Interactions of Particulate Radiation with Matter

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Purpose

• To describe the various mechanisms by which particulate radiation transfers energy to tissue

Importance of particulate interactions

• Radiation therapy with particulate radiation
  – Electrons, protons, heavy ions, neutrons, negative pions
• Photon interaction produces ion pair – electron ejected from atom causes additional ionizations
Particle interactions

- Interaction produces ion pair – particle loses energy in producing ion pair
  - Overcome binding energy to eject electron
  - Kinetic energy of ejected electron

W value

- Average energy lost by charged particle in producing ion pair
  - Function of nature of radiation and nature of absorbing medium
  - Generally $W = 30-35 \text{ eV/ion pair in air}$

W value

- Note importance of charged particle interaction:
  - 1 MeV photon ejects single electron of energy around 0.5 MeV
  - This electron can produce approximately 15,000 secondary electrons
**Specific ionization (SI)**

- Number of ion pairs produced per unit path length traversed by charged particle
  - For alpha particles in air, SI in range 30,000 – 70,000 IP/cm
  - Less for protons and deuterons

**Linear energy transfer (LET)**

- Average energy loss per unit track length
  - similar to stopping power
  \[ LET = SI \times W \]

**Example:** Assuming that the specific ionization is 40,000 IP/cm, calculate the LET of alpha particles in air

\[
LET = SI \times W \\
= 40,000 \text{ IP/cm} \times 35 \text{ eV/IP} \\
= 1400 \text{ keV/cm}
\]
Range

• Range of charged particles determined by
  \[ \text{range} = \frac{E}{\text{LET}} \]
  where \( E \) is the incident energy

Example: Calculate the range in air for 4 MeV alpha particles with an average LET equal to the LET calculated in the previous example

\[ \text{range} = \frac{E}{\text{LET}} = \frac{4 \text{ MeV} \times 10^6 \text{ eV/MeV}}{1400 \text{ keV} \times 10^3 \text{ eV/keV}} = 2.9 \text{ cm air} \]

Ionization density, LET, range

Alpha particles: Dense ionization
High LET
Short range

Electrons: Sparse ionization
Low LET
Long range
Ionization density, LET, range

Note: Charged particles have finite range

• Range also dependent on mass density
• For tissue with density around 1 g/cm³, range of several-MeV alpha particle is a few microns

Ionization density, LET, range

• Assumption in range equation: LET constant along entire path
• SI increases as particle slows down
  – Nearby atoms influenced for longer period of time

Ionization density, LET, range

• This gives rise to enhanced energy deposition near end of track – Bragg peak
• Application in radiation therapy: dose enhancement at location of Bragg peak
Types of particulate radiation

- Electrons
- Neutrons
- Heavy charged particles

Differentiation due to differences in interactions

Electron interactions

- Collisional interactions
  - Electron-electron interactions
- Radiative interactions
  - Electron-nucleus interactions

Electron-electron scattering

- Incident electron excites or ionizes bound electron
- Probability of interaction increases with increasing Z of absorber and decreases with increasing energy of incident electrons
Electron-electron scattering

- Note that lower energy electrons have higher SI and LET than higher energy electrons

Electron-nucleus scattering

- Electron gives off kinetic energy in form of Bremsstrahlung
- Probability of interaction increases as $Z^2$ of absorber

Estimate ratio

$$\text{Radiation energy loss} = Z \times E(\text{MeV})$$
$$\text{Collisional energy loss} = 820$$
Neutron interactions
Classification of neutron energies:
- Slow 0 – 0.1 keV
- Intermediate 0.1 – 20 keV
- Fast 20 keV – 10 MeV
- High energy > 10 MeV

Elastic scattering
• Target nucleus then dissipates energy through ionization
  – Largest energy transfer occurs when mass of target = mass of neutron, i.e. for hydrogenous materials

Inelastic scattering
• Target nucleus becomes excited and may eject energetic charged particle
Neutron capture

- e.g., $^9\text{B}^{10} (n,\alpha) ^7\text{Li}$
  - Boron neutron capture therapy:
    - Incorporate $^{10}\text{B}$ into brain
    - Irradiate with slow neutrons
    - Product nuclei densely ionizing

Heavy charged particles

- Primary interaction is excitation and ionization of orbital electrons
- Bremsstrahlung production negligible

Compare protons to electrons

- Proton scattering and straggling small so sharper fall-off in dose distribution
Heavy charged particles

- Negative heavy charged particles, e.g., negative pions, attracted to nucleus.
- Slowly moving negative pion collides with nucleus, breaking it apart, producing stars.

Heavy charged particles

- Application in radiotherapy: Location of star is function of incident energy of pion, so choose incident energy so that star located at tumor.