Chapter 31

Nuclear Energy; Effects and Uses of Radiation
Units of Chapter 31

• Nuclear Reactions and Transmutation of Elements
• Nuclear Fission; Nuclear Reactors
• Nuclear Fusion
• Radiation and Matter; Radiation Damage
• Measurement of Radiation – Dosimetry
• Radiation Therapy
• Imaging in Research and Medicine
Nuclear Reactions and Transmutation of Elements

A nuclear reaction can take place when a nucleus is struck by another nucleus or particle.

If the original nucleus is transformed into another, this is called transmutation.

An example:

\[ ^4_2\text{He} + ^{14}_7\text{N} \rightarrow ^{17}_8\text{O} + ^1_1\text{H} \]
Energy and momentum must be conserved in nuclear reactions.

Generic reaction: \[ a + X \rightarrow Y + b \]

The reaction energy, or \( Q \)-value, is the sum of the initial masses less the sum of the final masses, multiplied by \( c^2 \).

\[ Q = (M_a + M_X - M_b - M_Y)c^2 \]
Nuclear Reactions and Transmutation of Elements

If $Q$ is positive, the reaction is exothermic, and will occur no matter how small the initial kinetic energy is.

If $Q$ is negative, there is a minimum initial kinetic energy that must be available before the reaction can take place. The reaction will occur when the net energy available is positive.
Nuclear Reactions and Transmutation of Elements

Neutrons are very effective in nuclear reactions, since they have no charge and therefore are not repelled by the nucleus.

(a) \( n + ^{238}_{92}U \rightarrow ^{239}_{92}U \)

Neutron captured by \(^{238}_{92}U\).

(b) \(^{239}_{92}U \rightarrow ^{239}_{93}Np + e^- + \bar{\nu} \)

\(^{239}_{92}U\) decays by \(\beta\) decay to neptunium-239.

(c) \(^{239}_{93}Np \rightarrow ^{239}_{94}Pu + e^- + \bar{\nu} \)

\(^{239}_{93}Np\) itself decays by \(\beta\) decay to produce plutonium-239.
After absorbing a neutron, a Uranium-235 nucleus will split into two roughly equal parts.

Neutrons are released when a heavy nucleus splits into two much smaller nuclei. **Why?**

One way to visualize this is to view the nucleus as a kind of liquid drop.
Nuclear Fission; Nuclear Reactors

The mass distribution of the fragments shows that the two pieces are large, but usually unequal.
Nuclear Fission; Nuclear Reactors

The energy release in a fission reaction is quite large. Also, since smaller nuclei are stable with fewer neutrons, several neutrons emerge from each fission as well.

These neutrons can be used to induce fission in other nuclei, causing a chain reaction.
Nuclear Fission; Nuclear Reactors

In order to make a nuclear reactor, the chain reaction needs to be **self-sustaining** – it will continue indefinitely – but **controlled**.

A moderator is needed to slow the neutrons; otherwise their probability of interacting is too small. Common moderators are heavy water and graphite.

Unless the moderator is heavy water, the fraction of fissionable nuclei in natural uranium is too small to sustain a chain reaction, about 0.7%. It needs to be enriched to about 2-3%. 
Neutrons that escape from the uranium do not contribute to fission. There is a critical mass below which a chain reaction will not occur because too many neutrons escape.
Finally, there are control rods, usually cadmium or boron, that absorb neutrons and can be used for fine control of the reaction, to keep it critical but just barely.
Nuclear Fission; Nuclear Reactors

Some problems associated with nuclear reactors include the disposal of radioactive waste and the possibility of accidental release of radiation.

An atomic bomb also uses fission, but the ‘core’ is designed to undergo a massive uncontrolled chain reaction when the uranium is formed into a critical mass during the detonation process.
Nuclear Fusion

The lightest nuclei can fuse to form heavier nuclei, releasing energy in the process. An example is the sequence of fusion processes that change hydrogen into helium in the Sun. They are listed here with the energy (heat) released in each:

\[ ^1\text{H} + ^1\text{H} \rightarrow ^2\text{H} + \text{e}^+ + \nu \quad \text{(0.42 MeV)} \quad (31-6a) \]

\[ ^1\text{H} + ^2\text{H} \rightarrow ^3\text{He} + \gamma \quad \text{(5.49 MeV)} \quad (31-6b) \]

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + ^1\text{H} + ^1\text{H} \quad \text{(12.86 MeV)} \quad (31-6c) \]
Nuclear Fusion

The net effect is to transform four protons into a helium nucleus plus two positrons, two neutrinos, and two gamma rays.

\[ 4 \text{ } ^1_1\text{H} \rightarrow ^4_2\text{He} + 2e^+ + 2\nu + 2\gamma. \]

More massive stars can fuse heavier elements in their cores, all the way up to iron, which is the most stable nucleus.
Nuclear Fusion: Power Generation

There are three fusion reactions that are being considered for power reactors:

\[ ^2\text{H} + ^2\text{H} \rightarrow ^3\text{H} + ^1\text{H} \hspace{1cm} (4.03 \text{ MeV}) \hspace{1cm} (31-8a) \]

\[ ^2\text{H} + ^2\text{H} \rightarrow ^3\text{He} + n \hspace{1cm} (3.27 \text{ MeV}) \hspace{1cm} (31-8b) \]

\[ ^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + n \hspace{1cm} (17.59 \text{ MeV}) \hspace{1cm} (31-8c) \]

These reactions use very common fuels – deuterium or tritium – and release much more energy per nucleon than fission does.
Nuclear Fusion

A successful controlled fusion reaction has not yet been achieved; but fusion based weapons exist, commonly called a hydrogen bomb - or to sound less threatening, a ‘thermonuclear device’.

Problem is control of a ‘small scale’ fusion reaction. Several geometries for the containment of the incredibly hot plasma (temperature of sun’s surface) that exists in a fusion reactor are being developed – the tokamak, which is a torus that can create magnetic confinement; or inertial confinement, tiny pellets of deuterium ignited by powerful lasers.
Passage of Radiation Through Matter; Radiation Damage

Radiation includes alpha, beta, and gamma rays; X rays; and protons, neutrons, pions, and other short-lived particles that can be created artificially.

All these are called ionizing radiation, because they ionize material that they go through.

This ionization can cause damage to materials, including biological tissue.
Measurement of Radiation – Dosimetry

Radiation damages biological tissue, but it can also be used to treat cancer and other diseases.

It is important to be able to measure the amount, or dose, of radiation received. The source activity is the number of disintegrations per second, often measured in curies, Ci.

\[ 1 \text{ Ci} = 3.70 \times 10^{10} \text{ disintegrations per second} \]

The SI unit for source activity is the becquerel (Bq):

\[ 1 \text{ Bq} = 1 \text{ disintegration/s} \]
Measurement of Radiation – Dosimetry

Another measurement is the ‘absorbed dose’ – the effect the radiation has on the absorbing material.

The rad, a unit of dosage, is the amount of radiation that deposits energy at a rate of $1.00 \times 10^{-2} \text{ J/kg}$ in any material.

The SI unit for dose is the gray, Gy:

$1 \text{ Gy} = 1 \text{ J/kg} = 100 \text{ rad}$
The effect on tissue of different types of radiation varies; alpha rays are the most damaging.

To define the ‘absorbed dose’, the actual dose is multiplied by a quality factor that is related to how much damage each one causes.

<table>
<thead>
<tr>
<th>TABLE 31–1</th>
<th>Quality Factor (QF) of Different Kinds of Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>QF</td>
</tr>
<tr>
<td>X- and γ rays</td>
<td>1</td>
</tr>
<tr>
<td>β (electrons)</td>
<td>≈ 1</td>
</tr>
<tr>
<td>Fast protons</td>
<td>1</td>
</tr>
<tr>
<td>Slow neutrons</td>
<td>≈ 3</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>Up to 10</td>
</tr>
<tr>
<td>α particles and heavy ions</td>
<td>Up to 20</td>
</tr>
</tbody>
</table>

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Measurement of Radiation – Dosimetry

If the dose is in \textit{rad}, the effective dose is in \textit{rem};
or dose in \textit{grays}, effective dose in \textit{sieverts}, \textit{Sv}.

Natural background radiation is \(\sim 0.3\) rem per year.
The maximum allowed for radiation workers is \(5\) rem in one year, and \(10\) rem over 5 years.

A short dose of 1000 rem is almost always fatal; a short dose of 400 rem has about a 50% fatality rate.
### Various Medical Imaging Techniques

Here is a summary of the medical imaging techniques discussed in the Textbook.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Where Discussed in This Book</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional X-ray</td>
<td>Section 25–12</td>
<td>$\frac{1}{2}$ mm</td>
</tr>
<tr>
<td>CT scan, X-ray</td>
<td>Section 25–12</td>
<td>$\frac{1}{2}$ mm</td>
</tr>
<tr>
<td>Nuclear medicine (tracers)</td>
<td>Section 31–7</td>
<td>1 cm</td>
</tr>
<tr>
<td>SPET (single photon emission)</td>
<td>Section 31–8</td>
<td>1 cm</td>
</tr>
<tr>
<td>PET (positron emission)</td>
<td>Section 31–8</td>
<td>3–5 mm</td>
</tr>
<tr>
<td>NMR</td>
<td>Section 31–9</td>
<td>$\frac{1}{2}$–1 mm</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>Section 12–9</td>
<td>2 mm</td>
</tr>
</tbody>
</table>
Summary of Chapter 31

- Nuclear reaction occurs when nuclei collide and different nuclei are produced.

- Reaction energy or Q-value:

  \[ a + X \rightarrow Y + b \]

  \[ Q = (M_a + M_X - M_b - M_Y)c^2 \]

- Fission: a heavy nucleus splits into two intermediate-sized nuclei.

- Chain reaction: neutrons emitted in one fission reaction trigger another, and so on.

- Critical mass: minimum to sustain chain reaction.
Summary of Chapter 31

• **Moderator:** material used to slow neutrons in reactor

• **Fusion:** small nuclei combine to form larger ones

• Sun’s energy comes from fusion reactions

• Useful fusion reactors have not yet been built, Optimists claim about 30 - 50 years away

• Radiation damage is measured using dosimetry

• Effect of absorbed dose depends on type of radiation