Chapter 24: Nuclear Reactions and Their Applications

24.1 Radioactive Decay and Nuclear Stability

24.2 The Kinetics of Radioactive Decay

24.3 Nuclear Transmutation: Induced Changes in Nuclei

24.4 The Effects of Nuclear Radiation on Matter

24.5 Applications of Radioisotopes

24.6 The Interconversion of Mass and Energy

24.7 Applications of Fission and Fusion
## Comparison of Chemical and Nuclear Reactions

<table>
<thead>
<tr>
<th>Chemical Reactions</th>
<th>Nuclear Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. One substance is converted to another, but atoms never change identity.</td>
<td>1. Atoms of one element typically change into atoms of another.</td>
</tr>
<tr>
<td>2. Orbital electrons are involved as bonds break and form; nuclear particles do not take part.</td>
<td>2. Protons, neutrons, and other particles are involved; orbital electrons rarely take part.</td>
</tr>
<tr>
<td>3. Reactions are accompanied by relatively small changes in energy and no measurable changes in mass.</td>
<td>3. Reactions are accompanied by relatively large changes in energy and measurable changes in mass.</td>
</tr>
<tr>
<td>4. Reaction rates are influenced by temperature, concentration, catalysts, and the compound in which an element occurs.</td>
<td>4. Reaction rates are affected by number of nuclei, but not by temperature, catalysts, or the compound in which an element occurs.</td>
</tr>
</tbody>
</table>

Table 24.1
\[ A^Z_X \quad A - \text{mass number} = p^+ + n^0 \]

\[ Z - \text{number of protons(atomic no.)} = p^+ \]

Number of neutrons(N) in a nucleus

\[ N = A - Z \]

\[ {}^{238}_{92}\text{U} \quad N = 238 - 92 = 146 \text{ of } n^0 \]

\[ {}^{238}_{92}\text{U} \quad \text{has} \quad 92e^- \quad 92 \text{ p}^+ \]

\[ {}^{235}\text{U} \quad \text{- atomic bomb} \]
Subatomic elementary particles

Electron $^0_{-1} \text{e}$

Proton $^1_1 \text{p}$

Neutron $^1_0 \text{n}$

**Nuclide** - nuclear species with specific numbers of two types of **nucleons**

**Nucleons** - made up of protons and neutrons
### Properties of Fundamental Particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Charge</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>p</td>
<td>+1.60218</td>
<td>1.672623</td>
</tr>
<tr>
<td>Neutron</td>
<td>n</td>
<td>0</td>
<td>1.674929</td>
</tr>
<tr>
<td>Electron</td>
<td>e</td>
<td>-1.60218</td>
<td>0.0005486</td>
</tr>
</tbody>
</table>
NUCLEAR STABILITY
Modes of Radioactive Decay

- Alpha decay—heavy isotopes: $^4_2\text{He}^{2+}$ or $\alpha$
- Beta decay—neutron rich isotopes: $e^-$ or $\beta^-$
- Positron emission—proton rich isotopes: $\beta^+$
- Electron capture—proton rich isotopes: x-rays
- Gamma-ray emission($\gamma$)–Decay of nuclear excited states
- Spontaneous fission—very heavy isotopes
Behavior of Three Types of Radioactive Emissions in an Electric Field

Fig. 24.1
Table 24.2 Modes of Radioactive Decay*

<table>
<thead>
<tr>
<th>Mode</th>
<th>Emission</th>
<th>Decay Process</th>
<th>Change in</th>
</tr>
</thead>
<tbody>
<tr>
<td>α Decay</td>
<td>α ((^4_2)He)</td>
<td><img src="image" alt="α Decay Diagram" /></td>
<td>-4 -2 -2</td>
</tr>
<tr>
<td>β Decay</td>
<td>(^0_{-1})β</td>
<td><img src="image" alt="β Decay Diagram" /></td>
<td>0 +1 -1</td>
</tr>
<tr>
<td>Positron emission</td>
<td>(^0_{+1})β</td>
<td><img src="image" alt="Positron Emission Diagram" /></td>
<td>0 -1 +1</td>
</tr>
<tr>
<td>Electron capture</td>
<td>x-ray photon</td>
<td><img src="image" alt="Electron Capture Diagram" /></td>
<td>0 -1 +1</td>
</tr>
<tr>
<td>γ Emission</td>
<td>(^0_{0})γ</td>
<td><img src="image" alt="γ Emission Diagram" /></td>
<td>0 0 0 0</td>
</tr>
</tbody>
</table>

*Neutrinos (\(γ\)) are involved in several of these processes but are not shown.

(p. 1046)
Alpha Decay–Heavy Elements

- $^{238}\text{U} \rightarrow ^{234}\text{Th} + \alpha + e$
  
  $t_{1/2} = 4.48 \times 10^9$ years

- $^{210}\text{Po} \rightarrow ^{206}\text{Pb} + \alpha + e$
  
  $t_{1/2} = 138$ days

- $^{256}\text{Rf} \rightarrow ^{252}\text{No} + \alpha + e$
  
  $t_{1/2} = 7$ ms

- $^{241}\text{Am} \rightarrow ^{237}\text{Np} + \alpha + e$
  
  $t_{1/2} = 433$ days
## Beta Decay–Electron Emission

<table>
<thead>
<tr>
<th>Decay Source</th>
<th>Decay Equation</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^90\text{Sr}$</td>
<td>$^90\text{Sr} \rightarrow ^{90}\text{Y} + \beta^- + \text{Energy}$</td>
<td>$t_{1/2} = 30 \text{ years}$</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>$^{14}\text{C} \rightarrow ^{14}\text{N} + \beta^- + \text{Energy}$</td>
<td>$t_{1/2} = 5730 \text{ years}$</td>
</tr>
<tr>
<td>$^{247}\text{Am}$</td>
<td>$^{247}\text{Am} \rightarrow ^{247}\text{Cm} + \beta^- + \text{Energy}$</td>
<td>$t_{1/2} = 22 \text{ min}$</td>
</tr>
<tr>
<td>$^{131}\text{I}$</td>
<td>$^{131}\text{I} \rightarrow ^{131}\text{Xe} + \beta^- + \text{Energy}$</td>
<td>$t_{1/2} = 8 \text{ days}$</td>
</tr>
</tbody>
</table>
Electron Capture–Positron Emission

\[ p^+ + e^- \rightarrow n + \text{Energy} = \text{Electron capture} \]

\[ p^+ \rightarrow n + e^+ + \text{Energy} = \text{Positron emission} \]

\[ ^{51}\text{Cr} + e^- \rightarrow ^{51}\text{V} + \text{Energy} \]
\[ t_{1/2} = 28 \text{ days} \]

\[ ^{7}\text{Be} \rightarrow ^{7}\text{Li} + \beta^+ + \text{Energy} \]
\[ t_{1/2} = 53 \text{ days} \]

\[ ^{177}\text{Pt} + e^- \rightarrow ^{177}\text{Ir} + \text{Energy} \]
\[ t_{1/2} = 11 \text{ s} \]

\[ ^{144}\text{Gd} \rightarrow ^{144}\text{Eu} + \beta^+ + \text{Energy} \]
\[ t_{1/2} = 4.5 \text{ min} \]
Fig. 24.2

Plot of Neutrons vs. Protons for the Stable Nuclides
<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number (Z)</th>
<th>Number of Nuclides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>48</td>
<td>8</td>
</tr>
<tr>
<td>In</td>
<td>49</td>
<td>2</td>
</tr>
<tr>
<td>Sn</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Sb</td>
<td>51</td>
<td>2</td>
</tr>
<tr>
<td>Te</td>
<td>52</td>
<td>8</td>
</tr>
<tr>
<td>I</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>Xe</td>
<td>54</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 24.3 (p. 1049)
# Distribution of Stable Nuclides

<table>
<thead>
<tr>
<th>Protons</th>
<th>Neutrons</th>
<th>Stable Nuclides</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even</td>
<td>Even</td>
<td>157</td>
<td>58.8</td>
</tr>
<tr>
<td>Even</td>
<td>Odd</td>
<td>53</td>
<td>19.9</td>
</tr>
<tr>
<td>Odd</td>
<td>Even</td>
<td>50</td>
<td>18.7</td>
</tr>
<tr>
<td>Odd</td>
<td>Odd</td>
<td>7</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Total = 267 100.0%

(c.f. Table 24.4, p. 1050)
The $^{238}\text{U}$ Decay Series

Fig. 24.3
CHEM 1332

Exam 1 is Friday Feb. 11 at 5:30 PM

Room 117 SR1

Web site http://www.uh.edu/~chem1p

User ID = chem1332

Password = ggw85p
Predicting the Mode of Decay

Unstable nuclide generally decays in a mode that shifts its N/Z ratio toward the band of stability.

1. Neutron-rich nuclides undergo β decay, which converts a neutron into a proton, thus reducing the value of N/Z.

2. Proton-rich nuclides undergo positron decay or electron capture, thus increasing the value of N/Z.

3. Heavy Nuclides Z > 83 undergo alpha decay, thus reducing the Z and N values by two units per emission.
\[ ^{243}_{95}\text{Am} \rightarrow ^{4}_{2}\text{He} + ^{239}_{93}\text{Np} \]

\[ ^{239}_{93}\text{Np} \rightarrow 0^{-}_{-1}\beta + ^{239}_{94}\text{Pu} \]

\[ ^{239}_{94}\text{Pu} \rightarrow ^{4}_{2}\text{He} + ^{235}_{92}\text{U} \]

\[ ^{235}_{92}\text{U} \rightarrow ^{4}_{2}\text{He} + ^{231}_{90}\text{Th} \]
Kinetics of Radioactive Decay

The decay rate or activity \( (A) = - \frac{\Delta N}{\Delta t} \)

\( N = \) Change in number of nuclei

\( t = \) change in time

SI unit of radioactivity is the becquerel (Bq), defined as one disintegration per second (d/s): \( 1 \text{Bq} = 1 \text{ d/s} \)

1 curie (Ci) equals the number of nuclei disintegrating each second in a 1g of radium-226. \( 1 \text{ Ci} = 3.70 \times 10^{10} \text{ d/s} \)
For a large collection of radioactive nuclei, the number decaying per unit time is proportional to the number present:

\[ \text{Decay rate (A) } \propto N \text{ or } A = kN \]

\( k \) = decay constant

The larger the value of \( k \), the higher is the decay rate. \( A = -\frac{\Delta N}{\Delta t} = kN \)

The activity depends only on \( N \) raised to the first order so radioactivity decay is a first-order process. We consider the number of nuclei than their concentration.
Half-life of Radioactive Decay \( t_{1/2} \)

The half-life \( (t_{1/2}) \) of a nuclide is the time it takes for half the nuclei present to decay.

\[ ^{14}_{6}\text{C} \rightarrow ^{14}_{7}\text{N} + ^{0}_{-1}\beta \]

The number of nuclei remaining is halved after each half-life.
Natural Decay Series of Existing Isotopes

- $^{40}$K $\rightarrow$ $^{40}$Ar
  - $t_{1/2} = 1.29 \times 10^9$ years
- $^{232}$Th $\rightarrow$ $^{208}$Pb
  - $t_{1/2} = 1.4 \times 10^{10}$ years
- $^{235}$U $\rightarrow$ $^{207}$Pb
  - $t_{1/2} = 7 \times 10^8$ years
- $^{238}$U $\rightarrow$ $^{206}$Pb
  - $t_{1/2} = 4.5 \times 10^9$ years
Natural Decay Series for Uranium-238

$^{238}\text{U} \rightarrow^{234}\text{Th}$

$^{234}\text{Pa}$

$^{234}\text{U} \rightarrow^{230}\text{Th} \rightarrow^{226}\text{Ra} \rightarrow^{222}\text{Rn} \rightarrow^{218}\text{Po} \rightarrow^{214}\text{Pb}$

$^{218}\text{At} \rightarrow^{214}\text{Bi} \rightarrow^{210}\text{Tl}$

$^{214}\text{Po} \rightarrow^{210}\text{Pb} \rightarrow^{206}\text{Hg}$

$^{210}\text{Bi} \rightarrow^{206}\text{Tl}$

$^{210}\text{Po} \rightarrow^{206}\text{Pb}$

$= \alpha$ decay

$= \beta^-$ decay

$^{238}\text{U}: 8 \alpha$ decays and 6 $\beta$ decays leaves you with $^{206}\text{Pb}$
Natural Decay Series for Uranium-235

\[
{^{235}\text{U} \rightarrow ^{231}\text{Th}}
\]

\[
{^{231}\text{Pa} \rightarrow ^{227}\text{Ac} \rightarrow ^{223}\text{Fr} \rightarrow ^{219}\text{At} \rightarrow ^{215}\text{Bi}}
\]

\[
{^{227}\text{Th} \rightarrow ^{223}\text{Ra} \rightarrow ^{219}\text{Ra} \rightarrow ^{215}\text{Po} \rightarrow ^{211}\text{Pb}}
\]

\[
{^{215}\text{At} \rightarrow ^{211}\text{Bi} \rightarrow ^{207}\text{Tl}}
\]

\[
{^{211}\text{Po} \rightarrow ^{207}\text{Pb}}
\]

\[\text{= } \alpha \text{ decay}\]

\[\text{= } \beta^- \text{ decay}\]

\[{^{235}\text{U}}: \text{ 8 } \alpha \text{ decays and 4 } \beta^- \text{ decays leaves you with } ^{207}\text{Pb}\]
232 Th: 7 α decays and 4 β⁻ decays leaves you with 208 Pb
Detection of Radioactivity by an Ionization Counter

- Sample
- Window
- Argon gas (+)
- Voltage source
- Amplifier and counter
- Toward anode (+)
- Toward cathode (-)

Fig. 24.A
Decrease in Number of $^{14}\text{C}$ Nuclei Over Time

Number of nuclei at time $t$, $N_t$, equals the initial number of nuclei, $N_0$, multiplied by $\left(\frac{1}{2}\right)^n$.

- After 1st half-life (5730 yr), $N = \frac{1}{2}N_0$
- After 2nd half-life (11,460 yr), $N = \frac{1}{4}N_0$
- After 3rd half-life (17,190 yr), $N = \frac{1}{8}N_0$

Time (yr): 0, 10,000, 20,000

$N_0$ is the initial number of $^{14}\text{C}$ nuclei.
\[ \ln \frac{N_t}{N_0} = -kt \]

\[ \ln \frac{N_0}{N_t} = kt \quad N_0 \text{ is the number of nuclei at } t = 0 \text{ and } N_t \text{ is the number of nuclei remaining at any time } t. \]

To calculate the half-time; set \( N_t = \frac{1}{2} N_0 \)

\[ \ln \frac{N_0}{(1/2N_0)} = k t_{1/2} \quad t_{1/2} = \ln 2 / k \]

The half-life is not dependent on the number of nuclei and is inversely related to the decay constant. Large \( k \) short \( t_{1/2} \).
## Decay Constants ($k$) and Half-lives ($t_{1/2}$) of Beryllium Isotopes

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$k$</th>
<th>$t_{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{7}\text{Be}$</td>
<td>$1.30 \times 10^{-2}$/day</td>
<td>53.3 day</td>
</tr>
<tr>
<td>$^{8}\text{Be}$</td>
<td>$1.0 \times 10^{16}$/s</td>
<td>$6.7 \times 10^{-17}$ s</td>
</tr>
<tr>
<td>$^{9}\text{Be}$</td>
<td>Stable</td>
<td></td>
</tr>
<tr>
<td>$^{10}\text{Be}$</td>
<td>$4.3 \times 10^{-7}$/yr</td>
<td>$1.6 \times 10^6$ yr</td>
</tr>
<tr>
<td>$^{11}\text{Be}$</td>
<td>$5.02 \times 10^{-2}$/s</td>
<td>13.8 s</td>
</tr>
</tbody>
</table>

*Table 24.5 (p. 1054)*
Radioisotopic Dating

\[ ^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}p \]

$^{12}C / ^{14}C$ ratio is constant in living organisms.

Dead organism $^{12}C / ^{14}C$ ratio increases.

$^{14}C$ decays $^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta$
Radiocarbon Dating for Determining the Age of Artifacts

Fig. 24.5
Nuclear Transmutation

$^{14}_{7}\text{N} \ + \ ^{4}_{2}\text{He} \rightarrow ^{1}_{1}\text{H} \ + \ ^{17}_{8}\text{O}$

Notation $^{14}\text{N} \ (\alpha, \ p) \ ^{17}\text{O}$

$^{27}_{13}\text{Al} \ + \ ^{4}_{2}\text{He} \rightarrow ^{1}_{0}\text{n} \ + \ ^{30}_{15}\text{P}$

Notation $^{27}\text{Al}(\alpha, \ n) \ ^{30}\text{P}$
A Linear Accelerator

Fig. 24.6A
The Cyclotron Accelerator

Fig. 24.7
### Formation of Some Transuranium Nuclides

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Half-life of Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{239}\text{Pu} + ^4\text{He}) \rightarrow (^{240}\text{Am} + ^1\text{H} + 2^1\text{n})</td>
<td>50.9 h</td>
</tr>
<tr>
<td>(^{239}\text{Pu} + ^4\text{He}) \rightarrow (^{242}\text{Cm} + ^1\text{n})</td>
<td>163 days</td>
</tr>
<tr>
<td>(^{244}\text{Cm} + ^4\text{He}) \rightarrow (^{245}\text{Bk} + ^1\text{H} + 2^1\text{n})</td>
<td>4.94 days</td>
</tr>
<tr>
<td>(^{238}\text{U} + ^{12}\text{C}) \rightarrow (^{246}\text{Cf} + 4^1\text{n})</td>
<td>36 h</td>
</tr>
<tr>
<td>(^{253}\text{Es} + ^4\text{He}) \rightarrow (^{256}\text{Md} + ^1\text{n})</td>
<td>76 min</td>
</tr>
<tr>
<td>(^{252}\text{Cf} + ^{10}\text{B}) \rightarrow (^{256}\text{Lr} + 6^1\text{n})</td>
<td>28 s</td>
</tr>
</tbody>
</table>

Table 24.6 (p. 1059)
Penetrating Power of Radioactive Emissions

\[ \alpha (\sim 0.03 \text{ mm}) \]

\[ \beta (\sim 2 \text{ mm}) \]

\[ \gamma (\sim 10 \text{ cm}) \]
Units of Radiation Dose

\[ \text{rad} = \text{Radiation-absorbed dose} \]

The quantity of energy absorbed per kilogram of tissue:  
\[ 1 \text{ rad} = 1 \times 10^{-2} \text{ J/kg} \]

\[ \text{rem} = \text{Roentgen equivalent for man} \]

The unit of radiation dose for a human:  
\[ 1 \text{ rem} = 1 \text{ rad} \times \text{RBE} \]

\[ \text{RBE} = 10 \text{ for } \alpha \]
\[ \text{RBE} = 1 \text{ for } x\text{-rays, } \gamma\text{-rays, and } \beta\text{'s} \]
## Examples of Typical Radiation Doses from Natural and Artificial Sources–I

<table>
<thead>
<tr>
<th>Source of Radiation</th>
<th>Average Adult Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Natural</strong></td>
<td></td>
</tr>
<tr>
<td>Cosmic radiation</td>
<td>30-50 mrem/yr</td>
</tr>
<tr>
<td>Radiation from the ground</td>
<td></td>
</tr>
<tr>
<td>From clay soil and rocks</td>
<td>~25-170 mrem/yr</td>
</tr>
<tr>
<td>In wooden houses</td>
<td>10-20 mrem/yr</td>
</tr>
<tr>
<td>In brick houses</td>
<td>60-70 mrem/yr</td>
</tr>
<tr>
<td>In light concrete houses</td>
<td>60-160 mrem/yr</td>
</tr>
<tr>
<td>Radiation from the air (mainly radon)</td>
<td></td>
</tr>
<tr>
<td>Outdoors, average value</td>
<td>20 mrem/yr</td>
</tr>
<tr>
<td>In wooden houses</td>
<td>70 mrem/yr</td>
</tr>
<tr>
<td>In brick houses</td>
<td>130 mrem/yr</td>
</tr>
<tr>
<td>In light concrete houses</td>
<td>260 mrem/yr</td>
</tr>
<tr>
<td>Internal radiation from minerals in tap water and daily intake of food ((^{40}\text{K},^{14}\text{C},\text{Ra}))</td>
<td>~40 mrem/yr</td>
</tr>
</tbody>
</table>

Table 24.7 (p. 1062)
# Examples of Typical Radiation Doses from Natural and Artificial Sources–II

<table>
<thead>
<tr>
<th>Source of Radiation</th>
<th>Average Adult Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Artificial</strong></td>
<td></td>
</tr>
<tr>
<td>Diagnostic x-ray methods</td>
<td></td>
</tr>
<tr>
<td>Lung (local)</td>
<td>0.04-0.2 rad/film</td>
</tr>
<tr>
<td>Kidney (local)</td>
<td>1.5-3.0 rad/film</td>
</tr>
<tr>
<td>Dental (dose to the skin)</td>
<td>≤ 1 rad/film</td>
</tr>
<tr>
<td>Therapeutic radiation treatment</td>
<td>locally ≤ 10,000 rad</td>
</tr>
<tr>
<td>Other sources</td>
<td></td>
</tr>
<tr>
<td>Jet flight (4 hr)</td>
<td>~1 mrem</td>
</tr>
<tr>
<td>Nuclear tests</td>
<td>&lt; 4 mrem/yr</td>
</tr>
<tr>
<td>Nuclear power industry</td>
<td>&lt; 1 mrem/yr</td>
</tr>
<tr>
<td><strong>Total Average Value</strong></td>
<td>100-200 mrem/yr</td>
</tr>
</tbody>
</table>

Table 24.7 (p. 1062)
## Acute Effects of a Single Dose of Whole-Body Irradiation–I

<table>
<thead>
<tr>
<th>Dose (rem)</th>
<th>Effect</th>
<th>Lethal Dose</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5-20</td>
<td>Possible late effect; possible chromosomal aberrations</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>20-100</td>
<td>Temporary reduction in white blood cells</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>50+</td>
<td>Temporary sterility in men (100+ rem = 1 yr duration)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>100-200</td>
<td>“Mild radiation sickness”: vomiting, diarrhea, tiredness in a few hours</td>
<td>Reduction in infection resistance Possible bone growth retardation in children</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 24.8 (p. 1063)
### Acute Effects of a Single Dose of Whole-Body Irradiation–II

<table>
<thead>
<tr>
<th>Dose (rem)</th>
<th>Effect</th>
<th>Lethal Dose</th>
<th>Population (%)</th>
<th>No. of Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>300+</td>
<td>Permanent sterility in women</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>500</td>
<td>“Serious radiation sickness”: marrow/intestine destruction</td>
<td>50-70</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>400-1000</td>
<td>Acute illness, early deaths</td>
<td>60-95</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>3000+</td>
<td>Acute illness, death in hours to days</td>
<td>100</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Table 24.8 (p. 1063)
24.6 Inter conversion of Mass and Energy

Nuclear Fission: A heavy nucleus splits into two lighter nuclei.

Nuclear Fusion: Two lighter nuclei combine to form a heavier one.

The Mass Defect ($\Delta m$) - The mass decrease that occurs when nucleons combine to form a nucleus.

The size of the mass change is nearly 10 million times that of bond breakage.
NUCLEAR ENERGY

• EINSTEIN’S EQUATION FOR THE CONVERSION OF MASS INTO ENERGY

  \[ E = mc^2 \]

  • \( m = \) mass (kg)
  
  • \( c = \) Speed of light

  \[ c = 2.998 \times 10^8 \text{ m/s} \]
Nuclear Binding Energy

Energy required to break up 1 mol of nuclei into their individual nucleons.

Nucleus + nuclear binding energy $\rightarrow$ nucleons

For $^{12}$C $\Delta E = \Delta mc^2$

$$= (9.894 \times 10^{-5}\text{kg/mol})(2.9979 \times 10^8\text{m/s})^2$$

$$= 8.8921 \times 10^{12}\text{ J/mol}$$
Figure 24.12: Variation in Binding Energy Per Nucleon

- Region of very stable nuclides
- Fusion
- Fission
Electron volt (ev)

The energy an electron acquires when it moves through a potential difference of one volt:

\[ 1 \text{ ev} = 1.602 \times 10^{-19} \text{J} \]

Binding energies are commonly expressed in units of *megaelectron volts* (Mev)

\[ 1 \text{ Mev} = 10^6 \text{ ev} = 1.602 \times 10^{-13} \text{J} \]

A particularly useful factor converts a given mass defect in atomic mass units to its energy equivalent in electron volts:

\[ 1 \text{ amu} = 931.5 \times 10^6 \text{ ev} = 931.5 \text{ Mev} \]
Deuterium has a mass of 2.01410178 amu.

Hydrogen atom = 1 x 1.007825 amu = 1.007825 amu
Neutrons = 1 x 1.008665 amu = 1.008665 amu

\[
\text{Mass difference} = \text{theoretical mass} - \text{actual mass} = 2.016490 \text{ amu} - 2.01410178 \text{ amu} = 0.002388 \text{ amu}
\]

Calculating the binding energy per nucleon:

\[
\begin{align*}
\text{Binding energy per nucleon} &= \frac{0.002388 \text{ amu} \times 931.5 \text{ Mev/amu}}{2 \text{ nucleons}} \\
&= 1.1123 \text{ Mev/nucleon}
\end{align*}
\]
Calculation of the Binding Energy per Nucleon for Iron-56

The mass of iron-56 is 55.934939 amu; it contains 26 protons and 30 neutrons.

\[ N = A - Z \]

Theoretical mass of Fe-56:

- Hydrogen atom mass \( = 26 \times 1.007825 \text{ amu} = 26.203450 \text{ amu} \)
- Neutron mass \( = 30 \times 1.008665 \text{ amu} = 30.259950 \text{ amu} \)

56.463400 amu

Mass defect = theoretical mass - actual mass:

56.463400 amu - 55.934939 amu = 0.528461 amu

Calculating the binding energy per nucleon:

\[
\frac{\text{Binding energy}}{\text{Nucleon}} = \frac{0.528461 \text{ amu} \times 931.5 \text{ Mev/amu}}{56 \text{ nucleons}}
\]

= 8.7904 Mev/nucleon
Calculation of the Binding Energy per Nucleon for Uranium-238

The actual mass of uranium-238 = 238.050785 amu; it has 92 protons and 146 neutrons.

\[ N = A - Z \]

Theoretical mass of uranium-238:

Hydrogen atom mass = 92 x 1.007825 amu = 92.719900 amu

Neutron mass = 146 x 1.008665 amu = 147.265090 amu

Mass defect = theoretical mass - actual mass:

239.98499 amu - 238.050785 amu = 1.934205 amu

Calculating the binding energy per nucleon:

\[
\frac{\text{Binding energy}}{\text{Nucleon}} = \frac{1.934205 \text{ amu} \times 931.5 \text{ Mev/amu}}{238 \text{ nucleons}}
\]

= 7.5702 Mev/nucleon
Consider the alpha decay of $^{212}\text{Po}$ 

$$^{212}\text{Po} \rightarrow ^{208}\text{Pb} + \alpha + \text{Energy}$$

$211.988842 \text{ g/mol}$  
$207.976627 \text{ g/mol} + 4.00151 \text{ g/mol}$

Products $= 207.976627 + 4.00151 = 211.97814 \text{ g/mol}$

Mass $= \text{Po} - \text{Pb} + \alpha = 211.988842 - 211.97814 = 0.01070 \text{ g/mol}$

$$E = mc^2 = (1.070 \times 10^{-5} \text{ kg/mol})(3.00 \times 10^8 \text{ m/s})^2$$

$= 9.63 \times 10^{11} \text{ J/mol}$

$$\frac{9.63 \times 10^{11} \text{ J/mol}}{6.022 \times 10^{23} \text{ atoms/mol}} = 1.60 \times 10^{-12} \text{ J/atom}$$
The energy for the decay of $^{212}$Po is $1.60 \times 10^{-12} \text{J/atom}$

\[
\frac{1.60 \times 10^{-12} \text{J/atom}}{1.602 \times 10^{-19} \text{J/ev}} = 1.00 \times 10^7 \text{ ev/atom}
\]

\[
\frac{10.0 \times 10^6 \text{ ev}}{\text{atom}} \times \frac{1.0 \times 10^{-6} \text{ Mev}}{\text{ev}} = 10.0 \text{ Mev/atom}
\]

The decay energy of the alpha particle from $^{212}$Po is 8.8 Mev.
Induced Fission of $^{235}\text{U}$
Fig. 24.14  Critical Mass: Mass needed to achieve a chain reaction.
A Light-Water Nuclear Reactor

1. Enriched uranium in fuel rods releases energy from fission
2. Control rods regulate rate of chain reaction
3. Extremely hot water under high pressure passes into steam generator
4. Steam produced operates turbine-generator
5. Cool water from nearby source condenses steam and is warmed

Fig. 24.15B
There are three isotopes with sufficiently long half-lives and significant fission cross-sections that are known to undergo neutron induced fission, and are useful in fission reactors, and nuclear weapons. Of these, only one exists on earth ($^{235}$U which exists at an abundance of 0.72% of natural uranium) and that is the isotope that we use in nuclear reactors for fuel and some weapons.

**The three isotopes are:**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$t_{1/2}$ (years)</th>
<th>Sigma Fission (barns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{233}$U</td>
<td>$1.59 \times 10^5$</td>
<td>531</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>$7.04 \times 10^8$</td>
<td>585</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>$2.44 \times 10^5$</td>
<td>750</td>
</tr>
</tbody>
</table>
Breeding Nuclear Fuel

There are two relatively common heavy isotopes that will not undergo neutron induced fission, that can be used to make other isotopes that do undergo neutron induced fission, and can be used as nuclear fuel in a nuclear reactor.

Natural thorium is $^{232}\text{Th}$ which is common in rocks.

$$^{232}\text{Th} + ^1_0\text{n} \rightarrow ^{233}\text{Th} + \text{Energy} \quad t_{1/2} = 22.3 \text{ min}$$

$$^{233}\text{Th} \rightarrow ^{233}\text{Pa} + \beta^- + \text{Energy} \quad t_{1/2} = 27.0 \text{ days}$$

$$^{233}\text{Pa} \rightarrow ^{233}\text{U} + \beta^- + \text{Energy} \quad t_{1/2} = 1.59 \times 10^5 \text{ years}$$

Natural uranium is $^{238}\text{U}$ which is common in rocks as well.

$$^{238}\text{U} + ^1_0\text{n} \rightarrow ^{239}\text{U} + \text{Energy} \quad t_{1/2} = 23.5 \text{ min}$$

$$^{239}\text{U} \rightarrow ^{239}\text{Np} + \beta^- + \text{Energy} \quad t_{1/2} = 2.36 \text{ days}$$

$$^{239}\text{Np} \rightarrow ^{239}\text{Pu} + \beta^- + \text{Energy} \quad t_{1/2} = 24400 \text{ years}$$
Hydrogen Burning in Stars and Nuclear Weapons

\[ ^1H + ^1H \rightarrow ^2H + \beta^+ + 1.4 \text{ Mev} \]
\[ ^1H + ^2H \rightarrow ^3\text{He} + 5.5 \text{ Mev} \]
\[ ^2H + ^2H \rightarrow ^3\text{He} + ^1\text{n} + 3.3 \text{ Mev} \]
\[ ^2H + ^2H \rightarrow ^3\text{H} + ^1H + 4.0 \text{ mev} \]
\[ ^2H + ^3\text{H} \rightarrow ^4\text{He} + ^1\text{n} + 17.6 \text{ Mev} \text{ Easiest!} \]
\[ ^2H + ^3\text{He} \rightarrow ^4\text{He} + ^1H + 18.3 \text{ Mev} \text{ Highest cross-section!} \]
\[ ^1H + ^7\text{Li} \rightarrow ^4\text{He} + ^4\text{He} + 17.3 \text{ Mev} \]
Helium Burning Reactions in Stars

\[ ^{12}\text{C} + ^{4}\text{He} \rightarrow ^{16}\text{O} \]
\[ ^{16}\text{O} + ^{4}\text{He} \rightarrow ^{20}\text{Ne} \]
\[ ^{20}\text{Ne} + ^{4}\text{He} \rightarrow ^{24}\text{Mg} \]
\[ ^{24}\text{Mg} + ^{4}\text{He} \rightarrow ^{28}\text{Si} \]
\[ ^{28}\text{Si} + ^{4}\text{He} \rightarrow ^{32}\text{S} \]
\[ ^{32}\text{S} + ^{4}\text{He} \rightarrow ^{36}\text{Ar} \]
\[ ^{36}\text{Ar} + ^{4}\text{He} \rightarrow ^{40}\text{Ca} \]
Element Synthesis in the Life Cycle of a Star

Fig. 24.C (p. 1077)
The Tokamak Design for Magnetic Containment of a Fusion Plasma

Fig. 24.16
24.42

\[ k = \frac{0.693}{t_{1/2}} = \frac{0.693}{1.6 \times 10^3 \text{ yr}} = -4.331 \times 10^{-4} \text{ yr}^{-1} \]

\[ \ln \frac{N_t}{N_o} = -kt \]

\[ t = \ln \left( \frac{0.185 \text{ g}}{2.50 \text{ g}} \right) / -4.33 \times 10^{-4} \text{ yr}^{-1} = 6.01 \times 10^5 \text{ yr} \]

24.44

\[ k = \frac{0.693}{5730 \text{ yr}} = 1.21 \times 10^{-4} \text{ yr}^{-1} \]

\[ t = \ln \left( \frac{N_t}{N_o} \right) / -k = \ln \left( \frac{0.735}{1.000} \right) / -1.21 \times 10^{-4} \text{ yr}^{-1} \]

\[ t = 2.54 \times 10^3 \text{ yr} \]