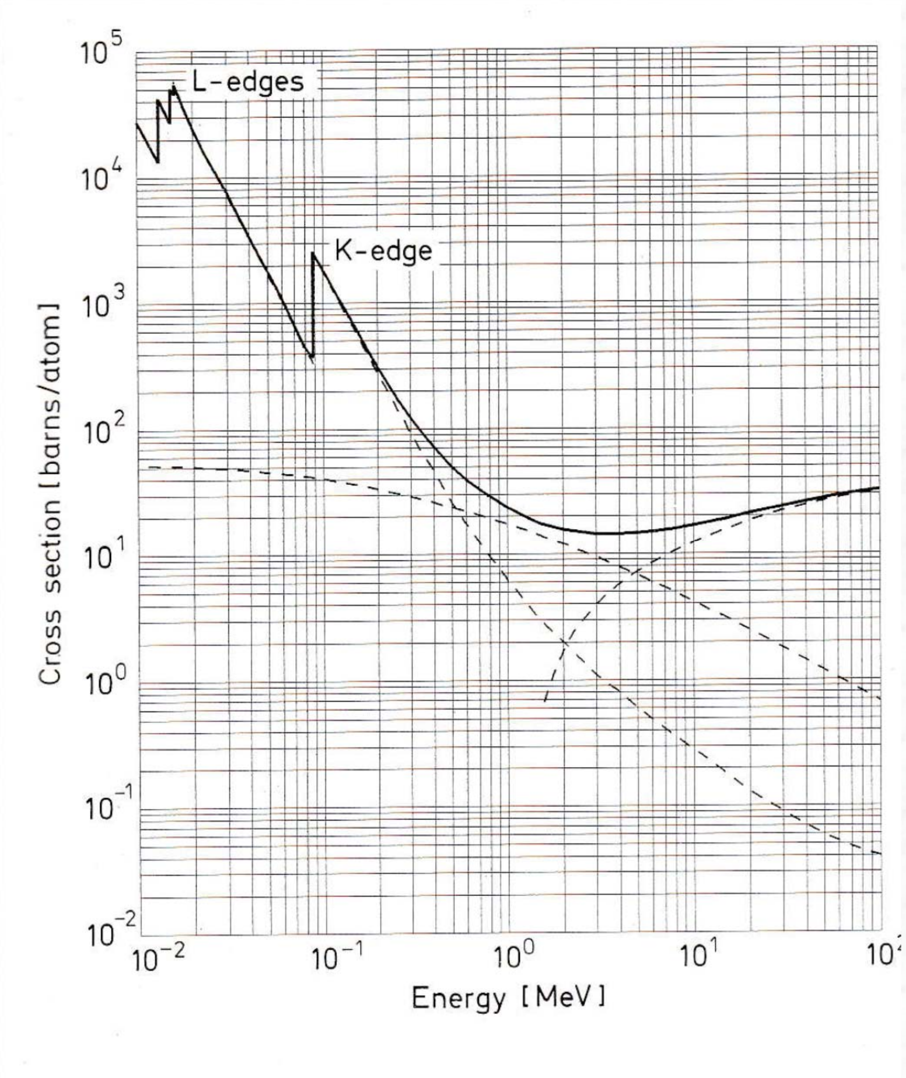
$$x = \frac{E_+ - m_e c^2}{E_\gamma - 2 m_e c^2} = \frac{E_+^{kin}}{E_{Pair}^{kin}}$$

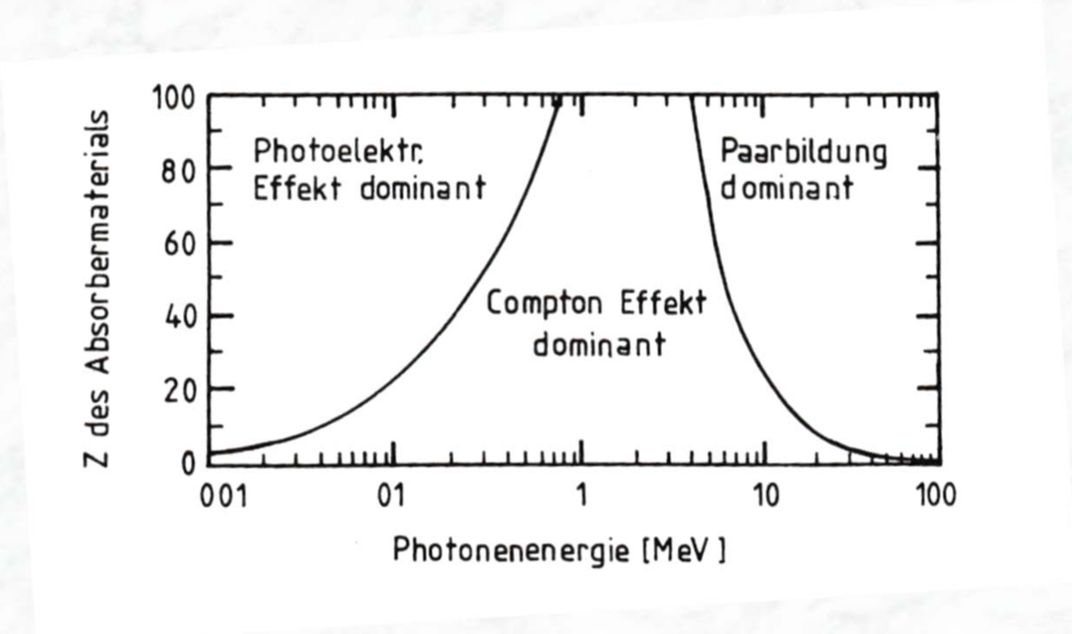
- The differential cross section is then given by:

$$\frac{d\sigma_{Pair}}{dE_+} = \frac{\alpha \cdot r_e^2}{E_\gamma - 2 m_e c^2} \cdot Z^2 \cdot f(\varepsilon, Z)$$



The energy sharing function f(ε, Z)
(from Ref. [3])

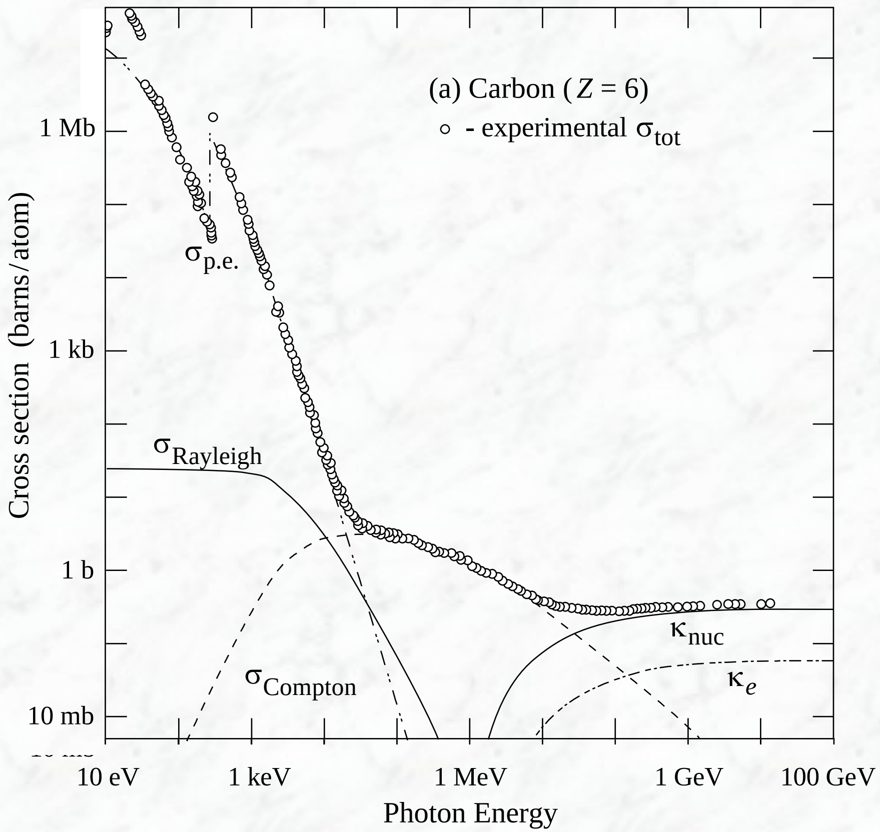


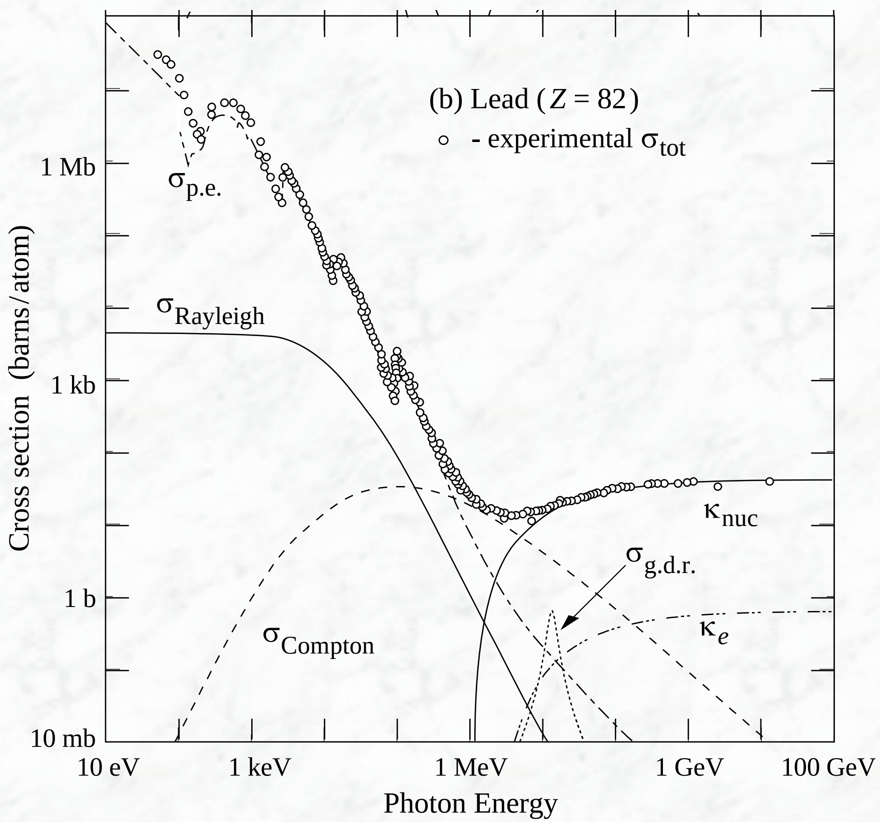


The total photon absorption cross section for lead;
The areas dominated by the photoelectric effect,
by Compton scattering and by pair creation are visible
(from Ref. [2])

Areas in which photoelectric effect, Compton scattering and pair creation are dominant as a function of the photon energy and the proton number Z of the absorber material
(from Ref. [3])

Photon interaction cross sections





Overview on energy loss / interaction processes

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<tr><th>Charged particles</th><th>Photons, γ</th></tr>
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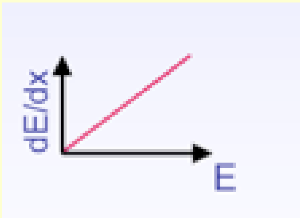
Ionisation and excitation

Bremsstrahlung



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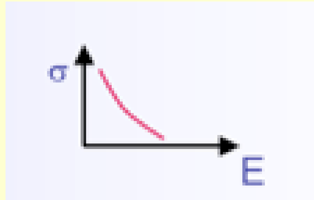
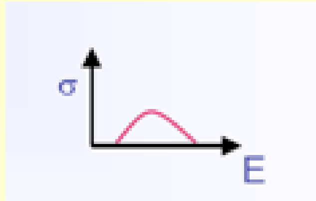
Photoelectric effect

(dominant in ~ keV energy range)



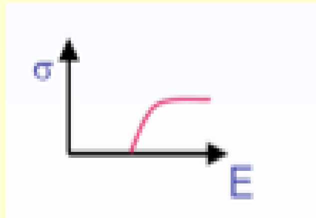
Compton scattering

(dominant in MeV energy range)



Pair creation

(threshold energy = 2 m_e = 1,022 MeV)



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Cherenkov radiation

Transition radiation
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The total absorption coefficient

- The absorption probability for a photon in matter is given by the sum of the cross sections discussed above:

$$\sigma = \sigma_{Photo} + Z \cdot \sigma_c + \sigma_{Pair}$$

- The probability for photon absorption per unit length is given by the product of the cross section and the density of atoms N:

$$\mu := N \cdot \sigma = \left(\frac{N_A \cdot \rho}{A} \right) \cdot \sigma$$

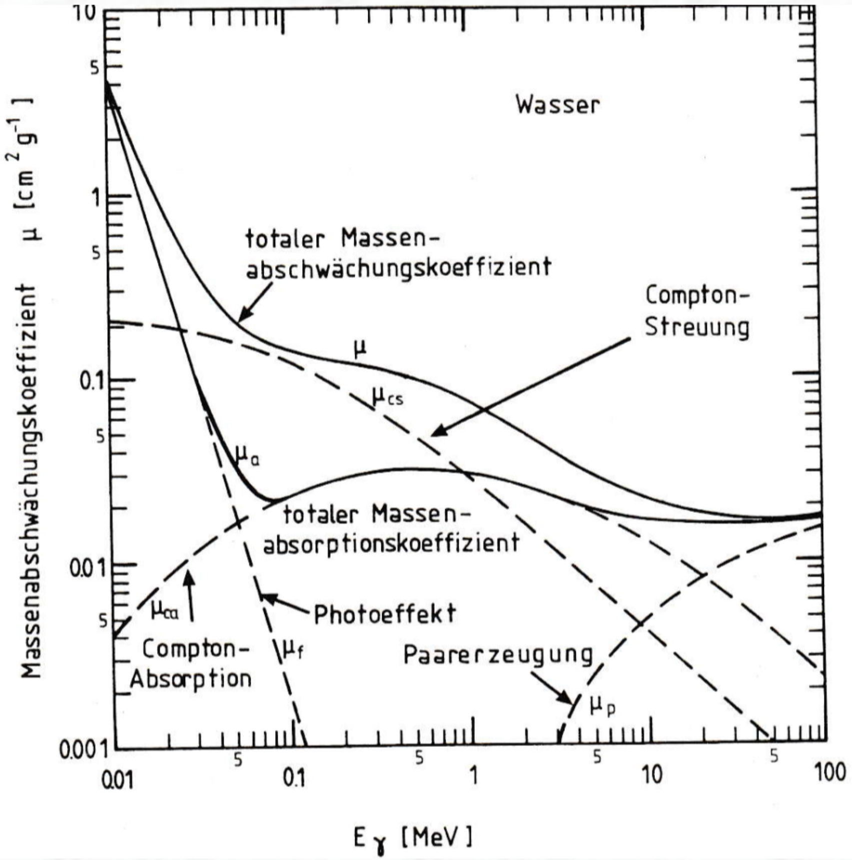
where: N_A : Avogadro's number
ρ : density of the material
A : molecular weight

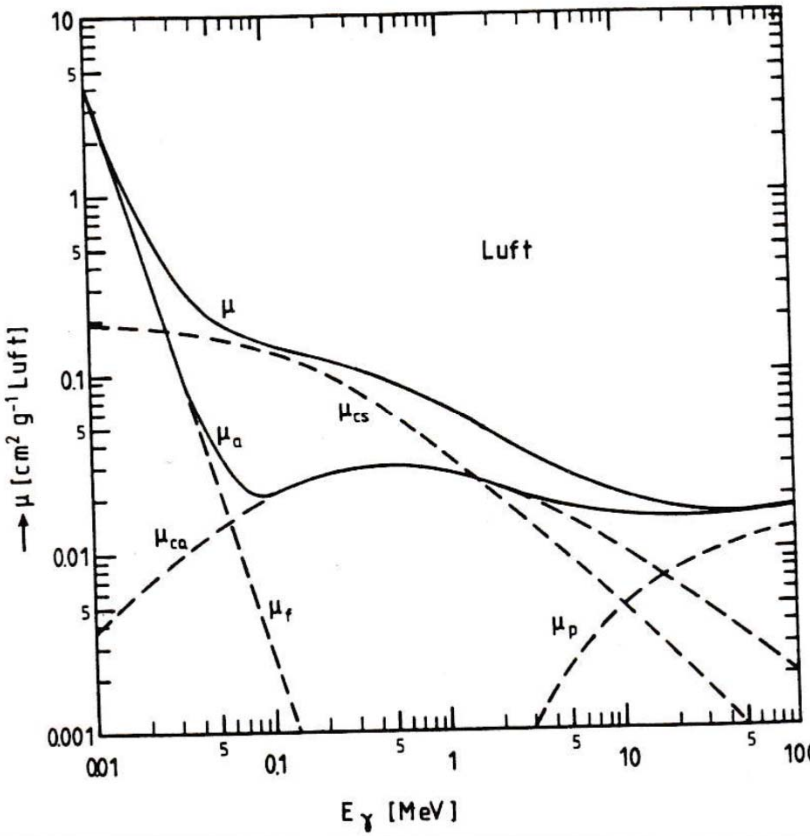
- From these relations the exponential attenuation of the photon beam with x follows:

$$I(x) = I_0 \cdot e^{-\mu \cdot x}$$

where: x = path length
μ = absorption coefficient

(Often the so called mass attenuation coefficient μ' is given:
$\mu' = \mu / \rho$ $[\mu'] = cm^2 / g$





Mass attenuation coefficients as a function of the photon energy for water (left) and air (right); (from Ref. [3])

3.2 Interactions of neutrons with matter

- Neutrons are electrically neutral; like photons they must transfer their energy to charged particles in order to be detected
- Neutrons are also sensitive to the strong interaction, however, short range ~10^{-14} m, characterized by the hadronic interaction length (see chapter 2.7)
- In general: neutrons show strong penetration power, however, interaction and penetration power are strongly dependent on their energy;
- Classification of neutrons according to their kinetic energy (E_n):

- 100 MeV < E_n:	high energy neutrons
- 100 keV < E_n < 100 MeV:	fast neutrons
- 0.1 eV < E_n < 100 keV;	epithermal neutrons (nuclear resonance reactions)
- E_n ~0.025 eV:	thermal or slow neutrons
- E_n ~ meV – μeV:	cold or ultra-cold neutrons

Major interaction processes of neutrons with matter:

	Process		Energy range*
(i)	High energy hadron shower production	n + A → hadrons (inelastic)	> 100 MeV
(ii)	Elastic Scattering	n+A → n+A A(n,n)A	~10 – 100 MeV
(iii)	Inelastic Scattering	A(n,n')A*, A(n,2n')B, …	1 MeV $< E_n <$ 10 MeV energy of nuclear excitation
(iv)	Radiative neutron capture, (n,γ) reaction	n + (Z,A) → (Z,A+1) + γ (example neutron capture in Cd)	< ~few MeV
(v)	Other nuclear reactions	(n,p), (n,d), (n,α), (n,αp)	eV – keV range
(vi)	Nuclear fission	(n,f)	< 1 eV (most likely at thermal energies, 0.025 eV)

(iii) Neutron is absorbed by nucleus, which is left in an excited state; accompanying radiation
(iv) Example: neutron capture in Cd, cross sections are energy dependent, scale as 1/v
(v = velocity of the neutrons), resonances for absorption may occur, depending on material
(v) Cross section also scales as 1/v

*) energy range where this type of interaction is the principle mechanism of energy loss

Die Wirkungsquerschnitte für die induzierte Spaltung und für die (n, γ)-Reaktionen hängen stark von der kinetischen Energie / Geschwindigkeit v der Neutronen ab.

Im thermischen Bereich (E = 0,025 eV) gilt:

σ (n, γ) und σ (n,f) sind prop. zu 1/v (v= Geschwindigkeit)
(dominiert durch Wechselwirkungszeit, d.h. Zeit, während der sich das Neutron in der Umgebung des Kerns aufhält)

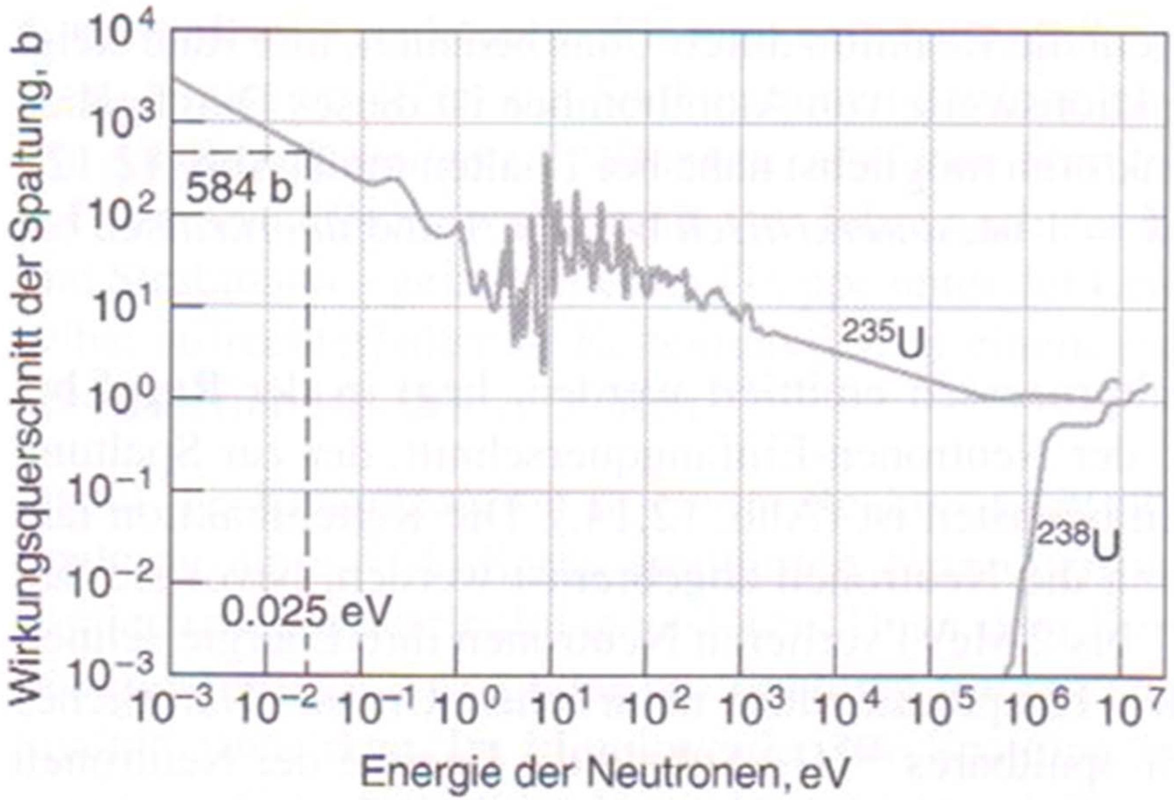


Abb. 12.14. Wirkungsquerschnitte der neutroneninduzierten Spaltung von ^{235}U und ^{238}U. Im Bereich unterhalb von 0,01 eV erkennt man bei ^{235}U dieselbe $1/v$-Abhängigkeit wie beim Wirkungsquerschnitt der (n, γ)-Reaktion (aus dem gleichen Grund wie dort!). Die „radiative" Absorption (n, γ) konkurriert mit der Spaltung, sie hat bei 0,025 eV einen Wirkungsquerschnitt von 97 barn. Die zahlreichen Resonanzen zwischen 1 eV und 100 eV gehören zu angeregten Zuständen des ^{236}U-Kerns.

The total interaction cross section

- The total interaction cross section for neutrons in matter is given by the cross sections discussed above:

$$\sigma = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{capture} + \ldots$$

- The probability for a neutron interaction per unit length is given by the product of the cross section and the density of atoms N:

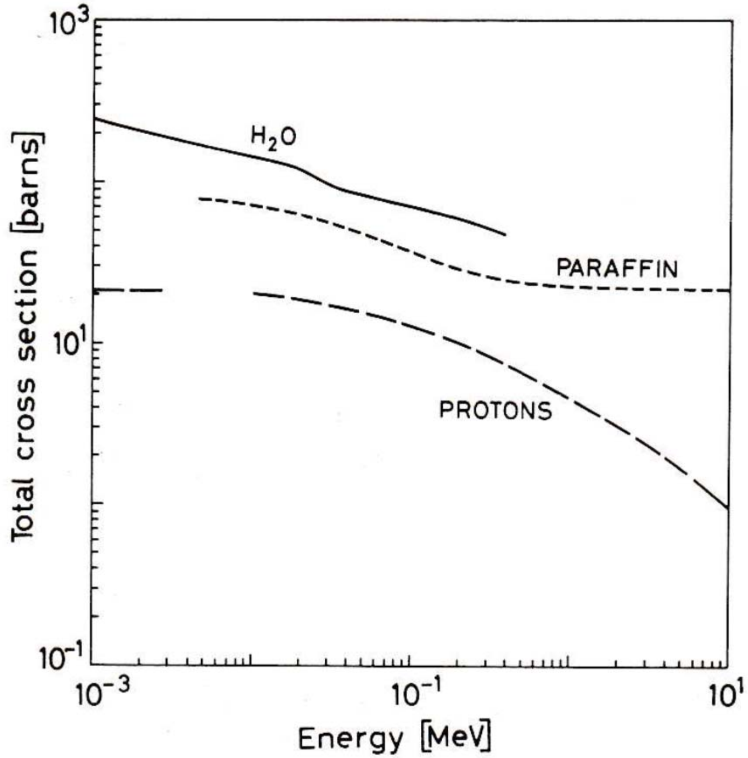
$$\mu := N \cdot \sigma = \left(\frac{N_A \cdot \rho}{A} \right) \cdot \sigma$$

where: N_A : Avogadro's number
ρ : density of the material
A : molecular weight

- In analogy to photons, a beam of neutrons with a fixed energy passing through matter is exponentially attenuated

$$I_n(x) = I_{n,0} \cdot e^{-\mu_n \cdot x}$$

(note the difference between interaction, e.g. scattering, and absorption):



Total reaction cross sections for neutrons in water, paraffin (CH_2) and protons; (from Ref. [3])

Moderation of neutrons:

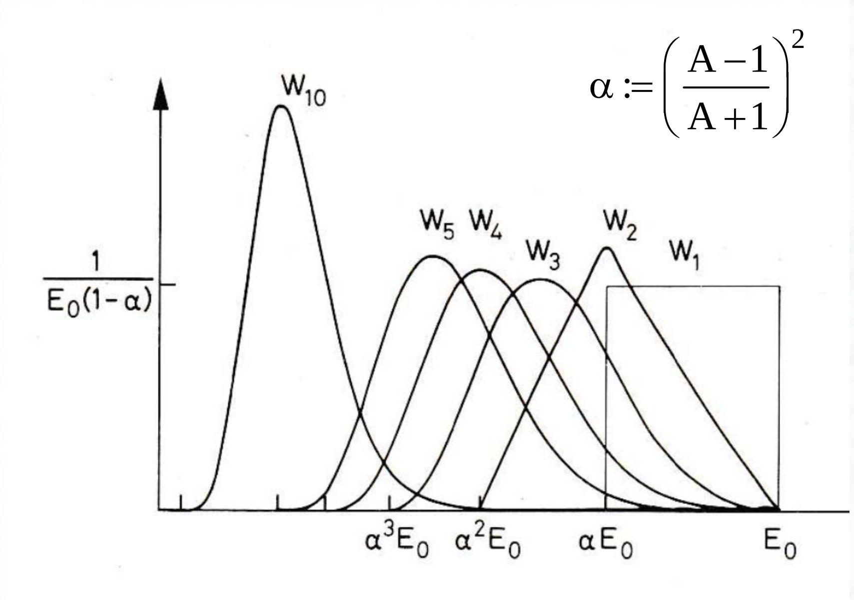
- Fast neutrons (E_{kin} > 100 keV) are dangerous for detectors, e.g. damage of the lattice structure of semiconductor material
  → wish to capture or moderate neutrons

- Moderation process: elastic scattering
  $n(E_0) + A \rightarrow n(E_1) + A$
  where $E_1 < E_0$

- The energy transfer depends strongly on the mass of the recoil partner (A); extreme value (back scattering):

$$\rightarrow \left(\frac{A-1}{A+1}\right)^2 \cdot E_0 < E_1 < E_0$$

- Example: (A = atomic mass number)
  A = 56 (iron): $0.93\, E_0 < E_1 < E_0$
  A = 1 (hydrogen): $0 < E_1 < E_0$



Energy distribution (probability densities) of neutrons after several elastic scatterings (from Ref. [2])

Energy loss is efficient for collisions of neutrons with protons (H atoms)
→ usage of paraffin (CH_2) or other hydrogen-containing materials;

Example: moderation of 1 MeV neutrons to thermal energies (0.025 eV) requires on average 111 collisions with carbon (C^{12}) and 17 collisions with H atoms

Technical realisation of neutron counters

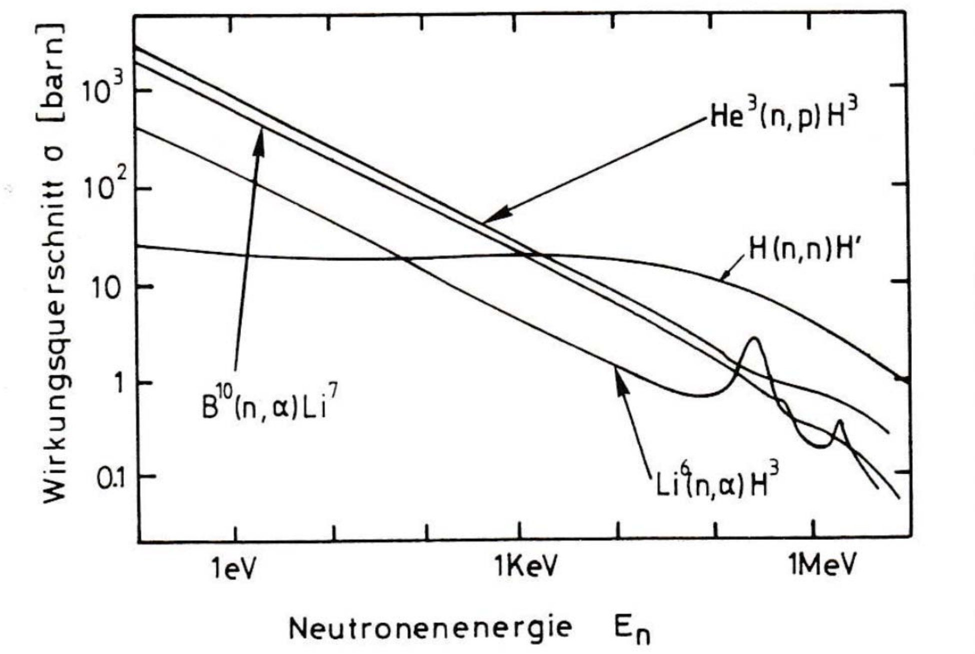
- Principal mechanism: neutron absorption, energy transfer on electrically charged particles

  Important reactions:

  $n + {}^{6}Li \rightarrow \alpha + {}^{3}H$
  $n + {}^{10}B \rightarrow \alpha + {}^{7}Li$
  $n + {}^{3}He \rightarrow p + {}^{3}H$
  $n + p \rightarrow n + p$

- Cross sections show a strong energy dependence
  MeV range: elastic (n,p) dominant

  Moderation increases absorption power, thereby efficiency of neutron counters



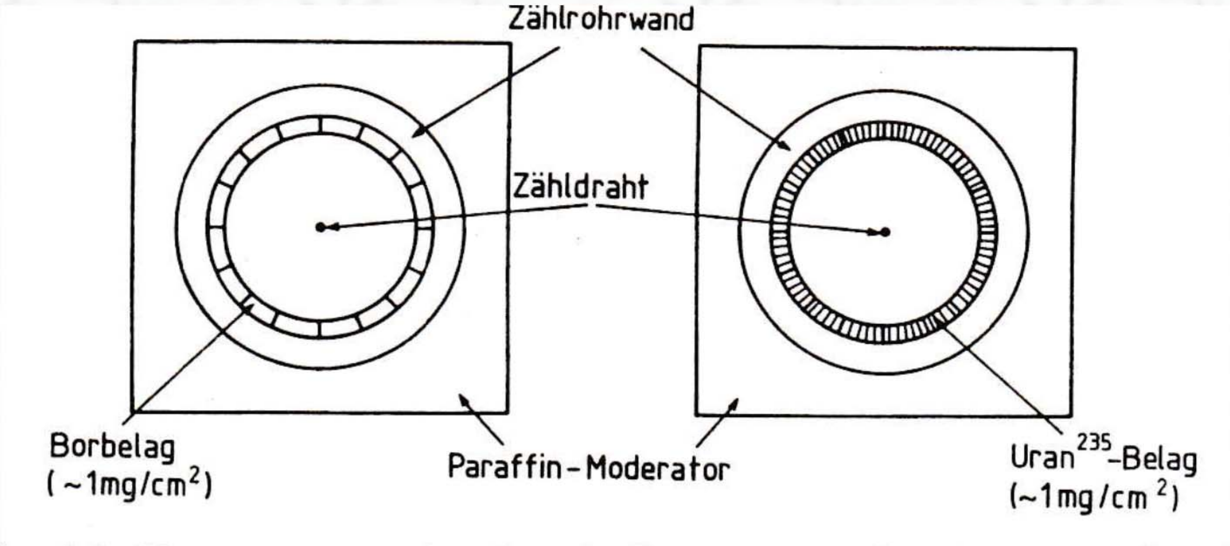
Cross sections for neutron induced reactions as a function of the kinetic energy of the neutrons (from Ref. [3])

- In order to distinguish neutron signals from signals of other charge particles, neutron counters are surrounded by anti-coincidence counters

- Thermal neutrons can be absorbed in ionisation chambers or proportional counters, filled with Bor-tri-fluoride gas (BF_3)

- Higher energy neutrons have to be moderated to reduce their kinetic energy and to enhance the absorption cross section
  moderators: paraffine, water, ..

- Alternative: use fission reactions (n,f) with ^{235}U



Principal method of neutron detection using ionisation counters (from Ref. [3])

- Other detection technologies:
  - Semiconductor counters with ^{6}LiF coating → α particle detection in detector
  - LiJ scintillation counters → α particle detection
  - Organic scintillators, → detection of recoil protons (1 – 100 MeV)

Neutron fluences in the ATLAS experiment