3. Wechselwirkung von Photonen mit Materie

3.1 Absorption über Photoeffekt

3.2 Compton-Streuung

3.3 Paarerzeugung

3.4 Abschwächung, Absorptionskoeffizienten

3.5 Anwendungen

Overview of interaction processes of electrons and photons

Energy loss due to excitation and ionisation

Bethe Bloch formula

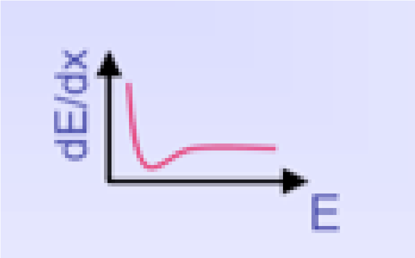
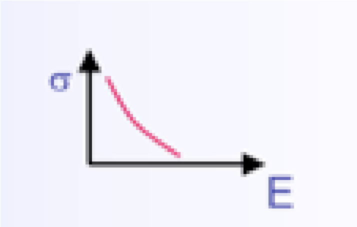
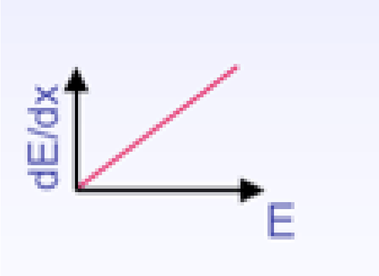


Photo effect

(dominant in ~ keV energy range)

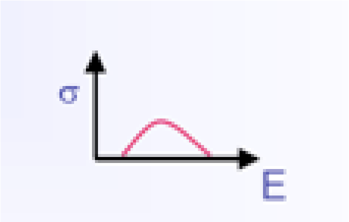


Bremsstrahlung



Compton effect

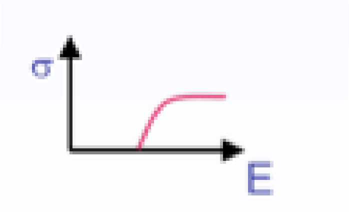
(dominant in MeV energy range)



Cherenkov radiation

Pair creation

(threshold energy $= 2\ m_e = 1{,}022$ MeV)



In order to be detected, photons must transfer their energy to charged particles

- Photo electric effect
- Compton scattering
- Pair creation

Photons “disappear” via these reactions. The intensity of a photon beam is exponentially attenuated in matter:

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

3.1 Photo electric effect:

$$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$$

- Release of electrons from the inner shells (K, L, ..) of atoms
  (Only possible in the close neighbourhood of a third collision partner)

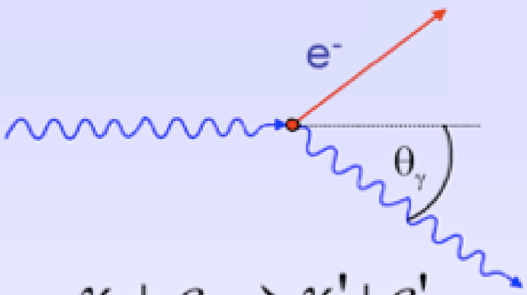
- The cross section shows a strong modulation if $E_\gamma \approx E_{bin}$ (binding energy)

$$\sigma^K_{photo} = \left(\frac{32}{\varepsilon^7}\right)^{\frac{1}{2}} \alpha^4 Z^5 \sigma^e_{Th} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2} \qquad \sigma^e_{Th} = \tfrac{8}{3}\pi r_e^2 \quad \text{(Thomson)}$$

At high energies (ε>>1)

$$\sigma^K_{photo} = 4\pi r_e^2 \alpha^4 Z^5 \frac{1}{\varepsilon} \qquad \boxed{\sigma_{photo} \propto Z^5}$$

3.2 Compton scattering



$$\gamma + e \rightarrow \gamma' + e'$$

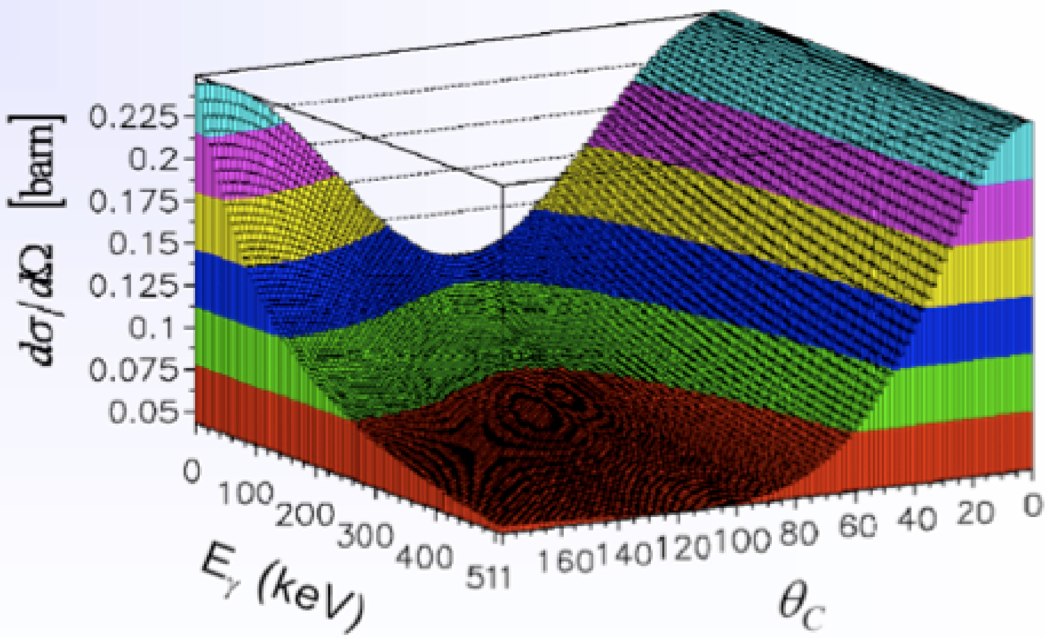
$$E'_\gamma = E_\gamma \frac{1}{1+\varepsilon(1-\cos\theta_\gamma)}$$

$$E_e = E_\gamma - E'_\gamma$$

Compton cross-section (Klein-Nishina)

Assume electron as quasi-free.

Klein-Nishina $\frac{d\sigma}{d\Omega}(\theta,\varepsilon)$ →



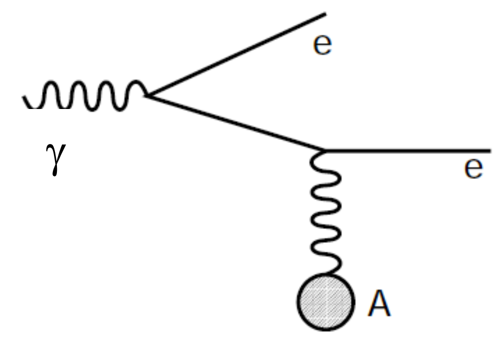
At high energies approximately

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

Atomic Compton cross-section:

$$\sigma_c^{atomic} = Z \cdot \sigma_c^e$$

3.3 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):

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

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

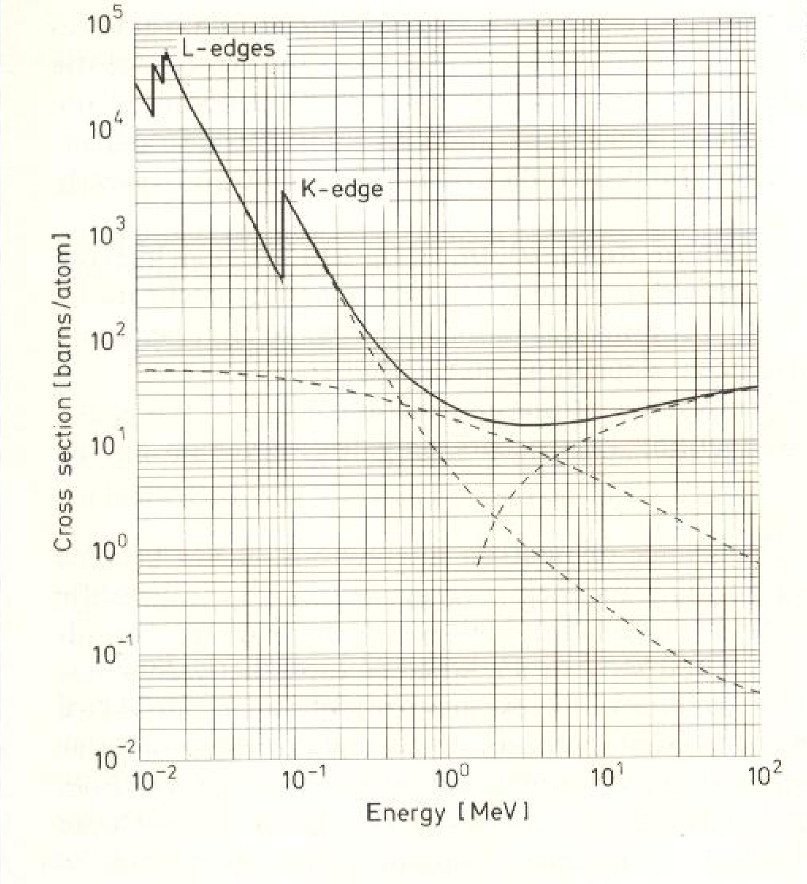
- After traversing a material thickness of $9/7\, X_0$, the photon intensity –due to pair creation- is decreased by 1/e

  .or.

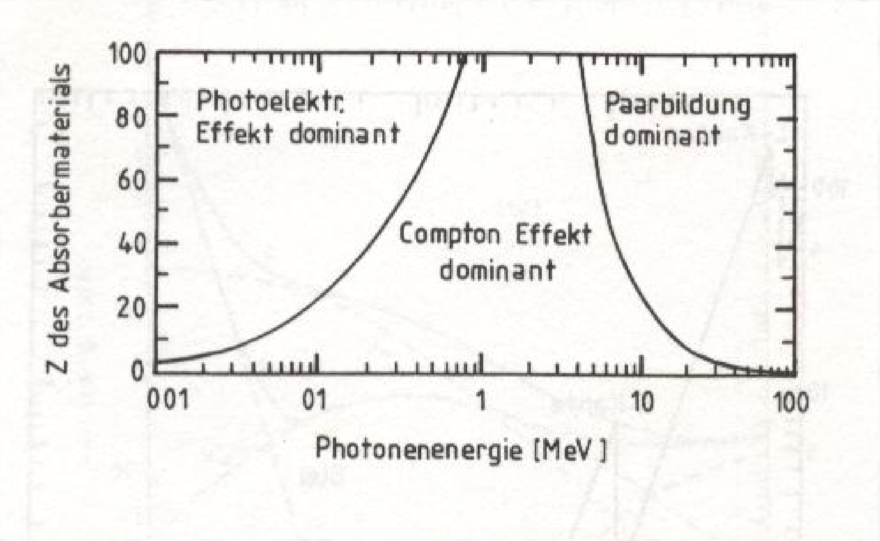
- For high photon energies, pair production occurs after traversing a material thickness corresponding to one radiation length with a probability of

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

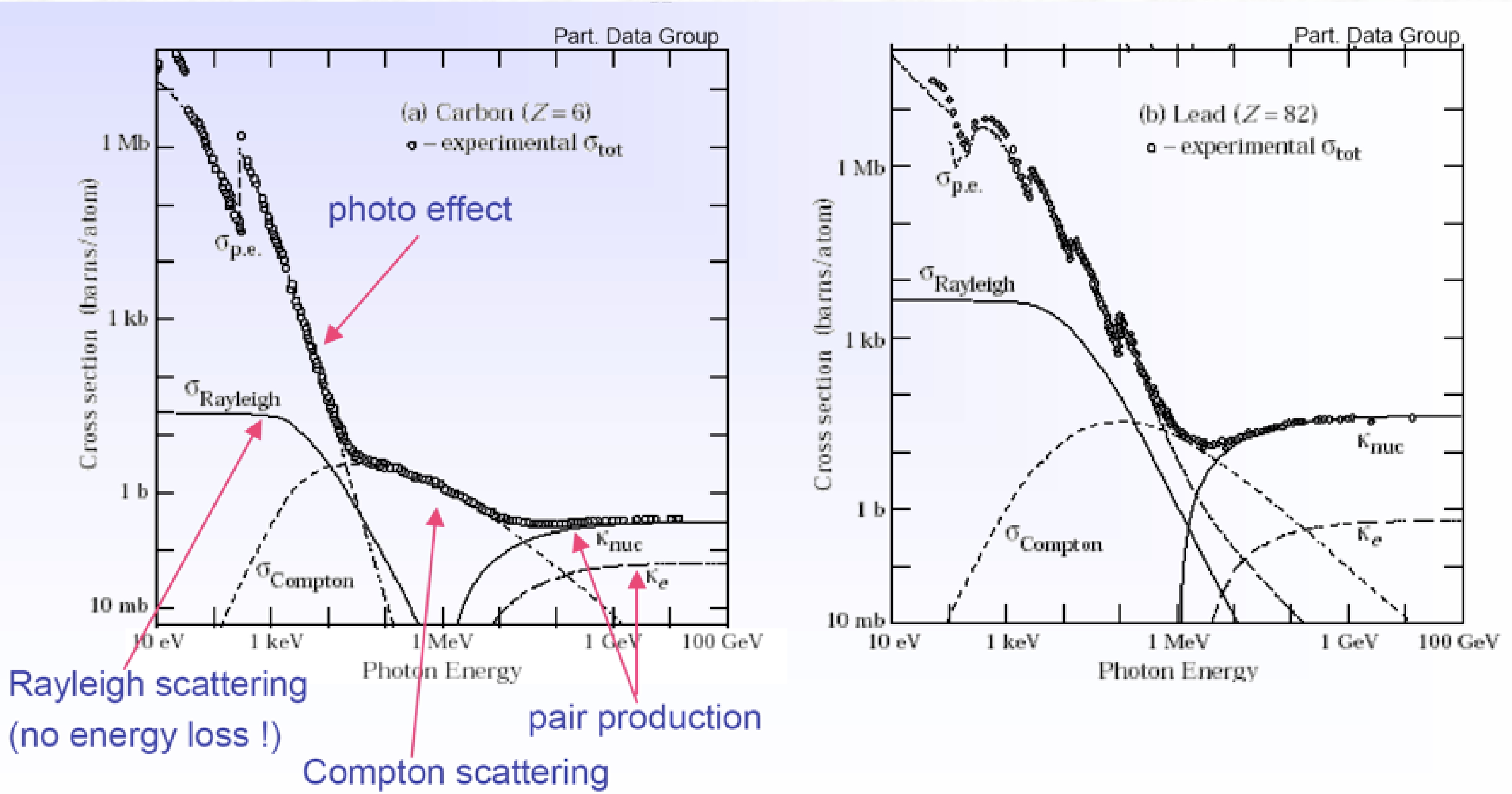
3.4 Photon interaction cross sections



Total photon absorption cross section for lead (Z=82) as a function of the photon energy. The contributions from photo absorption, Compton scattering and pair creation are show separately [Ref. Leo]



Regions in which photo effect, Compton scattering, and pair creation dominate, as a function of the photon energy and the atomic charge (Z) of the absorber [Ref. Grupen]


Part. Data Group
(a) Carbon (Z = 6)
o – experimental σtot
photo effect
σp.e.
σRayleigh
σCompton
κnuc
κe
1 Mb
1 kb
1 b
10 mb
Cross section (barns/atom)
10 eV
1 keV
1 MeV
1 GeV
100 GeV
Photon Energy
Rayleigh scattering
(no energy loss !)
pair production
Compton scattering
Part. Data Group
(b) Lead (Z = 82)
o – experimental σtot
σp.e.
σRayleigh
σCompton
κnuc
κe
1 Mb
1 kb
1 b
10 mb
Cross section (barns/atom)
10 eV
1 keV
1 MeV
1 GeV
100 GeV
Photon Energy

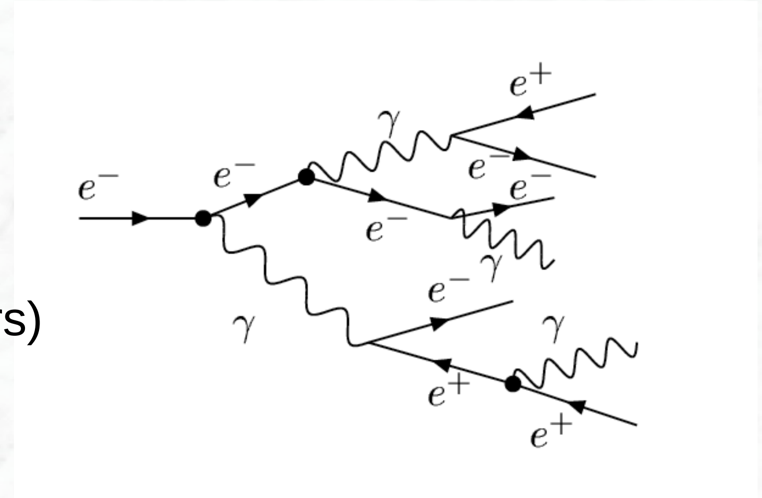
3.5 Applications

- Use photon attenuation for investigations of material structure
  (X-ray imaging, …)

- Tumor therapy
  (with drawback of non-localized energy deposition)

- Energy measurement of electrons and photons in so-called electromagnetic calorimeters

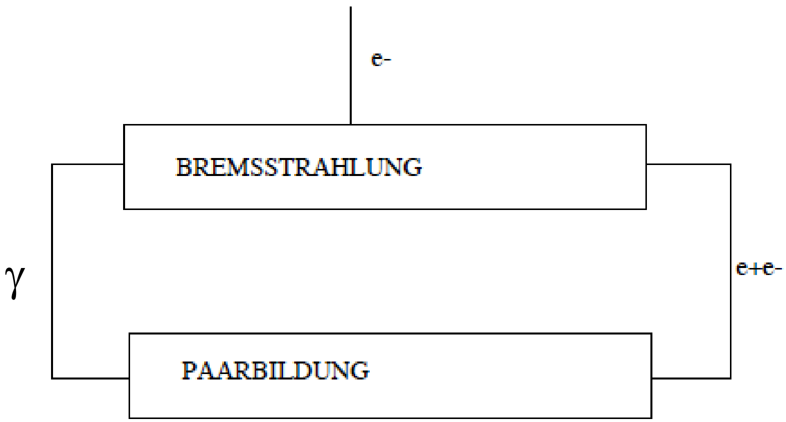
  (Bremsstrahlung, pair-creation processes
  → formation of so-called electromagnetic showers)



Concept of electromagnetic calorimeters

- Particle showers created by electrons/positrons or photons are called electromagnetic showers (only electromagnetic interaction involved)

- Basic processes for particle creation: bremsstrahlung and pair creation



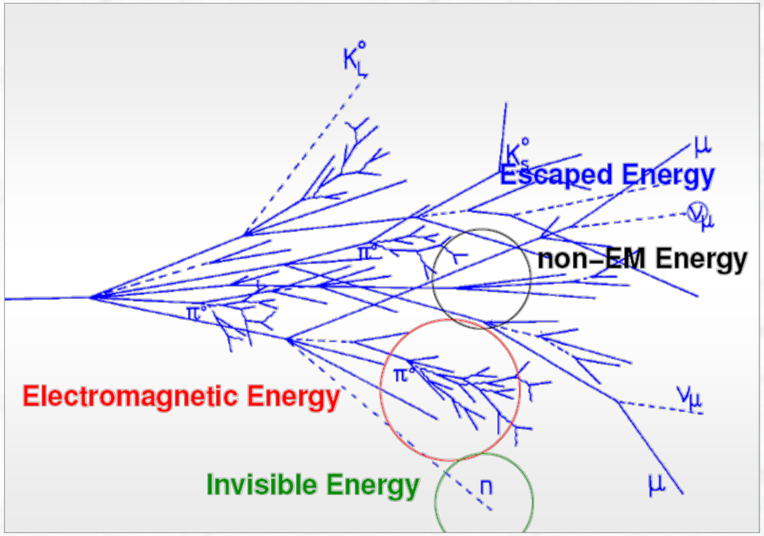
- Characteristic interaction length: radiation length X_0

- Number of particles in the shower increases, until the critical energy E_c is reached; For $E < E_c$ the energy loss due to ionization and excitation dominates, the number of particles decreases, due to stopping in material

Hadronic showers / calorimeters

- Hadrons initiate their energy shower by inelastic hadronic interactions; (strong interaction responsible, showers are called hadronic showers)

- Hadronic showers are much more complex then electromagnetic showers



- Several secondary particles, meson production, multiplicity ~ln(E)

- π^0 components, $\pi^0 \rightarrow \gamma\gamma$, electromagnetic sub-showers;
  The fraction of the electromagnetic component grows with energy,
  $f_{EM} = 0.1 \ln E$ (E in GeV, in the range 10 GeV < E < 100 GeV)

- During the hadronic interactions atomic nuclei are broken up or remain in exited states

  Corresponding energy (excitation energy, binding energy) comes from original particle energy
  → no or only partial contribution to the visible energy

- In addition, there is an important neutron component

  The interaction of neutrons depends strongly on their energy;
  Extreme cases:
  - Nuclear reaction, e.g. nuclear fission → energy recovered
  - Escaping the calorimeter (undergo only elastic scattering, without inelastic interaction)

- Decays of particles (slow particles at the end of the shower)
  e.g. $\pi \rightarrow \mu\, \nu_\mu$ → escaping particles → missing energy

These energy loss processes have important consequences:
in general, the response of the calorimeter to electrons/photons and hadrons is different ! The signal for hadrons is non-linear and smaller than the e/γ signal for the same particle energy

Layers of the ATLAS detector