9.1 Natural Radioactivity

Radioactive Isotopes

A radioactive isotope
- has an unstable nucleus.
- emits radiation to become more stable.
- can be one or more of the isotopes of an element

<table>
<thead>
<tr>
<th>Stable Isotopes</th>
<th>Unstable Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg-24</td>
<td>Mg-25</td>
</tr>
<tr>
<td>Mg-24</td>
<td>Mg-26</td>
</tr>
<tr>
<td>Mg-25</td>
<td>Mg-26</td>
</tr>
</tbody>
</table>

Types of Radiation

<table>
<thead>
<tr>
<th>Alpha (α) particle</th>
<th>Beta (β) particle</th>
<th>Positron (β⁺)</th>
<th>Gamma ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two protons and two neutrons.</td>
<td>A high-energy electron.</td>
<td>A positive electron.</td>
<td>High-energy radiation released from a nucleus.</td>
</tr>
</tbody>
</table>

Radiation Protection

Radiation protection requires
- paper and clothing for alpha particles.
- a lab coat or gloves for beta particles.
- a lead shield or a thick concrete wall for gamma rays.
- limiting the amount of time spent near a radioactive source.
- increasing the distance from the source.

Shielding for Radiation Protection

<table>
<thead>
<tr>
<th>Property</th>
<th>Alpha (α) particle</th>
<th>Beta (β) particle</th>
<th>Gamma (γ) ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel distance in air</td>
<td>2-4 cm</td>
<td>300-500 cm</td>
<td>500 cm</td>
</tr>
<tr>
<td>Tissue depth</td>
<td>0.05 mm</td>
<td>4-5 mm</td>
<td>50 cm or more</td>
</tr>
<tr>
<td>Shielding</td>
<td>Paper, clothing, heavy clothing, lead, concrete,</td>
<td>Heavy clothing, lead, concrete,</td>
<td>Lead, thick concrete, concrete,</td>
</tr>
<tr>
<td>Typical source</td>
<td>Radon-222</td>
<td>Carbon-14</td>
<td>Thorium-230</td>
</tr>
</tbody>
</table>

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Chapter 9 Nuclear Radiation

9.2 Nuclear Reactions

Alpha Decay

When a radioactive nucleus emits an alpha particle, a new nucleus forms that has
- a mass number that is decreased by 4.
- an atomic number that is decreased by 2.

Balancing Nuclear Equations

In a balanced nuclear equation, the sum of the mass numbers and the sum of the atomic numbers are equal for the nuclei of the reactants and the products.

**MASS NUMBERS**

\[
\begin{align*}
\text{Total} &= 251 \\
241\text{Cf} &= 247\text{Cm} + 4\text{He} \\
\text{Total} &= 98
\end{align*}
\]

**ATOMIC NUMBERS**

\[
\begin{align*}
\text{Total} &= 86 \\
\end{align*}
\]

Changes in Nuclear Particles Due to Radiation

When radiation occurs,
- particles are emitted from the nucleus.
- mass number may change.
- atomic number may change.

Equation for Alpha Emission

Write an equation for the alpha decay of Rn-222.

**STEP 1:** Write the incomplete equation

\[
222\text{Rn} \rightarrow ? + 4\text{He}
\]

**STEP 2:** Determine the mass number

\[222 - 4 = 218\]

**STEP 3:** Determine the atomic number

\[86 - 2 = 84\]

**STEP 4:** Determine the symbol of element

\[84 = \text{Po}\]

**STEP 5:** Complete the equation

\[
222\text{Rn} \rightarrow 218\text{Po} + 4\text{He}
\]
**Beta Emission**

- A beta particle:
  - is an electron emitted from the nucleus.
  - forms when a neutron in the nucleus breaks down.
  - $^1n \rightarrow ^0e + ^1H$

**Writing An Equation for a Beta Emitter**

**STEP 1:** Write an equation for the decay of $^{42}$potassium, a beta emitter.

$^{42}$K $\rightarrow$ new nucleus $+ ^0e$

**STEP 2:** Mass number: (same) $= 42$

**STEP 3:** Atomic number: $19 + 1 = 20$

**STEP 4:** Symbol of element: $20 = Ca$

**STEP 5**

$^{42}$K $\rightarrow$ $^{42}$Ca $+ ^0e$

---

**Learning Check**

Write the nuclear equation for the beta decay of $^{60}$Co.

**Solution**

$^{60}$Co $\rightarrow$ $^{60}$Ni $+ ^0e$

---

**Positron Emission**

- In positron emission,
  - a proton is converted to a neutron and a positron.
  - $^1p \rightarrow ^0n + ^0e$
  - the mass number of the new nucleus is the same, but the atomic number decreases by 1.

$^{49}$Mn $\rightarrow$ $^{49}$Cr $+ ^0e$

---

**Gamma Radiation**

- In gamma radiation,
  - energy is emitted from an unstable nucleus, indicated by $m$ following the mass number.
  - the mass number and the atomic number of the new nucleus are the same.

$^{99m}$Tc $\rightarrow$ $^{99}$Tc $+ \gamma$
Producing Radioactive Isotopes

Radioactive isotopes are produced
• when a stable nucleus is converted to a radioactive nucleus by bombarding it with a small particle.
• in a process called transmutation.

Learning Check

What radioactive isotope is produced when a neutron bombards $^{59}$Co?

$^{59}$Co + 1\text{n} → ? + 4\text{He}

Solution

A Geiger counter
• detects beta and gamma radiation.
• uses ions produced by radiation to create an electrical current.
Radiation Units

Units of radiation include
- **Curie**
  - measures activity as the number of atoms that decay in 1 second.
- **rad (radiation absorbed dose)**
  - measures the radiation absorbed by the tissues of the body.
- **rem (radiation equivalent)**
  - measures the biological damage caused by different types of radiation.

Units of Radiation Measurement

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Curie Unit</th>
<th>SI Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity</td>
<td>curie (Ci)</td>
<td>3.7 x 10^10</td>
</tr>
<tr>
<td>Absorbed dose</td>
<td>rad</td>
<td>1 curie (Ci) = 3.7 x 10^10</td>
</tr>
<tr>
<td>Biological damage</td>
<td>rem</td>
<td>rad x factor</td>
</tr>
</tbody>
</table>

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Exposure to Radiation

Exposure to radiation occurs from
- naturally occurring radioisotopes.
- medical and dental procedures.
- air travel, radon, and smoking cigarettes.

Learning Check

A typical intravenous dose of I-125 for a thyroid diagnostic test is 100 µCi. What is this dosage in megabecquerels (MBq)? (3.7 x 10^10 Bq = 1 Ci)

1) 3.7 MBq
2) 3.7 x 10^6 MBq
3) 2.7 x 10^2 MBq

Solution

A typical intravenous dose of I-125 for a thyroid diagnostic test is 100 µCi. What is this dosage in megabecquerels (MBq)? (3.7 x 10^10 Bq = 1 Ci)

1) 3.7 MBq

\[
100 \mu\text{Ci} \times \frac{1 \text{ Ci}}{3.7 \times 10^{10} \text{ Bq}} \times \frac{3.7 \times 10^{10} \text{ Bq}}{1 \text{ Ci}} = 3.7 \text{ MBq}
\]

Chapter 9 Nuclear Radiation

9.4 Half-Life of a Radioisotope
9.5 Medical Applications Using Radioactivity
Half-Life

The half-life of a radioisotope is the time for the radiation level to decrease (decay) to one half of the original value.

Decay Curve

A decay curve shows the decay of radioactive atoms and the remaining radioactive sample.

Half-Lives of Some Radioisotopes

Radioisotopes
- that are naturally occurring tend to have long half-lives.
- used in nuclear medicine have short half-lives.

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Decay Curve</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-14</td>
<td>1000 g</td>
<td>5730 yr</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>238 U</td>
<td>4.5 b</td>
</tr>
<tr>
<td>Carbon-12</td>
<td>12 C</td>
<td>1.2 yr</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>235 U</td>
<td>703 yr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Decay Curve</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium-24</td>
<td>24 Na</td>
<td>14.9 h</td>
</tr>
<tr>
<td>Copper-64</td>
<td>64 Cu</td>
<td>12.7 d</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>40 K</td>
<td>1.28 yr</td>
</tr>
<tr>
<td>Gold-198</td>
<td>198 Au</td>
<td>2.69 yr</td>
</tr>
</tbody>
</table>

Half-Life Calculations

In one half-life, 40 mg of a radioisotope decays to 20 mg. After two half-lives, 10 mg of radioisotope remain.

Learning Check

The half-life of $^{123}I$ is 13 hr. How much of a 64 mg sample of $^{123}I$ is left after 26 hours?

1) 32 mg
2) 16 mg
3) 8 mg

Solution

2) 16 mg

<table>
<thead>
<tr>
<th>STEP 1</th>
<th>Given</th>
<th>64 g; 26 h; 13 hr/half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEP 2</td>
<td>Plan</td>
<td>26 hours</td>
</tr>
<tr>
<td>STEP 3</td>
<td>Equalities</td>
<td>1 half-life = 13 h</td>
</tr>
<tr>
<td>STEP 4</td>
<td>Set Up Problem</td>
<td>Number of half-lives</td>
</tr>
</tbody>
</table>

Number of half-lives = $26 \div 13 = 2$ half-lives
Medical Applications

Radioisotopes with short half-lives are used in nuclear medicine because
- they have the same chemistry in the body as the nonradioactive atoms.
- in the organs of the body, they give off radiation that exposes a photographic plate (scan), giving an image of an organ.

Thyroid scan

Some Radioisotopes Used in Nuclear Medicine

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Medical Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-60</td>
<td>5.29 y</td>
<td>Gamma radiation therapy</td>
</tr>
<tr>
<td>Ge-68</td>
<td>154 d</td>
<td>Imaging of brain and bone cancers</td>
</tr>
<tr>
<td>Is-131</td>
<td>3.01 h</td>
<td>Imaging of bone and bone cancers</td>
</tr>
<tr>
<td>P-32</td>
<td>14.3 d</td>
<td>Imaging of bone and bone cancers</td>
</tr>
<tr>
<td>R-113</td>
<td>7.1 h</td>
<td>Imaging of bone and bone cancers</td>
</tr>
<tr>
<td>Tc-99m</td>
<td>6.0 h</td>
<td>Imaging of bone and bone cancers</td>
</tr>
<tr>
<td>I-131</td>
<td>8.0 d</td>
<td>Imaging of thyroid and heart muscles</td>
</tr>
<tr>
<td>I-124</td>
<td>2.0 h</td>
<td>Imaging of thyroid and heart muscles</td>
</tr>
</tbody>
</table>

Learning Check

Which of the following radioisotopes are most likely to be used in nuclear medicine?
1) $^{40}$K half-life $1.3 \times 10^9$ years
2) $^{42}$K half-life 12 hours
3) $^{131}$I half-life 8 days

Solution

Which of the following radioisotopes are most likely to be used in nuclear medicine?

Radioisotopes with short half-lives are used in nuclear medicine.
2) $^{42}$K half-life 12 hours
3) $^{131}$I half-life 8 days

Chapter 9 Nuclear Radiation

9.6 Nuclear Fission and Fusion

In nuclear fission,
- a large nucleus is bombarded with a small particle.
- the nucleus splits into smaller nuclei and several neutrons.
- large amounts of energy are released.
When a neutron bombards $^{235}\text{U}$, there are several effects:

- An unstable nucleus of $^{236}\text{U}$ undergoes fission (splits).
- Smaller nuclei are produced, such as Kr-91 and Ba-142.
- Neutrons are released to bombard more $^{235}\text{U}$.

The nuclear fission can be represented as:

$$\begin{align*}
1\text{n} + ^{235}\text{U} &\rightarrow ^{236}\text{U} + ^{91}\text{Kr} + ^{142}\text{Ba} + 3\text{~n} + \text{energy} \\
&0 + 92 \rightarrow 0 + 92 + 36 + 56 + 0
\end{align*}$$

**Learning Check**

Supply the missing atomic symbol to complete the equation for the following nuclear fission reaction:

$$1\text{n} + ^{235}\text{U} \rightarrow ^{137}\text{Te} + ^{97}\text{Zr} + 2\text{~n} + \text{energy}$$

**Solution**

$$1\text{n} + ^{235}\text{U} \rightarrow ^{137}\text{Te} + ^{97}\text{Zr} + 2\text{~n} + \text{energy}$$

**Chain Reaction**

A chain reaction occurs when a critical mass of uranium undergoes fission, releasing a large amount of heat and energy that produces an atomic explosion.

**Nuclear Power Plants**

In nuclear power plants:

- Fission is used to produce energy.
- Control rods in the reactor absorb neutrons to slow and control the chain reactions of fission.
Nuclear Fusion

- occurs at extremely high temperatures (100,000,000 °C).
- combines small nuclei into larger nuclei.
- releases large amounts of energy.
- occurs continuously in the sun and stars.

Learning Check

Indicate if each of the following describes 1) nuclear fission or 2) nuclear fusion.

- A. a nucleus splits.
- B. large amounts of energy are released.
- C. small nuclei form larger nuclei.
- D. hydrogen nuclei react.
- E. several neutrons are released.

Solution

Indicate if each of the following is 1) nuclear fission or 2) nuclear fusion.

- A. a nucleus splits.
- B. large amounts of energy are released.
- C. small nuclei form larger nuclei.
- D. hydrogen nuclei react.
- E. several neutrons are released.