2. Passage of Radiation Through Matter
Passage of Radiation Through Matter: Contents

• Energy Loss of Heavy Charged Particles by Atomic Collision
• Cherenkov Radiation
• Energy loss of Electrons and Positrons
• Multiple Coulomb Scattering
• The Interaction of Photons:
  • Photo electric effect
  • Compton scattering
  • Pair production
  • Electron-photon shower etc.
• The Interaction of Neutrons
The Interaction of Photons

• Behavior of photons (in our case gamma and x rays) in matter is very different from that of charged particles
• Why: the lack of electric charge makes it impossible to have many inelastic collisions with atomic electrons like charged particles do
• Main interactions of x-rays and gamma-rays in matter are:
  • Photoelectric effect
  • Compton Scattering (including Thomson and Rayleigh Scattering)
  • Pair Production
  • (also possible, but less common: nuclear dissociation reactions, e.g. ($\gamma$,n), which we will neglect in our discussion)
• These reactions explain two principle qualities of gamma and x rays:
  1) X-rays and gamma-rays are many more times penetrating in matter than charged particles
  2) A beam of photons is not degraded in energy when passing through matter, but attenuated in intensity
The Interaction of Photons (cont.)

1) More penetrating:
   • Due to the much smaller cross-section of the three processes relative to the inelastic collision cross-sections of charged particles

2) Attenuation of Beam Intensity:
   • The three processes remove the photon from the beam entirely either by absorption or scattering
   • The attenuation of a photon beam can be shown to be exponential with respect to the thickness:
     \[ I(x) = I_0 \exp(-\mu x) \]
     
     \( I_0 \): incident beam energy
     \( x \): thickness of absorber
     \( \mu \): attenuation coefficient, characteristic of the absorbing material and directly related to the total interaction cross-section, often used when discussing gamma-ray detectors
The Photoelectric Effect

- Albert Einstein received the Nobel prize in physics in 1921 for explaining the photoelectric effect in 1905
- Absorption of a photon by an atomic electron with the subsequent ejection of the electron from the atom
- Energy of the outgoing electron, e:
  \[ E = h \nu - \text{B.E.} \]
  B.E.: binding energy of e
- Momentum conservation: photoelectric effect always occurs on bound electrons with the nucleus absorbing the recoil momentum

Calculated for lead,
\[ \text{barn} = 10^{-24} \text{ cm}^2 \]
Photoelectric Effect (cont.)

- Theoretically difficult to treat because of the complexity of the Dirac wavefunctions for the atomic electrons.
- For photons energies above the K-shell however: almost only K electrons are involved.
- If this assumed and energy non-relativistic ($h\nu \ll m_e c^2$) → cross-section can be calculated in the Born approximation (perturbation by photon is weak), rough approximation:

$$\sigma \approx \text{constant} \cdot \frac{Z^n}{E_Y^{3.5}}, \quad n \text{ between 4 and 5}$$

→ important consideration for gamma-ray shields and detectors.

Note: photo electric interaction creates an ionized absorber → electron capture/rearrangement of electrons from other shells may create characteristic x-rays (mostly absorbed, but can influence detector response for example and needs to be considered).
Compton Scattering

- Discovered in 1922 by Arthur H. Compton, Nobel Prize 1927
- Scattering of photons on free electrons: in matter electrons are bound, however, if photon energy is large with respect to the binding energy, the latter can be ignored and the electrons can be considered essentially free
- It is most often the predominant interaction mechanism for gamma energies typical of radioisotope sources
Compton Scattering (cont.)

Expression that relates energy transfer and scattering angle can derived from conservation of energy and momentum. It can be shown that:

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2(1 - \cos \theta)}}$$

$m_0c^2$: rest-mass energy of electron (511 keV)

Scattered gamma ray energy vs angle
Compton Scattering (cont.)

Klein-Nishina Formula:

\[
\frac{d\sigma}{d\Omega} = Zr_0^2 \left( \frac{1}{1 + \alpha(1 - \cos \theta)} \right)^2 \left( \frac{1 + \cos^2 \theta}{2} \right) \left( 1 + \frac{\alpha^2(1 - \cos \theta)^2}{(1 + \cos^2 \theta)[1 + \alpha(1 - \cos \theta)]} \right)
\]

\(\alpha \equiv \frac{\hbar v}{m_0 c^2}, \; r_0 = \frac{e^2}{m_e c^2} : \text{classical electron radius}\)

Polar plot of the number of photons (incident from the left) Compton scattered into a unit solid at the scattering angle \(\theta\)
Compton Scattering (cont.)

• Thomson and Rayleigh scattering:
  • Related to Compton scattering
  • Thomson scattering: scattering of photons by free electrons in the classical limit (photon energies low with respect to electron mass)
  • Rayleigh scattering: scattering of photons by atoms as a whole (electrons in the atom participate in a coherent manner → coherent scattering)
  • Both: NO energy is transferred to the medium, only direction is changed
  • At the relatively high energies of x- and gamma-rays both processes are small contributions and can be neglected
Pair Production

Pair production needs to take place in the coulomb field of a nucleus.

Simplified explanation: Momentum conservation, something must absorb the momentum of the initial photon (consider case when electron positron pair is produced at rest).

If gamma-ray energy exceeds twice the rest-mass energy of an electron (1.02 MeV) pair production becomes possible.

Practically: probability of interactions remains very low until gamma-ray energy approaches several MeV.

No simple expression exists for the cross-section of pair production, but approximately: \( \sigma \sim Z^2 \)
Summary of Photon-Interaction I: Energy and Z dependence
Attenuation coefficient (rev.)

• Linear attenuation coefficient:
  \[ \mu = \tau(\text{photo electric}) + \sigma(\text{compton}) + \kappa(\text{pair}) \]

• Mean free path: \( \lambda = 1/\mu \)

• Linear att. coeff. is limited by the fact that it varies with the density of the absorber, mass attenuation coefficient is more widely used: \( \mu/\rho \)
Summary of Photon-Interaction II: Energy dependence

Note: two quantities concerning Compton scattering in this plot:
1. Compton scattered
2. Compton absorption cross section

1. the average fraction of the total energy contained in the scattered photon
2. the average energy transferred to the recoil electron

\[ \sigma^c = \sigma_s + \sigma_a \]
Photo Multiplier Tube

• Devices which convert light into a measurable electrical current
• They are extremely sensitive (light signals they are measuring typically consists of only a few hundred electrons)
• Applications in nuclear and high-energy physics are very often associated with scintillation detectors (which we will discuss later)
Photomultiplier Tube:

- If set to appropriate High Voltage PMT output pulse ~ Photo electrons
- Much of the timing information is of the original light pulse will also be retained (typically: width of electron pulse: few ns, delay 20-50 ns)
Photomultiplier Issues:

• entrance window: UV cutoff
• (glass)-envelope: window, connectors
• photocathode: sensitivity
• electron multiplier
• HV polarity !!!
Entrance Window:

Kovar alloy for electrical pins: matches thermal expansion of Borosilicate glass (Kovar glass).

Other Window materials: graded seal (glasses of varying thermal expansion)

- MgF₂ crystal: > 115 nm
- Sapphire: > 150 nm
- Synthetic silica: > 160 nm
- UV glass: > 185 nm
- Borosilicate glass: > 300 nm
Photocathode:

- CsI: solar blind: < 200 nm
- CsTe: < 300 nm
- S11: SbCs
  - low resistance,
  - mostly reflection
- Bialkali: SbRbCs, SbKCs:
  - (compared to SbCs)
  - higher sensitivity,
  - lower dark current
  - matches NaI(Tl)
- SbNaK:
  - up to 450 K (temp)
  - very low dark current
- Trialkali: SbNaKCs:
  - wide wavelength range
- AgOCs: near infrared (300-1200 nm)
- GaAs(Cs): wide range, light degradable
- InGaAs(Cs): further into infrared,
  - better signal-to-noise than
  - AgOCs between 900-1000 nm
Collection Efficiency:

\[ \langle \text{NPE} \rangle = \text{NPH} \times \text{QE} \times \text{CE} \]

Field shaping (focusing) electrodes

Equipotential and field lines:
Secondary Electron Multiplier:

Dynodes:

Secondary emissive materials coated on a metal substrate

Secondary Emission Ratio:
\[ \delta = \frac{N_{\text{out}}}{N_{\text{in}}} \]
Classical Dynode Configurations:

Venetian Blind:
- large photocathode,
- simple design

Grid + Box:
- high collection efficiency
- => good uniformity

Linear Focused:
- fast response, good timing
- excellent linearity

Up to 19 stages
Amplification:
- $10 - 10^8$

Circular Cage:
- fast timing
- compact
HV dividers:

Typically in the base:
distribute voltage to cathode, dynodes, and anode
Current Amplification:

Secondary emission ratio $\delta = f(E)$; $E =$ voltage between dynodes:

$$\delta = aE^k$$

with $0.7 < k < 0.8$

Photocathode to first dynode: $\delta_1$, first dynode to second dynode: $\delta_2$, ...

$CE =$ collection efficiency, anode current $= I_A$, cathode current $= I_K$

$$\Rightarrow I_A = CE \delta_1 \delta_2 \ldots \delta_n I_K$$

Thus, for $CE = 1$, the overall current amplification $\mu$ is:

$$\mu = A \ V^{kn}$$

with $V = E_1 + E_2 + \ldots + E_n$