Absorption of Radiation

Lecture 28

www.physics.uoguelph.ca/~pgarrett/teaching.html

Review of L-26

- β's loose energy in matter via 3 main processes
  - Ionization
  - Bremsstrahlung
  - Annihilation
- α's interact with matter mainly through ionization
- A quantity called *range* is defined as

  $$range = penetration\ depth \times density$$

- For kinetic energy of β's (or e^-) > 0.6 MeV, empirical relation

  $$\text{Range}\left({}^{kg}\!/\!_{m^2}\right) = 5.42E - 1.33$$

  where E is in MeV
- Distance of penetration D for α particle of energy E (MeV) *in air* is

  $$D(cm) \approx 0.325E^{3/2}$$

Review of L-26

- Main processes for γ rays interacting with matter
  - Coherent scattering
  - Compton scattering
  - Photoelectric effect
  - Pair production
  - Photonuclear reactions

Linear energy transfer (*LET*)

- Particles can lose energy continuously along their path when interacting with matter, and so continuously slow down
- When working out the impact to biological systems (or matter), the amount of energy lost by the particle per unit distance, called the *linear energy transfer*, or *LET*, is important

$$LET = \frac{dE}{dx}$$

- Particles with a large *LET* can do a large amount of damage, but usually over a very short range
- Particles with a small *LET* do lesser damage, but can affect tissues further from the source
- The energy of a particle is a nonlinear function of the distance travelled, so the *LET* can vary enormously over a particles path
- Very often the *LET* is largest towards the *end* of a particles path, so radiation treatments for cancer "tune" energies of, e.g. e^- beams so that the e^- stop in tumours

Particles and *LET*

- Heavy charged particles and α's have a very high *LET*
- $e^{\pm}$ have a *LET* that varies from small for high energies, to large for low energies
  - This is what makes *e* beams useful for cancer therapies
  - Do minimal amount of damage to tissue at entry point, maximum damage to tumour
- Protons have a larger *LET* than e^{-}, but smaller than α's
  - Also used in cancer therapies
- Other particles used in beam therapies for cancer treatment
  - Neutrons
  - Muons – like "heavy" electrons
  - Pions
  - Accelerated ions
- Each has its advantages/disadvantages
- By far most popular is X-ray beam therapy since every hospital has X-ray facility, but not always particle accelerator

Absorption of radiation

- Radiation classified in two main ways
  - Ionizing (charged particles, UV, X-rays, γ-rays, neutrons,…
  - Non-ionizing (microwaves, radiowaves, …)
- Most damaging form of radiation are those causing ionization
- Ionizing radiation quantified by amount of ionization the radiation causes in dry air at NTP
- Physical processes that deposit energy in matter lead to ionization if an electron – positive-ion pair can be created
  - In dry air, this requires ~35 eV of energy (at NTP)
  - ex. An electron of energy 5 MeV is stopped in air at NTP, how many e^--ion pairs are created?
    - $n = 5\times10^6/35 \approx 143000$ ion pairs

Exposure

- The strength of the radiation field is quantified by the *exposure* – the amount of radiation that will produce charge of either sign in dry air at NTP
- Exposure units are Coulombs/kg
  - Unit is *Röntgen* (R)
  - $1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C/kg}$
- Ex. A radiation field causes the total production of 10^9 ion-pairs per kg of air
  - Exposure = $10^9 \times 1.602 \times 10^{-19} = 1.6 \times 10^{-10}\ \mathrm{C/kg} = 0.62\ \mu\mathrm{R}$
- Very often, exposure is given in form of a *rate*, i.e. R/hr
  - If the same field now causes 10^9 ion pairs/s, $0.62\ \mu\mathrm{R/s} = 2.23\ \mathrm{mR/hr}$

Radiation dose

- *Dose* = amount of energy absorbed per unit mass
  - SI unit Gray (Gy) = 1 J / kg
  - Old unit rad = 0.01 J / kg
- For charged particles, dose calculations straightforward (add up energy of all particles emitted divide by total mass of matter)
- For photons, more difficult (since photons are not slowed down and stopped by matter, but attenuated and scattered)
- Photon attenuation is (works for γ and X and UV,…)

$$I = I_0 e^{-\mu x}$$

μ is attenuation coefficient

- Need energy absorption

Absorption coefficient

- Photon scattering – photon can leave volume without depositing all its energy
- *Absorption* coefficient takes into account photoelectric, pair, Compton absorption
- *Scattering* coefficient takes into account scattered photons
- Attenuation coefficient = absorption + scattering
- Very often, quantities expressed as mass attenuation, absorption,… coefficients

$$\mu_m = \frac{\mu}{\rho} \quad \mathrm{m^2/kg}$$

with ρ density

- For γ rays with 100 keV< E_γ < 5 MeV, $\mu_m \sim 3.0\times10^{-3}\ \mathrm{m^2/kg}$

Absorbed dose

- For photons, dose (D) is

$$D \approx 3.0\times10^{-3} NEt \quad \text{J/kg}$$

  E is the photon energy (J), *N* is photon rate (#/s), *t* the time

- Ex. A 1 μCi source is ingested that is both a β and γ emitter, and spreads uniformly over the body of a 60 kg person. The average β energy is 1 MeV, and for each decay, a 1.5 MeV γ is emitted. What is the dose rate?
  - The β energy is totally absorbed = 1 MeV × 1 × 10^{-6} × 3.7 ×10^{10} = 3.7 × 10^{4} MeV/s ⇒ 617 MeV/kg/s (divide by body mass)
  - The γ energy absorbed

$$D_\gamma \quad s^{-1} = 3.0\times10^{-3}\times3.7\times10^{4}\times1.5 = 166.5 \quad \text{MeV/kg/s}$$

  - Dose rate = 45 μrad/hr

Biological half life

- Body processes ingested materials at specific rates, depending on the chemistry and metabolism
- Elimination of materials by body can be described by an exponential with a *biological* half life $t^b_{1/2}$
- Radionuclide ingested by body
  - Amount left after time *t* is

$$N_b(t) = N_0 e^{-\lambda t} e^{-\lambda_b t} = N_0 e^{-\lambda_{eff} t}$$

where

$$\lambda_{eff} = \lambda + \lambda_b = \frac{t_{1/2} + t^b_{1/2}}{t_{1/2} t^b_{1/2}}$$

Total dose

- Take our previous example, work out the total dose assuming a half life of 5 yr, and biological half life of 6 days
- $\lambda_{\mathrm{eff}} \approx \ln 2 / 6\ \mathrm{d}^{-1}$
- At time t, the # decays that occur in the body in interval *dt* is *A dt* (*A* is the activity = λN)
- Total # decays in the body is

$$\int_0^T A\,dt = \int_0^T \lambda N_0 e^{-\lambda_{eff} t}\,dt = \frac{\lambda}{\lambda_{eff}} N_0\left(1 - e^{-\lambda_{eff} T}\right)$$

- With our example of a 1 μCi source, #decays=37000×6×24×3600/ln(2) = 2.77×10^{10}, and the total dose is $2.77\times10^{10}\times(1/60\ (\beta\text{'s})+0.003(\gamma\text{'s}))\times1.6\times10^{-13}$ $=8.72\times10^{-5}$=87 μGy=8.7 mrad

Dose equivalent

- Different radiations have different consequences on biological tissues
- Take this into account by giving each type of radiation a weighting factor so that they can be compared to the equivalent dose of X-rays
  - Relative biological effectiveness (RBE) or radiation weighting factor (w_R) – these are just numbers
- Taking into account the weighting factor, we have the dose equivalent *H*
  - SI unit Sievert (Sv)
  - Old unit rem 100 rem = 1 Sv

$$H = \Sigma\, w_R \times D$$

So our previous example, β and γ have $w_R = 1$, so the dose equivalent is 87 μSv or 8.7 mrem