Lecture 3

Radiation Interactions

- 2 classes: uncharged undergoing a catastrophic event and charged particulate

1) Uncharged: Neutrons ($\lambda \cong 10^{-1}$ m) $\Rightarrow$ heavy charged particles
   x-rays or γ-rays ($\lambda \cong 10^{-1}$ m) $\Rightarrow$ fast e^-.
2) Charged: Heavy charged particles ($\lambda \cong 10^{-5}$ m); Fast e^- ($\lambda \cong 10^{-3}$ m).

Heavy Charged Particles

Nature of interaction:

- Primary interaction through coulomb forces with the orbital e^-'s of the absorber.
- Nuclei interactions are much less likely (Rutherford scattering).
- Results in: Excitation (raise E of e^-); ionization (remove an e^-).
- Maximum deliverable energy from a particle of mass m with kinetic energy E to electron of mass m_o is: $4Em_o/m$. This is about 1/500 of the particle energy per nucleon so many such interactions must occur to stop the particle.
- Particles tend to follow a straight path and have a definite range beyond which the particles do not penetrate.
- May excite e^-'s with enough energy to allow more interactions. These secondary e^-'s are known as delta rays.
- Delta rays tend to ionize close to the primary track and have smaller ranges than the primary particle.

Stopping Power:

- The differential energy loss per unit length in the absorber (S), also called the specific energy loss:

$$S = -\frac{dE}{dx}$$

- A charged particle will lose more energy with decreasing velocity: The relation is described by the Bethe formula:

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_o v^2} NB \ ; \quad B = Z\left[\ln\frac{2m_o v^2}{I} - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

where v & ze are the velocity and charge of the primary particle.
N & Z are the number density and atomic number of the absorber.
m_o & e are the rest mass and charge of the e^-.

I is the average ionization potential of the absorber and is considered an experimentally determined #.

- For particles with v << c:

$$B = Z \cdot \ln\left(\frac{2m_o v^2}{I}\right)$$

- B varies slowly with E, so behavior of dE/dx is in the multiplicative factor.
- $dE/dx \propto 1/v^2$ (inversely with particle energy), so the slower the particle the e^-'s feel the influence of the particle and the larger the energy transfer.
- For particles of the same velocity and differing charge the z^2 term dominates, showing more energy transfer for more highly charged particles (i.e. α's > protons).
- For varying the absorber, NZ dominates (outside the ln( ) term), this is the electron density, thus higher density materials and higher atomic # will have better stopping power.
- For large v/c (particles with velocities close to c) and light materials: $\frac{dE}{dx} \approx 2\frac{MeV}{g \cdot cm^2}$, also known as "minimally ionizing particles".
- Fast electrons fall into the min. ionizing particles at ~1 MeV due to light mass, allowing v to approach c at low energies.
- Bethe formula fails at low energies, where the particle picks up e^-'s from the absorber and becomes a neutral atom at the end of its range (attracts z e^-'s).

Energy loss Characteristics:

Bragg Curve:

- A plot of specific energy loss with distance into the absorber.
- Note the energy loss goes as 1/E (fig. 2.2) until it drops off at the end of the range, where it begins to acquire neutralizing charge.

Energy Straggling:

- Due to the statistical nature of the interactions within an absorber, there is a spread of energies produced in a monoenergetic beam after passing through a given thickness of absorber - this is termed "energy straggling".

Range:

Definitions of range:

- Experimental set-up of α emitter and detector with a varying thickness of absorber in between.
- By varying the thickness measuring the intensity of the α beam.

- We define 2 ranges from the variation in thickness.
  1) Mean range (R_m) is the thickness that reduces the α intensity to ½ the initial value.
  2) Extrapolated range (R_e) is the linear extrapolation along the linear portion of the end of the transmission curve to 0.
- Fig. 2.6 shows the range in air for α particles. Note that, for radiation safety purposes, you need less than 4 cm of air to stop a 4 MeV α particle.
- Note in fig. 2.7 that the range for various particles is suggested to have an empirical relation of $R=aE^b$, where b is relatively constant.
- Note also that to collect all the energy from a particle, a detector would need to have at least the thickness of the range of the particle in the detector material

Range Straggling:

- The fluctuation in path length is called range straggling and for charges particles is ~ a few percent.
- Can be qualitatively found by taking the derivative w.r.t. x in the dE/dx plot.
- The largest change (peak) occurs at the drop off of the dE/dx curve and the range straggling can be characterized by the width of the peak.
- The wider the peak, the more of an issue the range straggling is for that particle in the absorber.

Stopping Time

– For non-relativistic particles of mass m, and energy E:

$$v = \sqrt{\frac{2E}{m}} = c\sqrt{\frac{2E}{mc^2}} = (3.0\times10^8 \quad m/s^2)\sqrt{\frac{2E}{(931 \quad MeV/amu)\cdot m_A}}$$

where m_A is the particle mass in atomic mass units (amu).

– We assume the average particle velocity (as it slows) is <v> = Kv, where v is evaluated at the initial energy.

– Since the particle loses most of its energy at the end K > 0.5 (K=0.5 for a uniform deceleration), and we will assume 0.6:

$$T = \frac{R}{<v>} = \frac{R}{kv} = \frac{R}{kc}\sqrt{\frac{mc^2}{2E}} = \frac{R}{k(3.0\times10^8 \quad m/s)}\sqrt{\frac{931 \quad MeV/amu}{2}}\cdot\sqrt{\frac{m_A}{E}}$$

$$T \approx 1.2\times10^{-7} \quad R\cdot\sqrt{\frac{m_A}{E}};\ \ T[s],\ \ R[m],\ \ m_A[amu],\ \ E[MeV].$$

– *T* ranges from picoseconds (in solids & liquids) to nanoseconds (in gases).

– Only the fastest detectors would require attending to these stopping times.

Energy loss in thin absorbers

– Particles that penetrate an absorber (thin) lose energy as:

$$\Delta E = -\left(\frac{dE}{dx}\right)_{avg}\Delta x$$

where Δx is the thickness of the absorber and $(dE/dx)_{avg}$ is the linear stopping power averaged over the energy of the particle while in the absorber.

– One can use this equation and the linear portion of a (-dE/dx vs. E) plot to determine the thickness of an absorber from a given range.

– In some cases it may be simpler to use Range and Energy plots to determine the thickness of an absorber.

– Figure 2.12 shows increasing energy loss of protons in Si, where a discontinuity arises when the energy of the proton exceeds the range of the thickness of the detector.

– Once the energy exceeds the range, less energy is deposited in the Si (since the bragg curve shows most energy is deposited at the end of the range).

Scaling Laws

- For compound absorbers, one can approximate the stopping power of the compound, assuming it is additive (Bragg-Kleeman rule):

$$\frac{1}{N_c}\left(\frac{dE}{dx}\right) = \sum_i W_i \frac{1}{N_i}\left(\frac{dE}{dx}\right)_i ;$$

  where N is the atomic density, dE/dx is the linear stopping power, and W_i is the atom fraction of the i^{th} component of the compound (subscript c).
- Expect 10-20% differences from actual values for some components.
- Range scaling:

$$R_c = \frac{m_c}{\sum_i n_i \cdot \left(\frac{A_i}{R_i}\right)}$$

  where R_i is the range of element i, n_i is the number of atoms of element i in the molecule, A_i is the atomic weight of element i, and m_c is the molecular weight of the compound.
- If range data is not available, estimates can be based on semi-empirical formula (also called Bragg-Kleeman rule):

$$\frac{R_1}{R_0} \approx \frac{\rho_1\sqrt{A_1}}{\rho_0\sqrt{A_0}},$$

  where ρ & A are the density and atomic weight of the absorbers.
- The ratio of R's is only really reasonable for materials of similar atomic weight.
- By integrating the Bethe formula, it can be shown that the range of the particle of mass m and charge z is:

$$R(v) = \frac{m}{v^2} \cdot F(v)$$

  where $F(v)$ is a unique function of initial velocity for the particle.
- For particles of the same initial velocity:

$$R_a(v) = \frac{m_a z_a^2}{m_b z_b^2} \cdot R_b(v),$$

  where a and b refer to different charged particles.

Behavior of Fission Fragments

- Large effective charge (stripped of electrons) yield high initial specific energy loss.
- Range is ≈ ½ that of a 5 Mev α particle.
- Picking up electrons on path then decreases the specific energy loss for the particle.

Secondary e^- Emission from Surfaces

- e^-'s may be given enough energy to reach the surface and escape, these are secondary e^-'s (one type of secondary and different from those produced in γ–ray interactions – these are much lower energy).
- Generally the number produced will be proportional to the energy deposited at the surface of the absorber.
- One application is the photomultiplier tube, where a fast e^- hits a plate and excites 5-10 secondary e^-'s.