Assessing Potential Biological Damage from Radiation

Radioactive nuclides are sources of high-energy particles and/or photons. This radiation can break chemical bonds and ionize molecules. In order to assess the potential for biological damage from a particular source of radiation, the following characteristics need to be considered.

1. Energy of radiation
   - results from kinetic energy of particles and dosage
   - measured in “rads” (“radiation absorbed dose”)
   - 1 rad = $1 \times 10^{-2}$ J deposited per kg tissue

2. Penetrating ability
   - results from particle charge
   - uncharged particles (e.g., $\gamma$ rays and neutrons) have greater penetrating ability than charged particles (e.g., $\alpha$, $\beta^-$ and $\beta^+$)
   - also affected by the kinetic energies of the particles
   - low energy $\alpha$ stopped by dead layer of skin (external exposure)
   - low energy $\beta^-$ and $\beta^+$ penetrate about 1 cm (external exposure)
   - $\gamma$ rays and neutrons extremely penetrating

3. Ionizing ability
   - results from particle mass
   - $\alpha >$ neutron $> \beta^- \approx \beta^+ > \gamma$

4. Chemical properties
   - results from periodic trends
   - damage from an ingested/inhaled radioactive nuclide depends on its residence time
   - e.g., strontium-90 versus krypton-85 (both $\beta^-$ emitters); strontium-90 would be expected to have a much longer residence time in the body because it is chemically similar to calcium (krypton-85 is an inert gas)

5. External vs. internal exposure

Half-life, $t_{1/2}$

time required for half the sample to react

Recall: first-order half-life does not depend on the initial quantity.

Radioactive decay is a statistical process. It’s impossible to determine the half-life from a very small sample of radioactive atoms!!

**The Dating Game**

Carbon-14 has a half-life of 5730 years. How old is a sample of tree bark containing 67.9% of the $^{14}$C activity of living bark?

\[
\ln \frac{N}{N_0} = -kt
\]

\[
\ln \left( \frac{1}{2} \right) = -kt_{1/2}
\]

\[
-k t_{1/2} = \ln 2
\]

\[
t_{1/2} = \frac{\ln 2}{k}
\]

\[
\ln \left( \frac{N}{N_0} \right) = -kt
\]

\[
\ln \left( \frac{0.679}{N_0} \right) = \ln (0.679) = (-1.21 \times 10^{-4} \text{ yr}^{-1}) t
\]

\[
t = 3200 \text{ years}
\]

$^{3}$H \hspace{1cm} t_{1/2} = 12.5 \text{ years}
Applications/Problems

Radon $^{222}\text{Rn}$

- $^{222}\text{Rn}$ formed in a series of steps from $^{238}\text{U}$.

$$^{238}\text{U} \rightarrow \frac{4}{92} \text{He} + \frac{2}{86} \text{Pb} + rac{2}{92} \text{Po}$$

- Radon is colorless, odorless, chemically inert BUT its radioactive decay products are solids (dust). Any radon that decays in your lungs doesn’t get exhaled.

Smoke Detectors $^{241}\text{Am}$

- $\alpha$ particle ionizes air particles
- $+$ ions move toward $-$ electrode
- electrons move toward $+$ electrode
- smoke particles also ionized, but recombination of smoke$^+$ ions and e$^-$ more efficient. → current drops → signal to horn

Medical Applications (See Section 22.5)

Considerations for medical applications of radioactive nuclides:
- short half-life
- stable decay products
- small doses
- localization in body
- penetrating ability

$^{131}\text{I}$

- iodine concentrates in the thyroid gland.
- $^{131}\text{I}$ used in the treatment of hyperthyroidism; kills some of the thyroid cells.
- $^{131}\text{I}$ is one by-product of nuclear power plants.

After the 1986 Chernobyl meltdown, residents downwind of the meltdown were given KI pills containing non-radioactive iodine so as to saturate the body with iodine so $^{131}\text{I}$ would not concentrate in the thyroid gland.

$^{201}\text{Tl}$

- cardiac imaging
- Tl accumulates in healthy heart tissue

$^{99m}\text{Tc}$

- Elution of an ion-exchange column containing $^{99m}\text{MoO}_4^{2-}$ (CrO$_4^{2-}$ analog) yields $^{99m}\text{TcO}_4^{-}$ (MnO$_4^{-}$ analog). Difference in charge results in movement in column.
- Neuroreceptor targeting (Alzheimer’s, Parkinson’s, epilepsy, schizophrenia)
- Compound must be neutral to pass through blood-brain barrier
- Ceretec used in brain imaging
- TRODAT-1 (TROpane DopAmine Transporter): uses related to Parkinson’s
\( ^{18}\text{F} \\)  
\[ t_{1/2} = 110 \text{ min} \]  
\( ^{18}\text{F} \rightarrow ^{0}\text{e} + ^{18}\text{O} \)

- used in **Positron Emission Tomography (PET scan)**
  - choose molecule with high concentration in part of body of interest
  - synthesize compound, attach \( ^{18}\text{F} \)
  - administer to patient
  - detect reaction of positrons with electrons in surrounding matter 
    \[ +_{1}\beta + \gamma \rightarrow 2_{0}\gamma \]  
    “annihilation”
  - images metabolic activity very clearly (e.g., Alzheimer’s, epilepsy, CP, stroke)
  - PET scans still relatively uncommon: \( ^{18}\text{F} \) short half-life: need to make onsite. 
    Need a particle accelerator. Cost > $10^6 (scanner not included).
  - \( ^{62}\text{Cu} \) also used in PET scans (blood flow).

- Contrast to **Computerized Axial Tomography (CAT scan)**
  - X-rays passed through body in thin slices.
  - Based on different densities of matter/tissue
  - No radioactive nuclide involved
  - Nothing radioactive administered to patient

- Contrast to **Magnetic Resonance Imaging (MRI)**
  - Patient inserted into huge magnet
  - Based on relaxation of spinning of hydrogen nuclei when magnetic field turned off
  - Excellent for imaging soft tissues (e.g., plaque from MS)
  - No radioactive nuclide involved
  - Nothing radioactive administered to patient

**Binding Energy**

Mass of atom \( \leq \) Sum of masses of particles that make up atom

The “missing” mass (mass defect) was converted to energy, called binding energy

\[ E = mc^2 \]

\[ (1.0 \times 10^{-3} \text{ kg})(3.00 \times 10^8 \text{ m/s})^2 = 9.0 \times 10^{13} \text{ J} \]

1 gram of mass = \( 9 \times 10^{10} \text{ kJ of energy}! \)

To allow for fair comparison, the mass defect and corresponding binding energy are recorded on a per nucleon basis.

**largest binding energy:** \( ^{56}\text{Fe} \) per nucleon

Both fission and fusion have the goal of producing nuclides with higher binding energies per nucleon. 
(more stable). Both fission and fusion therefore release energy.