Fundamentals of Radiation Physics

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Objectives

- **Radioactive Decay**
  - Describe difference between gamma radiation and particulate radiation (beta particles)

- **Production of Radionuclides**

- **Interaction of photons and particles with matter** (tissue, lead, acrylic and air)
Nuclear Science

Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about 10^{-10} seconds, the universe consisted of a soup of quarks, gluons, electrons, and antiparticles. As the universe cooled, quarks and gluons combined to form protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and heavier nuclei. Still later, deuterons combined with protons and three low-mass nuclei to form neutral atoms. Due to gravity, clumps of atoms contracted into stars, where hydrogen and helium fused into heavier elements, igniting star superheats from the most massive electrons and dispersing them into outer space. Our earth was formed from supernova debris.

Radioactivity

- Alpha Decay
- Beta Minus Decay
- Beta Plus Decay
- Gamma Decay

The Nucleus

- Proton
- Neutron
- Quark
- Electron
- Strong field
- Electromagnetic field

Phases of Nuclear Matter

- Neutron star
- Normal nucleus
- Quark-gluon plasma
- Easily universe

Unstable Nuclei

- Stable nuclei form a narrow band on the Chart of the Nuclides. Scientists produce unstable nuclei far from this band and study their decay, thereby learning about the structure of nuclear conditions. In this part of the chart, this contains about 2500 different nuclei. Nuclear theory predicts that there are at least 6000 more to be discovered, with Z > 113.

Chart of the Nuclides

- Magic numbers (N or Z = 2, 8, 18, 32, 50, and 82) are indicated by a black outline on the chart. They correspond to major closed shells of greater nuclear binding energy.

Radioactive Dating

- Applicable to rocks over 100 million years old

Applications

- Nuclear Medicine
- Nuclear Reactors
- Magnetic Resonance Imaging
- Space Exploration
- Smoke Detectors

Nuclear Energy

- Fusion
- Fission
- Solar fusion
- Nuclear power
- Nuclear disarmament

Magnetic Resonance Imaging

- MRI uses magnetic fields and radio waves to create detailed images of the inside of the body.
Radioactive Decay
Gamma Decay
- Change in Nuclear Energy

- Nuclide has excessive energy
- **Becomes stable by releasing energy in form of gamma ray**
  - Gamma ray has discrete energy, no mass, and no charge
- Nuclide does not change
Beta Decay
- Change in Nuclear Energy

- Nuclide has excessive neutrons
- Neutron converts to proton + beta particle + anti-neutrino
- Energy released as kinetic energy of beta and anti-neutrino
  - Beta is similar to an electron
  - Anti-neutrino has very little mass and is neutral
- Nuclide changes due to addition of proton
Radioactivity

- Rate of transformation of radionuclides
  - through the emission of energy in the form of a particle or a photon
- 1 Bq = 1 transformation per second
Radionuclide decay

Half-Life = $T_{1/2}$
Production Methods
Reactor - Adding Neutrons

$\text{Y-89}(n,\gamma) \text{ Y-90}$

Blue "Cerenkov radiation" from MAPLE 1 reactor core during commissioning tests at high power (8 MW). The Cerenkov glow is caused by high-speed electrons (beta particles or secondary electrons due to the core’s operation) slowing down in the surrounding water.

Resource: http://www.nuclearfaq.ca/maple_core_cerenkov.jpg
Accelerators – Adding Protons
Ne-20(d,\(\alpha\)) F-18
Generator - Decay
Mo-99 → Tc-99m

Interaction of photons and particles with matter
Penetration of Radiation Types

- **Alpha Particles**: Stopped by a sheet of paper
- **Beta Particles**: Stopped by heavy clothing or less than an inch of a substance (e.g., plastic)
- **Gamma Rays**: Stopped by inches to feet of concrete or less than an inch of lead
- **Neutrons**: Stopped by a few feet of concrete
Interaction of photons with matter
### Electromagnetic Waves Interaction with Matter

<table>
<thead>
<tr>
<th>Type of Interaction</th>
<th>Photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh Scattering</td>
<td>Radio</td>
</tr>
<tr>
<td>Photoelectric Absorption</td>
<td>Microwave</td>
</tr>
<tr>
<td>Compton Absorption/Scatter</td>
<td>Infrared</td>
</tr>
<tr>
<td>Pair Production</td>
<td>Light</td>
</tr>
<tr>
<td>Photonuclear Activation</td>
<td>UV</td>
</tr>
<tr>
<td></td>
<td>X-Rays</td>
</tr>
<tr>
<td></td>
<td>Gamma Rays</td>
</tr>
</tbody>
</table>
Photo-electric Effect

All of gamma energy is given to orbiting electron in the material.
Compton Scattering

Fraction of gamma energy is given to orbiting electron in the material.
Absorption of X-ray and gamma
Gamma Attenuation/Absorption

- Energy of gamma
- Composition of material
- HVL – Half Value Layer

\[ y = e^{-ux} \]

X - Thickness of Absorber
Interaction particles with matter
Example of Beta Emitters

Light Source – Tritium gas (H³)

Food - Bananas
Beta Particle Kinetic Energy
Maximum Energy ~ 2.28 MeV
Average Energy ~ 0.9367 MeV

http://www.doseinfo-radar.com/BetaSpec.zip
Interaction of charged particles

- Coulombic Interaction
  - mechanical
  - knocks electron off its orbit

- Bremsstrahlung Production
  - Radiative Loss
  - Braking Radiation
Bremsstrahlung Production - Radiative Loss

Percentage of Radiative Loss \sim \frac{(Z_{\text{eff}} \cdot E_{\text{max}})}{3000} \times 100\%$

- Water, Tissue, or Plastic \sim 0.6\%
- Lead (Pb) \sim 6.2\%
Bremsstrahlung vs. Gamma Radiation

**Gamma**
- **Discrete** Energy dependent on radionuclide

**Bremsstrahlung**
- **Spectrum** of Energy dependent on beta particle energy and interaction with nucleus

http://www.search.com/reference/Neutron_activation_analysis
Coulombic Interaction - Collisional Loss

Water, Tissue, or Plastic ~ 99.4%
Lead (Pb) ~ 93.8%
Beta Particle Range Varies

Extrapolated Range

Background due to Bremsstrahlung Penetration

Relative # particles detected
## Particle Maximum Range

<table>
<thead>
<tr>
<th>Medium</th>
<th>Y-90 Maximum Range in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>10375</td>
</tr>
<tr>
<td>Plexiglass</td>
<td>9.8</td>
</tr>
<tr>
<td>Water</td>
<td>11.3</td>
</tr>
<tr>
<td>Glass, Pyrex</td>
<td>6.0</td>
</tr>
<tr>
<td>Lead</td>
<td>1.63</td>
</tr>
<tr>
<td><strong>Tissue, Soft</strong></td>
<td><strong>11.4</strong></td>
</tr>
<tr>
<td>Bone, Compact</td>
<td>6.6</td>
</tr>
<tr>
<td>Bone Cortical</td>
<td>6.8</td>
</tr>
</tbody>
</table>

The above data was generated using e-star software from the NIST website.
Effective Dose Range Depends on Radiation Absorbed Dose Rate – cGy/s

Y-90 Radiation Dose Rate

Dose Rate (cGy/s)

Distance (cm)
Radiation Measurement Terminology
Radiation Exposure

- Refers to the amount of ionization produced in air by x- or γ-rays only
- Σ charges (either + or -) produced in air when all the electrons liberated by photons in a mass of air are stopped.
- Roentgen (R) = 2.58 x 10^{-4} C/kg
Radiation Absorbed Dose

- Amount of ionizing energy (J) deposited in a kg of material such as liver tissue
- 1 Gy = 1 J/kg
- In air...
  - 1 C ~ 34 J
  - 1 R = 2.58 x 10^{-4} C/kg X 34 J/C
    = 8.8 x 10^{-3} J/kg
    = 8.8 mGy
- 1 Gy = 100 rad
Dose vs Dosage

- **Dose** generally refers to the radiation absorbed dose and should have units of Gray (Gy)
- **Dosage** generally refers to the quantity of material being administered and should have units such as:
  - Radioactivity (Bq)
  - Volume of the microspheres suspended (ml)
  - Mass of the microspheres administered (mg)
  - Vial labeled quantity such as the activity at the time of calibration (i.e. 3 GBq vial size)
Interior of drafty and leaky shed at the School of Physics where radium was discovered.\textsuperscript{3}

\begin{itemize}
\item Antonio-Henri Becquerel (1852-1908).\textsuperscript{1}
\item Marie Curie (1867-1934).\textsuperscript{3}
\item Pierre Curie (1859-1906).\textsuperscript{1}
\end{itemize}
Q1. Dosage in radioembolization is defined as

a) the radiation absorbed dose and should have units of Gray (Gy)

b) the quantity of material being administered and should have units of radioactivity (Bq)

c) the quantity of material being administered and should have units of volume (ml) or mass (mg)

d) Both b and c
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d) **Both b and c**
Q2. Y-90 is produced by

a) Adding a proton to Sr-90 in a cyclotron
b) Adding a neutron to Y-89 in a reactor
c) Decaying Sr-90 using an Al generator
d) None of the above
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Q3. Which of the following is true of Bremsstrahlung transmission through tissue or water?

a) The transmission varies exponentially with the thickness of tissue.

b) The transmission varies linearly with the thickness of tissue.

c) Bremsstrahlung cannot be transmitted through tissue.

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a) The HVL is equal to the extrapolated range.
b) The primary interaction involves the transfer of beta particle energy to an orbiting electron.
c) Gamma rays are produced.
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Q5. Beta particles may undergo Bremsstrahlung production in acrylic shielding; therefore the acrylic shielding should also be shielded with lead to protect the user from Bremsstrahlung. (True or False)

a) True
b) False
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a) True
b) False