Chapter 32

Nuclear Physics and Nuclear Radiation
Overview of Chapter 32

• The Constituents and Structure of Nuclei
• Radioactivity
• Half-Life and Radioactive Dating
• Nuclear Binding Energy
• Nuclear Fission
• Nuclear Fusion
• Practical Applications of Nuclear Physics
• Elementary Particles
32-1 The Constituents and Structure of Nuclei

- Nuclei contain positively charged protons and neutral neutrons.

- Characterized by the number of protons and neutrons they contain…

<table>
<thead>
<tr>
<th>TABLE 32–1</th>
<th>Numbers That Characterize a Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$</td>
<td>Atomic number = number of protons in nucleus</td>
</tr>
<tr>
<td>$N$</td>
<td>Neutron number = number of neutrons in nucleus</td>
</tr>
<tr>
<td>$A$</td>
<td>Mass number = number of nucleons in nucleus</td>
</tr>
</tbody>
</table>

$$A = Z + N$$
32-1 The Constituents and Structure of Nuclei

Notation for a particular nucleus of element $X$ is written:

$$\frac{A}{Z}X$$

E.g…

$^{14}_{6}C$  $^{27}_{13}Al$

### TABLE 32–2 Mass and Charge of Particles in the Atom

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (kg)</th>
<th>Mass (MeV/c²)</th>
<th>Mass (u)</th>
<th>Charge (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>$1.672623 \times 10^{-27}$</td>
<td>938.28</td>
<td>1.007276</td>
<td>$+1.6022 \times 10^{-19}$</td>
</tr>
<tr>
<td>Neutron</td>
<td>$1.674929 \times 10^{-27}$</td>
<td>939.57</td>
<td>1.008665</td>
<td>0</td>
</tr>
<tr>
<td>Electron</td>
<td>$9.109390 \times 10^{-31}$</td>
<td>0.511</td>
<td>0.0005485799</td>
<td>$-1.6022 \times 10^{-19}$</td>
</tr>
</tbody>
</table>
32-1 The Constituents and Structure of Nuclei

The atomic mass unit, u, is defined so the mass of $^{12}_6\text{C}$ is exactly 12 u.

**Definition of Atomic Mass Unit, u**

$$1 \text{ u} = 1.660540 \times 10^{-27} \text{ kg}$$

SI unit: kg

This mass may also be written in terms of MeV/$c^2$, using $E = mc^2$:

$$1 \text{ u} = 931.5 \text{ MeV} / c^2$$

Energy Unit

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$
• Measurements have related the size of the nucleus to its atomic number:

\[ r = (1.2 \times 10^{-15} \text{ m}) A^{1/3} \]

• In contrast, radius of an atom is on the order of 10^{-10} m.
  - Means density of the nucleus is extremely high.

• For convenience, we define:

  **Definition of the Fermi, fm**

  1 fermi = 1 fm = 10^{-15} m

  SI unit: m
32-1 The Constituents and Structure of Nuclei

- If the nucleus contains only positive charges, why doesn’t it fly apart due to their mutual repulsion?
  - Another force acting, called the **strong nuclear force**
  - Keeps **nucleus together**...

- Its properties?
  - **Strong force is short range**, acting only to distances of a couple fm.
  - **Always attractive**…
  - Acts with nearly **equal strength** between proton-proton, proton-neutron, and neutron-neutron…
Here is how number of neutrons in a nucleus depend on the number of protons...
Unstable nuclei can either decay into a stable nucleus of different $N$ and $Z$, or can return to the ground state from an excited state. Three different types of decay particles:

1. **Alpha particles**, which consist of two neutrons and two protons, and are nuclei of $^4_2\text{He}$

2. **Electrons and positrons**, also called (for historical reasons) beta rays. Positrons have the same mass as electrons but are positively charged.

3. **Gamma rays**, which are high-energy photons.
32-2 Radioactivity

Penetrating abilities:

- Alpha, $\alpha$, rays can barely penetrate a sheet of paper.

- Beta, $\beta$ rays (both $\beta^-$ and $\beta^+$) can penetrate a few millimeters of aluminum.

- Gamma, $\gamma$ rays can penetrate several centimeters of lead.
32-2 Radioactivity

When a nucleus decays by emitting an alpha particle, it loses two protons and two neutrons. Can write this as:

\[ ^{A\,X}_{Z\,X} \rightarrow ^{A-4\,Y}_{Z-2\,Y} + ^{4\,He}_{2\,He} \]

Here, \( X \) is the parent nucleus and \( Y \) is the daughter.
32-2 Radioactivity

The basic process in beta decay converts a neutron into a proton and an electron:

\[ _0^1n \rightarrow _1^1p + e^- \]

Therefore, a nucleus that decays via beta decay loses a neutron and gains a proton.

\[ _Z^A X \rightarrow _{Z+1}^A Y + e^- \]

If a nucleus emits a positron, a proton has become a neutron:

\[ _Z^A X \rightarrow _{Z-1}^A Y + e^+ \]
32-2 Radioactivity

• **Gamma ray is emitted** when an excited nucleus returns to its ground state from an excited state.

• **Nuclei may become excited through alpha or beta decay**, leading to a sequence such as this one:

\[ ^{14}_{6}\text{C} \rightarrow ^{14}_{7}\text{N}^{\ast} + e^{-} + \bar{\nu}_{e} \]

\[ ^{14}_{7}\text{N}^{\ast} \rightarrow ^{14}_{7}\text{N} + \gamma \]

• **Asterisk** indicates the excited nucleus...
32-2 Radioactivity

- Heavy nuclei decaying via alpha emission may very well decay to a daughter nucleus which is also unstable...
- Same can happen again...
- Decays will continue until a stable nucleus is reached.
Some nuclei decay more rapidly than others. The rate of decay – the number of decays per second – is called the activity.

Two units of activity:

\[
1 \text{ curie} = 1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays/s}
\]

\[
1 \text{ becquerel} = 1 \text{ Bq} = 1 \text{ decay/s}
\]

The curie (and the millicurie and micro-curie) are most commonly used.
Nuclear decay is a random process, in that we do not know which nucleus will decay at what time.

However, if we have a large number of similar nuclei, we can predict the decay rate...

Number of nuclei that haven’t decayed (i.e. remain radioactive) after time $t$ is:

$$N = N_0 e^{-\lambda t}$$

$N_0$ is initial number of radioactive particles…
Different nuclei have different decay constants $\lambda$. A larger decay constant means the material decays away more rapidly.
32-3 Half-Life and Radioactive Dating

• Nuclear decay can also be characterized by the half-life
  - Time it takes for half a sample to decay away.

• Half-life is related to the decay constant via:

\[ T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \]

The decay rate, or activity, is also related to the decay constant:

\[ R = \left| \frac{\Delta N}{\Delta t} \right| = \lambda N \]
32-3 Half-Life and Radioactive Dating

• The activity as a function of time:

\[ R = \lambda N_0 e^{-\lambda t} = R_0 e^{-\lambda t} \]

• This change in activity can be used in carbon-14 dating of organic materials....
32-4 Nuclear Binding Energy

• Mass of any stable nucleus is less than the sum of the masses of the protons and neutrons it contains.…

• This difference, multiplied by $c^2$, is called the binding energy…

• Can also be expressed as the binding energy per nucleon…
32-4 Nuclear Binding Energy

![Graph showing the binding energy per nucleon as a function of mass number. The graph includes labeled points for isotopes of various elements, such as \(_{1}^{2}\text{H}\), \(_{6}^{12}\text{C}\), \(_{8}^{16}\text{O}\), \(_{13}^{27}\text{Al}\), \(_{26}^{56}\text{Fe}\), \(_{33}^{75}\text{As}\), \(_{53}^{127}\text{I}\), \(_{65}^{159}\text{Tb}\), \(_{83}^{209}\text{Bi}\), and \(_{92}^{238}\text{U}\).]
32-5 Nuclear Fission

- Nuclear fission occurs when a heavy nucleus splits into two lighter ones, especially after capturing a neutron.

- Lighter nuclei do not need so many neutrons.

- …so there are **typically extra neutrons emitted** from the reaction….
32-5 Nuclear Fission

This emission of multiple neutrons can lead to a chain reaction, either controlled or uncontrolled.
32-6 Nuclear Fusion

• **Very light nuclei** can combine to form a heavier nucleus with greater binding energy:
  - Smaller mass per nucleon
  - Energy is therefore released...

• Can only occur at extremely **high temperatures**
  - Nuclei must be moving fast enough to overcome the electrical repulsion...

• Such temperatures are available in the **center of the Sun and other stars**; nuclear fusion is what powers them...
Nuclear fusion process in the Sun begins with two protons fusing to form deuterium, and then fusing with a third proton to form helium-3…. 

\[ \frac{1}{1}\text{H} + \frac{1}{1}\text{H} \rightarrow \frac{2}{1}\text{H} + e^+ + \nu_e \]
\[ \frac{1}{1}\text{H} + \frac{2}{1}\text{H} \rightarrow \frac{3}{2}\text{He} + \gamma \]

After that, a helium-4 nucleus is formed in one of the following two ways:

\[ \frac{1}{1}\text{H} + \frac{3}{2}\text{He} \rightarrow \frac{4}{2}\text{He} + e^+ + \nu_e \]
\[ \frac{3}{2}\text{He} + \frac{3}{2}\text{He} \rightarrow \frac{4}{2}\text{He} + \frac{1}{1}\text{H} + \frac{1}{1}\text{H} \]

Considerable energy is emitted in this interaction…
Nuclear radiation can be beneficial if used properly, but can also cause tissue damage. There are different ways of measuring this damage.

The first is by measuring the amount of ionization; the roentgen is the dosage that creates $2.58 \times 10^{-4}$ C when passing through 1 kg of matter.

**Definition of the Roentgen, R**

\[ 1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg} \quad (\text{X-rays or } \gamma \text{ rays in dry air at STP}) \]

SI unit: C/kg
Another measure is the amount of energy absorbed by the irradiated material:

**Definition of the Rad**

\[ 1 \text{ rad} = 0.01 \text{ J/kg} \quad \text{(any type of radiation)} \]

SI unit: J/kg

However, the same amount of energy of different types of radiation can have different biological effects.
In order to quantify these differences, we define the relative biological effectiveness:

**Definition of Relative Biological Effectiveness, RBE**

\[
RBE = \frac{\text{the dose of 200-keV X-rays necessary to produce a given biological effect}}{\text{the dose of a particular type of radiation necessary to produce the same biological effect}}
\]

SI unit: dimensionless
The RBE for different types of radiation:

<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>RBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy ions</td>
<td>20</td>
</tr>
<tr>
<td>$\alpha$ rays</td>
<td>10–20</td>
</tr>
<tr>
<td>Protons</td>
<td>10</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>10</td>
</tr>
<tr>
<td>Slow neutrons</td>
<td>4–5</td>
</tr>
<tr>
<td>$\beta$ rays</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>$\gamma$ rays</td>
<td>1</td>
</tr>
<tr>
<td>200-keV X-rays</td>
<td>1</td>
</tr>
</tbody>
</table>
32-7 Practical Applications of Nuclear Physics

This can be combined with the dose to give the biologically equivalent dose, measured in rem (roentgen equivalent in man).

**Definition of Roentgen Equivalent in Man, rem**

\[
dose \text{ in } \text{rem} = \text{dose in rad} \times \text{RBE}
\]

SI unit: J/kg
32-7 Practical Applications of Nuclear Physics

We receive some radiation from natural and manufactured sources every year.

<table>
<thead>
<tr>
<th>TABLE 32–4 Typical Radiation Dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of radiation</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Inhaled radon</td>
</tr>
<tr>
<td>Medical/dental examinations</td>
</tr>
<tr>
<td>Cosmic rays</td>
</tr>
<tr>
<td>Natural radioactivity in the Earth and atmosphere</td>
</tr>
<tr>
<td>Nuclear medicine</td>
</tr>
</tbody>
</table>
There are a number of medical applications for radioactivity:

- Radioactive tracers are useful in diagnoses

- PET scans (positron-emission tomography) are useful in looking at the brain, including normal activity, abnormalities, and tumors

- Magnetic resonance imaging (MRI) is particularly good at imaging soft tissue
32-8 Elementary Particles

All forces of nature are manifestations of just four fundamental forces:

<table>
<thead>
<tr>
<th>Force</th>
<th>Relative Strength</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>1</td>
<td>$\approx 1\text{ fm}$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>$10^{-2}$</td>
<td>Infinite ($\propto 1/r^2$)</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-6}$</td>
<td>$\approx 10^{-3}\text{ fm}$</td>
</tr>
<tr>
<td>Gravitational</td>
<td>$10^{-43}$</td>
<td>Infinite ($\propto 1/r^2$)</td>
</tr>
</tbody>
</table>

The only one we have not discussed so far is the weak force; it is the one responsible for beta decay.
There are two kinds of fundamental particles, leptons and hadrons. **Leptons** interact only via the electromagnetic force (if charged) and the weak force. These are the known leptons:

<table>
<thead>
<tr>
<th>Particle</th>
<th>Particle Symbol</th>
<th>Antiparticle Symbol</th>
<th>Rest Energy (MeV)</th>
<th>Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e^-$ or $\beta^-$</td>
<td>$e^+$ or $\beta^+$</td>
<td>0.511</td>
<td>Stable</td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu^-$</td>
<td>$\mu^+$</td>
<td>105.7</td>
<td>$2.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Tau</td>
<td>$\tau^-$</td>
<td>$\tau^+$</td>
<td>1784</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>Electron neutrino</td>
<td>$\nu_e$</td>
<td>$\bar{\nu}_e$</td>
<td>$\approx 0$</td>
<td>Stable</td>
</tr>
<tr>
<td>Muon neutrino</td>
<td>$\nu_\mu$</td>
<td>$\bar{\nu}_\mu$</td>
<td>$\approx 0$</td>
<td>Stable</td>
</tr>
<tr>
<td>Tau neutrino</td>
<td>$\nu_\tau$</td>
<td>$\bar{\nu}_\tau$</td>
<td>$\approx 0$</td>
<td>Stable</td>
</tr>
</tbody>
</table>
**32-8 Elementary Particles**

Hadrons are particles that interact strongly. They come in two varieties, baryons and mesons. Protons and neutrons are baryons.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Particle Symbol</th>
<th>Antiparticle Symbol</th>
<th>Rest Energy (MeV)</th>
<th>Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BARYONS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton</td>
<td>( p )</td>
<td>( \bar{p} )</td>
<td>938.3</td>
<td>Stable</td>
</tr>
<tr>
<td>Neutron</td>
<td>( n )</td>
<td>( \bar{n} )</td>
<td>939.6</td>
<td>900</td>
</tr>
<tr>
<td>Sigma</td>
<td>( \Sigma^+ )</td>
<td>( \bar{\Sigma}^- )</td>
<td>1189</td>
<td>( 0.8 \times 10^{-10} )</td>
</tr>
<tr>
<td></td>
<td>( \Sigma^0 )</td>
<td>( \bar{\Sigma}^0 )</td>
<td>1192</td>
<td>( 6 \times 10^{-20} )</td>
</tr>
<tr>
<td></td>
<td>( \Sigma^- )</td>
<td>( \bar{\Sigma}^+ )</td>
<td>1197</td>
<td>( 1.6 \times 10^{-10} )</td>
</tr>
<tr>
<td>Omega</td>
<td>( \Omega^- )</td>
<td>( \Omega^+ )</td>
<td>1672</td>
<td>( 0.8 \times 10^{-10} )</td>
</tr>
</tbody>
</table>
Mesons are created by cosmic rays and in particle accelerators.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Particle Symbol</th>
<th>Antiparticle Symbol</th>
<th>Rest Energy (MeV)</th>
<th>Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion</td>
<td>$\pi^+$</td>
<td>$\pi^-$</td>
<td>139.6</td>
<td>$2.6 \times 10^{-8}$</td>
</tr>
<tr>
<td></td>
<td>$\pi^0$</td>
<td>$\pi^0$</td>
<td>135.0</td>
<td>$0.8 \times 10^{-16}$</td>
</tr>
<tr>
<td>Kaon</td>
<td>$K^+$</td>
<td>$K^-$</td>
<td>493.7</td>
<td>$1.2 \times 10^{-8}$</td>
</tr>
<tr>
<td></td>
<td>$K_S^0$</td>
<td>$\bar{K}_S^0$</td>
<td>497.7</td>
<td>$0.9 \times 10^{-10}$</td>
</tr>
<tr>
<td></td>
<td>$K_L^0$</td>
<td>$\bar{K}_L^0$</td>
<td>497.7</td>
<td>$5.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>Eta</td>
<td>$\eta^0$</td>
<td>$\eta^0$</td>
<td>548.8</td>
<td>$&lt;10^{-18}$</td>
</tr>
</tbody>
</table>

Leptons appear to have no internal structure. The same is not true of hadrons, however.
It is now known that hadrons are made of point-like particles called quarks.

A meson is a quark plus an antiquark; a baryon is three quarks.
32-8 Elementary Particles

These are the known quarks and antiquarks:

<table>
<thead>
<tr>
<th>Name</th>
<th>Rest Energy (MeV)</th>
<th>Symbol</th>
<th>Charge</th>
<th>Symbol</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>360</td>
<td>u</td>
<td>$+\frac{2}{3}e$</td>
<td>$\bar{u}$</td>
<td>$-\frac{2}{3}e$</td>
</tr>
<tr>
<td>Down</td>
<td>360</td>
<td>d</td>
<td>$-\frac{1}{3}e$</td>
<td>$\bar{d}$</td>
<td>$+\frac{1}{3}e$</td>
</tr>
<tr>
<td>Charmed</td>
<td>1500</td>
<td>c</td>
<td>$+\frac{2}{3}e$</td>
<td>$\bar{c}$</td>
<td>$-\frac{2}{3}e$</td>
</tr>
<tr>
<td>Strange</td>
<td>540</td>
<td>s</td>
<td>$-\frac{1}{3}e$</td>
<td>$\bar{s}$</td>
<td>$+\frac{1}{3}e$</td>
</tr>
<tr>
<td>Top</td>
<td>173,000</td>
<td>t</td>
<td>$+\frac{2}{3}e$</td>
<td>$\bar{t}$</td>
<td>$-\frac{2}{3}e$</td>
</tr>
<tr>
<td>Bottom</td>
<td>5000</td>
<td>b</td>
<td>$-\frac{1}{3}e$</td>
<td>$\bar{b}$</td>
<td>$+\frac{1}{3}e$</td>
</tr>
</tbody>
</table>

Quarks cannot exist on their own; they are always found as bound states, either baryons or mesons.
And finally…
2. Identify $Z$, $N$, and $A$ for the following isotopes: (a) $^{202}_{80}$Hg, (b) $^{220}_{86}$Rn, (c) $^{93}_{41}$Nb.

Answer: a) $Z = 80$, $N = 122$, $A = 202$

Answer: b) $Z = 86$, $N = 134$, $A = 220$

Answer: c) $Z = 41$, $N = 52$, $A = 93$
4. A certain chlorine nucleus has a radius of approximately $4.0 \times 10^{-15}$ m. How many neutrons are in this nucleus?

Answer: $N = 20$
18. • Complete the following nuclear reaction:

\[ ? \rightarrow ^{14}_7 \text{N} + e^- + \bar{\nu} \]

Answer: $^{14}_6 \text{C}$
24. Find the energy released when $^{211}_{82}\text{Pb}$ undergoes $\beta^-$ decay to become $^{211}_{83}\text{Bi}$. Be sure to take into account the mass of the electrons associated with the neutral atoms.

Answer: 1.38 MeV
32. The half-life of \(^{15}\text{O}\) is 122 s. How long does it take for the number of \(^{15}\text{O}\) nuclei in a given sample to decrease by a factor of \(10^{-4}\)?

Answer: 1621 s
42. • The atomic mass of lithium-7 is 7.016003 u. How much energy is required to completely separate the nucleons in a lithium-7 nucleus?

Answer: 39.25 MeV
56. ⋅⋅ (a) Complete the following fusion reaction and determine the energy it releases:

\[ ^2_1H + ^3_1H \rightarrow ? + ^1_0n \]

(b) How many of these reactions must occur per second to produce a power output of 25 MW?

Answer: a) \(^4_2\text{He}\) and 17.589 MeV
Answer: b) \(8.9 \times 10^{18} \text{ s}^{-1}\)