Interactions of Charged Particles With Matter

Chapter # 4

Mode of Interaction depends:

– Type of Radiation

– Energy of Radiation

– Type of Material
General Properties of Radiation

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Charge</th>
<th>Rest Mass</th>
<th>Range</th>
<th>Ionizing Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Nucleus of He Atom</td>
<td>+2e</td>
<td>6.6×10⁻²⁷ kg</td>
<td>Very Short (&lt;0.1 mm in tissue)</td>
<td>Very High</td>
</tr>
<tr>
<td>β</td>
<td>Electron/ Positron</td>
<td>-1e/ +1e</td>
<td>9.1×10⁻³¹ kg</td>
<td>&gt; α (Few mm in tissue)</td>
<td>&lt; α</td>
</tr>
<tr>
<td>γ</td>
<td>Electromagnetic</td>
<td>0</td>
<td>≫ β (Whole Body)</td>
<td>≫ β (Several cm in tissue)</td>
<td>≪ β</td>
</tr>
<tr>
<td>n</td>
<td>Nucleon</td>
<td>0</td>
<td>1.67×10⁻²⁷ kg</td>
<td>≫ β</td>
<td>≪ β</td>
</tr>
</tbody>
</table>

Benefits of Radiation Interaction Studies

Nuclear Radiation is invisible to the eye, has no smell or taste. Only through its effects on matter one can

- Identify the type, intensity and energy of the radiation
- Understand radiation hazards to biological tissue
- Design suitable Radiation Shielding
- Build appropriate Radiation detectors
Radiation Groups with similar Mode of Interaction:

- Charged Particles
  - Heavy Particles: p, d, α, Heavy Ions
  - Light Particles: e−, e+
- Gamma Rays and X-Rays
- Neutrons

Interaction of Heavy Charged Particles with Matter

- Excitation of Atoms of matter
- Ionization of Atoms of Matter
- Bremsstrahlung Interaction with Coulomb Field of Atomic Nuclei of Matter
- Nuclear Reaction with Nuclei of Matter
Excitation Process

Ionization Process
Bremsstrahlung Process

- More probable with light charged particles such as electrons

Nuclear Reaction Process

- Possible only at high enough energy to penetrate the nucleus
- Much less likely than the other 3 processes
Some Important Terms in Charged Particle Interactions:

- **Stopping Power or Specific Energy Loss (S)**
  Rate of energy loss per unit length in the medium
  \[ S = - \frac{dE}{dX} \]

- **Linear Energy Transfer (LET)**
  Mean energy transferred to the medium per unit length

- **Specific Ionization (I_s)**
  Number of ion pairs produced in the medium per unit length. Greater for heavy particles than electrons

- **W Value (E_{av})**
  Average energy spent to create one ion pair. In air \( W \) is about 35 eV per ion pair

Some Important Terms in Charged Particle Interactions

- **Range (R)**
  Distance traveled by a particle before coming to a full stop
  Range of a particles in Air: \( R_{air} = 0.325 \times E^{3/2} \)
  \( (R \) is in cm and \( E \) is in MeV) \n  Range in other materials: \( R_M = 3.2 \times 10^{-4} \times R_{air} \times M^{1/2} / \rho \)
  \( (R_M \) is range is range in material of density \( \rho \) and atomic weight \( M \))

- **Relative Stopping Power:**
  Ratio of the range of a particle in air to its range in some other material
  Relative stopping power = \( R_{air}/R_M = 3100 \times \rho/M^{1/2} \)
Interaction of Beta Particles with Matter

• Excitation and Ionization
  Appreciable at low energy and in light (low Z) materials

• Bremsstrahlung Radiation
  Dominant at high energy (> 10 MeV)
  Greater in heavy (high Z) materials

• Range of Beta particles
  \[ R \times \rho = 0.412 \times E^{1.265} - 0.0954 \times \ln E \quad \text{for} \ E < 2.5 \text{ MeV} \]
  \[ R \times \rho = 0.412 \times E^{-0.106} \quad \text{for} \ E > 2.5 \text{ MeV} \]

R(range) in cm, \( \rho \) (density) in g/cm\(^3\), E(energy) in MeV,
R\( \times \rho \) (equivalent thickness) in g/cm\(^2\)

Energy Straggling

After passing through a material, a group of particles having the same initial energy will have a spread in energy.
Range Straggling

Range Straggling

Fluctuations in the range of a group of particles having the same initial energy

\[ R_p = \text{Mean Range inside a material} \]

Example 1:
Determine the number of ion pairs produced by a 10 MeV proton.

Solution:
Energy required to produce one ion pair = 35 eV
No. of ion pairs = \(10 \times 10^4\) eV/35 eV = \(2.86 \times 10^6\)

Example 2:
Calculate the thickness of Al (\(\rho = 2.7 \text{ g/cm}^3\)) necessary to stop 5 MeV alpha particles.

Solution:
\(R_m = 0.325 \times 35 = 0.325 \times (5)^{35} = 3.6 \text{ cm}\)
\(R_a = 3.2 \times 10^{-4} \times (3.6) \times \text{sqrt}(27) / 2.7 = 0.002 \text{ cm}\)
Example 3

Tritium emits beta- particles with a maximum energy of 18.6 keV. What is the maximum range of these beta rays in air and in water?

Solution

\[ R \times \rho = 0.412 \times 0.0186 \times 1.265 - 0.0954 \times \ln(0.0186) = 0.000586 \text{ g/cm}^2 \]

- At standard ambient temperature and pressure (25 °C and 100 kPa) dry air has a density of \( \rho_{SATP} = 1.168 \text{ kg/m}^3 = 0.001168 \text{ g/cm}^3 \)

\[ R_{air} = 0.5 \text{ cm} \]

- \( \rho_{Water} = 1 \text{ g/cm}^3 \)

\[ R_{Water} = 0.000586 \text{ cm} = 5.86 \mu\text{m} \]
Interactions of Neutrons with Matter

Chapter # 8

General Properties of Neutrons

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>$n$</td>
</tr>
<tr>
<td>Nature</td>
<td>Nucleon</td>
</tr>
<tr>
<td>Charge</td>
<td>0</td>
</tr>
<tr>
<td>Rest Mass</td>
<td>$1.6 \times 10^{-27}$ kg</td>
</tr>
<tr>
<td>Range</td>
<td>Much larger than $\alpha$ or $\beta$ particles</td>
</tr>
<tr>
<td>(can penetrate several cm of tissue)</td>
<td></td>
</tr>
<tr>
<td>Ionizing Power</td>
<td>Much less than $\alpha$ or $\beta$ particles</td>
</tr>
</tbody>
</table>
Sources of Neutrons

A. Radioisotope Sources

1. \((\alpha, n)\) Sources: \(^{241}\text{Am-Be}, \, ^{210}\text{Po-Be}\)

2. \((\gamma, n)\) Sources: \(^{124}\text{Sb-Be}, \, ^{24}\text{Na-Be}\)

3. Spontaneous Fission: \(^{252}\text{Cf}\)

Sources of Neutrons

B. Accelerator Sources

1. Electron Accelerators: High Energy Bremsstrahlung radiation from these accelerators is used in nuclear reactions to produce neutrons

\[ ^{9}\text{Be} + \gamma = ^{8}\text{Be} + n \]

2. Low Energy Positive Ion Accelerators (~ 300 keV): Deuterons and Tritons from these accelerators are used in nuclear reactions to produce neutrons

a. D-T reactions: \(^{2}\text{H} + ^{3}\text{H} = ^{4}\text{He} + n\) \((E_n = 14\text{ MeV})\)

b. D-D Reactions: \(^{2}\text{H} + ^{2}\text{H} = ^{3}\text{He} + n\) \((E_n = 3\text{ MeV})\)
Sources of Neutrons

B. Accelerator Sources

3. High Energy Positive Ion Accelerators (~ 1-10 MeV):
Particles with MeV energies from these accelerators are used in nuclear reactions to produce neutrons

\[ ^7\text{Li} + p = ^7\text{Be} + n \]

4. Fission Reactor Sources
Reactors are good sources of high flux neutrons arising from the fission process

\[ ^{235}\text{U} + n = \text{Fission Fragments} + (2-3) \text{ neutrons} \]
Average energy of fission neutrons \( E_n = 2 \text{ MeV} \)

Classification of Neutrons

1. Thermal Neutrons: \( E = 0.025 \text{ eV} \)
2. Slow Neutrons: \( E < 0.5 \text{ eV} \)
3. Intermediate Energy Neutrons: \( 0.5 \text{ eV} < E < 10 \text{ keV} \)
4. Fast Neutrons: \( E > 10 \text{ keV} \)
Neutron Interaction Cross Section

Defined as the probability of interaction with a material

- **Macroscopic Cross Section:** $\Sigma$
  Probability of Interaction per unit length in a material:
  Unit: cm$^{-1}$

- **Microscopic Cross Section:** $\sigma$
  Probability of interaction per nucleus of material
  Unit: Barn
  $1$ Barn $= 10^{-24}$ cm$^2$

Relation Between Macroscopic and Microscopic Cross Sections

$$\Sigma = N \sigma$$

$N$ is the number of atoms per cm$^3$ of the material

$$N = \rho N_A / M$$

$\rho$ = Density of the material (g/cm$^3$)

$M$ = Molar Mass of the material (g/mole)

$N_A$ = Avogadro’s Number $= 6.02 \times 10^{23}$ (atoms/mole)
Neutron Interaction Processes

A. Elastic Scattering from Nuclei of Material: (Billard Ball)

Most probable Interaction Process

- Elastic Scattering:
  \[ KF_n + KE_N \text{ (before)} = KF_n + KE_N \text{ (after)} \]

- Amount of energy lost by a neutron in each elastic collision
  \[ \Delta E = [(1-\alpha)/2]E_o \]

\[ E_o = \text{Initial Neutron energy} \]
\[ \alpha = [(A-1)/(A+1)]^2 \]
\[ A = \text{Atomic mass of the target} \]

**Example 1**

Calculate energy lost by a 1 MeV neutron in one collision with a hydrogen nucleus

**Solution**

Here \( A = 1 \), so \( \alpha = [(A-1)/(A+1)]^2 = 0 \) therefore \( \Delta E = [(1-\alpha)/2]E_o = 0.5 \text{ MeV} \)

Light nuclei are more efficient to reduce neutron energy by elastic collision. For example:

<table>
<thead>
<tr>
<th>Scattering Nucleus</th>
<th>Energy Loss Per Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>50%</td>
</tr>
<tr>
<td>Carbon</td>
<td>14%</td>
</tr>
<tr>
<td>Uranium</td>
<td>1%</td>
</tr>
</tbody>
</table>

This is why water or graphite is mostly used as moderator in reactors.
Neutron Interaction Processes

B. Inelastic Scattering

\[ KE_n + KE_N \text{ (before)} = KE_n + KE_N \text{ (after)} \]

C. Radiative Capture Process

Neutrons are absorbed giving \( \gamma \) radiation:

\[ ^1H + n = ^2H + \gamma \quad (E_\gamma = 2.52 \text{. MeV}) \]

D. Charged Particle Reactions

\[ ^{10}B + n = ^7Li + \alpha \]

E. Fission Reactions

\[ ^{235}U + n = \text{Fission Fragments} + (2-3) \, n \]
Mean Free Path

Average distance that a neutron travels between collisions.
It is related to the linear absorption coefficient $\Sigma$ by:

$$\lambda = \frac{1}{\Sigma}$$

Relaxation Length $R_l$

Thickness of Material necessary to attenuate a neutron beam by $1/e$ (37%); $e=2.72$ is the base of natural logarithm.

$$\frac{I(X=R_l)}{I_0} = e^{-\Sigma \times R_l} = \frac{1}{e} = e^{-1}$$

$$\Sigma \times R_l = 1$$

$$R_l (cm) = \frac{1}{\Sigma}$$
Relative Hazards of Charged Particles

- Hazard from external α sources is minimal since α particles have short ranges. α’s are easily stopped by the skin. Protective eye cover required.
- Hazard from internal α sources can be significant in some sensitive organs from direct ionization.
- Because of their greater range, external beta particles can penetrate the skin and deposit their energy in sensitive tissues.
- Internally, beta sources can cause significant damage by ionization.
Relative Hazards Gamma Rays

- $\gamma$-Rays and X-rays from external sources are significant hazards because of their long range.

- Because photons penetrate large thicknesses, the damage to tissue will extend throughout the body.

Relative Hazards of Neutrons

- Neutrons are uncharged, and so they travel long distances, and can be an external hazard.

- Deeper, sensitive tissues are exposed to external neutron field

- Damage to tissues is dependent on neutron energy. 50% of neutron energy is lost in tissues in a single collision with hydrogen nuclei.

- Absorption and inelastic collisions with tissue materials gives rise to $\gamma$ radiation which compounds the problem

- Neutrons can also produce recoil charged particles in tissue which can cause ionization damage
Interaction of Photons with Matter

Chapter # 6

General Properties of Photons

- Category = Gamma rays ($\gamma$) and X-rays
- Nature = Electromagnetic Radiation
- Charge = 0
- Rest Mass = 0
- Range = Much larger than $\alpha$ and $\beta$ particles (can penetrate whole body)
- Ionizing Power = Much less than $\alpha$ and $\beta$ particles
Interaction Processes for Photons with Matter

- **Photoelectric Effect**
  An incident photon spends all its energy to eject an electron (photoelectron) from the atom of the material.

- **Compton Scattering**
  Incident Photon loses part of its energy in ejecting an electron from the atom, and is itself scattered with a lower energy.

- **Pair Production Process**
  A photon passing near a nucleus of the material disappears, giving up all its energy to create an electron-positron pair. A positron is an electron with a positive charge.

\[ E \propto \frac{Z^4}{E_i^2} \]
Compton Scattering

Most dominant process in the photon energy range between 0.1 and 10 MeV.

The scattered photon energy is given by

\[ E' = \frac{E_e}{1 + (E_e / 0.511 \text{ MeV})(1 - \cos \theta)} \]

Pair Production Process

- Dominant process at photon energy above 10 MeV.
- Minimum photon energy necessary for pair production: \( E_e = 1.02 \text{ MeV} \)
  = Sum of the Rest Mass Energies of the positron and the electron
- Rest Mass Energy of an Electron or a Positron: \( E_{\text{rest}} = m_e c^2 = 0.51 \text{ MeV} \)
Pair Annihilation Phenomenon

\[ e^+ + e^- \rightarrow \gamma_a + \gamma_b \]

Attenuation of Photons in Matter

\[ I(x) = I_0 e^{-\mu x} \]

- \( \mu \) = Linear Attenuation Coefficient
  - Probability of attenuation per unit length in the absorber (cm\(^{-1}\)).
- Mass Attenuation Coefficient = Linear Attenuation Coeff / Density
  \[ \mu_{\text{m}} = \mu \rho \]
  Unit of \( \mu_{\text{m}} \): (cm\(^{-1}\)) g/cm\(^3\) = cm\(^2\)/g

\[ I(d) = I_0 e^{-\mu_{\text{m}} d} \]
  \( d \) = equivalent thickness = \( x/\rho = (g/cm^2) \)

Att. Coeff vary with \( \gamma \) energy and material type.
Total Absorption Coefficient for a Material

\[ \mu_{\text{total}} = \mu_{\text{pe}} + \mu_c + \mu_{\text{pp}} \]

where

pe = photoelectric process

c = Compton Scattering process

pp = pair production process
Attenuation Coefficient for a Mixed Material

\[
\mu = \left[ W_1 \mu_1 + W_2 \mu_2 + W_3 \mu_3 + \ldots \right]/100
\]

where

\( \mu_1, \mu_2, \mu_3 = \) attenuation coefficient for individual components in the mixture

\( W_1, W_2, W_3 = \) percents by weight of the constituents

Mean Free Path

Average distance a photon travels between collisions with the atoms in the absorber. It is related to the linear absorption coefficient.

\[
\lambda = 1/\mu
\]
Relaxation Length

Thickness of material necessary to attenuate the photon beam by 1/e (or by 37%)

e is the base of the natural logarithm = 2.72

\[ I = I_0 \times e^{-\mu x} \]

\[ \frac{I}{I_0} = \frac{1}{e} = e^{-\mu R_l} \]

Take ln of both sides

\[ -1 = -\mu R_l \]

Therefore

\[ R_l = \frac{1}{\mu} \]

Half Value Layer (HVL)

Thickness of material needed to reduce initial radiation intensity by half

Putting \( I(X = \text{HVL}) = \frac{1}{2} I_0 \) in the attenuation equation \( I = I_0 \times e^{-\mu x} \)

\[ \frac{1}{2} = e^{-\mu \times \text{HVL}} \]

Taking ln of both sides

\[ -0.693 = -\mu \times \text{HVL} \]

\[ \text{HVL} = \frac{0.693}{\mu} \]
Example 1

The linear attenuation coefficient of lead for 1 MeV gamma ray is 0.74 cm⁻¹. Calculate

(a) Half value thickness
(b) Thickness of lead necessary to reduce the intensity of the gamma rays to 1/1000 of its initial value.

Solution

(a) HVL \[ X_{\text{hal}} = \frac{0.693}{\mu} = \frac{0.693}{0.74} = 0.94 \text{ cm} \]

(b) \[ I = I_0 e^{-\mu x} \quad \frac{I}{I_0} = 1/1000 = e^{-\mu x} \quad 0.001 = e^{-0.74x} \]

\[ \ln (0.001) = \ln (e^{-0.74x}) \]

\[ -6.9 = -0.74x \]

\[ x = 9.3 \text{ cm} \]

Example 2.

A 5-cm thick Pb plate is used to attenuate gamma rays from Co-60. What percent of the initial radiation penetrates the plate?

Linear attenuation coefficient for maximum energy gamma rays from Co-60 in Pb = 0.66 cm⁻¹.

Solution

Highest energy gamma rays from Co-60 = 1.33 MeV

\[ I = I_0 e^{-\mu x} \quad \frac{I}{I_0} = e^{-\mu x} = e^{-0.66} \quad (5) \]

Take ln

\[ \ln \frac{I}{I_0} = \ln (e^{-0.66}) = -0.66 \quad (5) \]

\[ \ln \frac{I}{I_0} = -3.3 \]

Take anti ln

\[ \frac{I}{I_0} = 0.037 = 3.7 \% \]
Example 3
Calculate (a) the mass attenuation coefficient and (b) the mean free path for 1 MeV gamma rays in lead from the following data: 4.5 cm thickness of lead reduces the radiation intensity by 95%.

Solution

(a) \( I = I_0 e^{-\mu x} \)
\( \frac{I}{I_0} = \frac{5}{100} = e^{-\mu x} \)
\[ 0.05 = e^{-\mu \cdot 4.5} \]
\[ \ln(0.05) = \ln(e^{-4.5\mu}) \]
\[ -3 = -4.5\mu \]
\[ \mu = 0.7 \text{ cm}^{-1} \]
\[ \mu_{\text{m}} = \frac{\mu}{\rho} = \frac{0.7 \text{ cm}^{-1}}{11.4} = 0.06 \text{ cm}^2 / \text{g} \]

(b) Mean Free Path, \( \lambda = \frac{1}{\mu} = 1.4 \text{ cm} \)