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

Bremsstrahlung

Cherenkov radiation

Photo effect

(dominant in ~ keV energy range)

Compton effect

(dominant in MeV energy range)

Pair creation

(threshold energy $= 2m_e = 1,022$ 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:

- 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 $E_\gamma \approx E_{\text{bin}}$ (binding energy)

\[ \sigma^K_{\text{photo}} = \left( \frac{32}{\varepsilon^7} \right)^{\frac{1}{2}} \alpha^4 Z^5 \sigma^e_{\text{Th}} \]

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

\[ \sigma^e_{\text{Th}} = \frac{8}{3} \pi r_e^2 \quad \text{(Thomson)} \]

At high energies ($\varepsilon \gg 1$)

\[ \sigma^K_{\text{photo}} = 4\pi r_e^2 \alpha^4 Z^5 \frac{1}{\varepsilon} \]

\[ \sigma_{\text{photo}} \propto Z^5 \]
3.2 Compton scattering

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

\[ E_e = E_\gamma - E'_\gamma \]

\[ \gamma + e \rightarrow \gamma' + e' \]

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: \( E_\gamma > 2 m_e c^2 = 1.022 \text{ MeV} \)
- Cross section (high energy approximation):

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

\[
\mu_{\text{pair}} = \frac{7}{9} \frac{1}{X_0}
\]

- After traversing a material thickness of \(9/7 \times X_0\), 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]
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 $\sim \ln(E)$

- $\pi^0$ 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 $10 \text{ GeV} < E < 100 \text{ GeV}$)
• 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
\[ \rightarrow \text{no or only partial contribution to the visible energy} \]

• 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 \[ \rightarrow \text{energy recovered} \]
- Escaping the calorimeter (undergo only elastic scattering, without inelastic interaction)

• Decays of particles (slow particles at the end of the shower)
e.g. \[ \pi \rightarrow \mu \nu_\mu \rightarrow \text{escaping particles} \rightarrow \text{missing energy} \]

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/\gamma signal for the same particle energy
Layers of the ATLAS detector