Lecture 1

Introduction to Nuclear Science
Composition of atoms

- Atoms are composed of electrons and nuclei.
- The electrons are held in the atom by a Coulomb attraction between the positively charged nucleus and the negatively charged electrons.
- The electrons are in restricted regions of space around the nucleus referred to as orbitals.
  (Planetary model of the atom)
Composition of nuclei

• Nuclei are composed of protons (Z of them) and neutrons (N of them). The protons have a charge of +1, the neutrons have no charge. Each has a mass of about 1 amu.

• Neutrons and protons are referred to collectively as nucleons.

• In a nucleus there are A nucleons where \( A = N + Z \)

• Since each nucleon has a mass of about 1 amu (1.66x10\(^{-24}\) g), the mass of a nucleus is about A amu.
Nomenclature

- Nuclei are referred to by a shorthand notation, $Z^A_{\text{Chem}}$ symbol $^N$.
- A nucleus with 6 protons and 8 neutrons is $^6_{14}C_8$, or just $^{14}C$. 
Sizes

- The radii of atoms are $1-10 \times 10^{-8}$ cm.
- The radii of nuclei are $1-10 \times 10^{-13}$ cm.
- A rough rule for the radii of nuclei is $R = 1.2A^{1/3} \times 10^{-13}$ cm.
Nuclear density

- density = mass/volume
- \( \text{density}_{\text{nucleus}} = \frac{\text{mass}_{\text{nucleus}}}{\text{volume}_{\text{nucleus}}} \)
- \( \text{mass} = A \text{ amu} = A \times 1.66 \times 10^{-24} \text{g} \)
- \( \text{volume} = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi (1.2A^{1/3})^3 \times 10^{-39} \text{cm}^3 \)
- note density independent of \( A \)

- **density \sim 200,000 \text{ tonnes/mm}^3**

- That is what nuclear weapons and nuclear power are all about!!
Radioactivity

• What causes something to be radioactive?
• Nuclei emit radiation spontaneously because it is energetically favorable for them to do so. In radioactive decay, the nucleus goes from a less stable energy state to a more stable state.
Types of Radioactive Decay

**Alpha decay (α)**

- Decay by the emission of doubly charged helium nuclei $^4\text{He}^{2+}$.
- $^{238}\text{U} \rightarrow ^{234}\text{Th} + ^4\text{He}$
- $\Delta Z = -2, \Delta N=-2, \Delta A=-4$
- All nuclei with $Z \geq 83$ decay by $\alpha$-decay as do some rare earth nuclei.
Alpha Decay

• The emitted α-particles are monoenergetic, ranging in energy from 4-11 MeV.

• They can be stopped by a piece of paper and are thus an internal radiation hazard rather than an external hazard.

• The naturally occurring α-emitters form long series of nuclei that decay to one another. Some of these naturally occurring decays series involve isotopes of Rn, a gas.
Beta -decay

• Beta decay is a term used to describe three types of decay in which a nuclear neutron (proton) changes into a nuclear proton (neutron). The decay modes are $\beta^-$, $\beta^+$ and electron capture (EC).

• $\beta^-$ decay involves the change of a nuclear neutron into a proton and is found in nuclei with a larger than stable number of neutrons relative to protons, such as fission fragments.

• An example of $\beta^-$ decay is

\[ ^{14}C \rightarrow ^{14}N + \beta^- + \bar{\nu}_e \]
Beta decay (cont)

• In $\beta^-$ decay, $\Delta Z = +1$, $\Delta N = -1$, $\Delta A = 0$
• Most of the energy emitted in the decay appears in the rest and kinetic energy of the emitted electron ($\beta^-$) and the emitted anti-electron neutrino,
• The decay energy is shared between the emitted electron and neutrino.
• $\beta^-$ decay is seen in all neutron-rich nuclei
• The emitted $\beta^-$ are easily stopped by a thin sheet of Al
• The second type of beta decay is $\beta^+$ (positron) decay.
• In this decay, $\Delta Z = -1$, $\Delta N = +1$, $\Delta A = 0$, i.e., a nuclear proton changes into a nuclear neutron with the emission of a positron, $\beta^+$, and an electron neutrino, $\nu_e$
• An example of this decay is
  \[ ^{22}\text{Na} \rightarrow ^{22}\text{Ne} + \beta^+ + \nu_e \]
• Like $\beta^-$ decay, in $\beta^+$ decay, the decay energy is shared between the residual nucleus, the emitted positron and the electron neutrino.
• $\beta^+$ decay occurs in nuclei with larger than normal p/n ratios. It is restricted to the lighter elements
• $\beta^+$ particles annihilate when they contact ordinary matter with the emission of two 0.511 MeV photons.
Beta decay (cont)

• The third type of beta decay is electron capture (EC) decay. In EC decay an orbital electron is captured by a nuclear proton changing it into a nuclear neutron with the emission of a electron neutrino.

• An example of this type of decay is

\[ e^- + ^{209}Bi \rightarrow ^{209}Pb + \nu_e \]

• The occurrence of this decay is detected by the emitted X-ray (from the vacancy in the electron shell).

• It is the preferred decay mode for proton-rich heavy nuclei.
Electromagnetic decay

- There are two types of electromagnetic decay, γ-ray emission and internal conversion (IC). In both of these decays \( \Delta N = \Delta Z = \Delta A = 0 \), with just a lowering of the excitation energy of the nucleus.
- In γ-ray emission, most of the emitted energy appears in the form of a photon.
- These emitted photons are mono-energetic and have an energy corresponding to almost all of the energy difference between the final and initial state of the system. This is typically depicted as
Electromagnetic decay (cont.)

- $\gamma$-rays are the most penetrating nuclear radiation and to attenuate them requires massive shielding. They represent an external radiation hazard.

- An example of a $\gamma$-emitter is $^{60}$Co. $^{60}$Co is longer lived nuclide ($t_{1/2} = 5.3$ y) that emits $\beta^-$ particles, that populate the excited states of $^{60}$Ni, which emits two $\gamma$-rays of energy, 1.17 and 1.33 MeV. This nuclide can be created in an “Doomsday machine”, (Dr. Strangelove) with disastrous consequences.

- The second type of electromagnetic decay is internal conversion. In IC decay, the emitted energy is transferred (radiationlessly) to an orbital electron, ejecting that electron which carries away most of the decay energy.
Radioactive decay kinetics

• The concept of a half-life, $t_{1/2}$
Decay equations

There are two equations, with differing meanings, that describe radioactive decay

\[ N(t) = N_0 e^{-\lambda t} \]
\[ A(t) = A_0 e^{-\lambda t} \]

where the decay constant, \( \lambda \), is given by

\[ \lambda = \frac{\ln(2)}{t_{1/2}} \]

These equations are related by the relationship

\[ A = \lambda N \]
## Types of Forces

<table>
<thead>
<tr>
<th>Force</th>
<th>Range (m)</th>
<th>Relative Strength</th>
<th>Force Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational</td>
<td>$\infty$</td>
<td>$10^{-38}$</td>
<td>Graviton</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-18}$</td>
<td>$10^{-5}$</td>
<td>$W^\pm, Z^0$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>$\infty$</td>
<td>$\alpha=1/137$</td>
<td>Photon</td>
</tr>
<tr>
<td>Strong</td>
<td>$10^{-15}$</td>
<td>1</td>
<td>Gluon</td>
</tr>
</tbody>
</table>
Exchange Particles and Force Carriers

Forces occur through the notion of the virtual exchange of bosons that are force carriers

\[ \Delta t = \frac{\hbar}{\Delta E} \]
PARTICLES OF FORCE

BOSONS

At the quantum level, each force of nature is transmitted by a dedicated particle or set of particles.

PHOTON
Electric charge: 0
Mass: 0
Carrier of electromagnetism, the quantum of light acts on electrically charged particles. It acts over unlimited distances.

Z BOSON
Electric charge: 0
Mass: 91 GeV
Mediator of weak reactions that do not change the identity of particles. Its range is only about $10^{-14}$ meter.

W^+/-W^- BOSONS
Electric charge: +1 or -1
Mass: 80.4 GeV
Mediators of weak reactions that change particle flavor and charge. Their range is only about $10^{-18}$ meter.

GLUONS
Electric charge: 0
Mass: 0
Eight species of gluons carry the strong interaction, acting on quarks and on other gluons. They do not feel electromagnetic or weak interactions.

HIGGS (not yet observed)
Electric charge: 0
Mass: Expected below 1 TeV, most likely between 114 and 192 GeV.
Believed to endow W and Z bosons, quarks and leptons with mass.
HOW THE FORCES ACT

An interaction among several colliding particles can change their energy, momentum or type. An interaction can even cause a single particle in isolation to decay spontaneously.

STRONG INTERACTION
The strong force acts on quarks and gluons. It binds them together to form protons, neutrons and more. Indirectly, it also binds protons and neutrons into atomic nuclei.

WEAK INTERACTION
The weak interaction acts on quarks and leptons. Its best-known effect is to transmute a down quark into an up quark, which in turn causes a neutron to become a proton plus an electron and a neutrino.

ELECTROMAGNETIC INTERACTION
The electromagnetic interaction acts on charged particles, leaving the particles unchanged. It causes like-charged particles to repel.

HIGGS INTERACTION
The Higgs field (gray background) is thought to fill space like a fluid,impeding the W and Z bosons and thereby limiting the range of weak interactions. The Higgs also interacts with quarks and leptons, endowing them with mass.
Structure within the Atom

Quark
Size $< 10^{-18}$ m

Electron
Size $< 10^{-18}$ m

Nucleus
Size $= 10^{-14}$ m

Neutron and Proton
Size $= 10^{-15}$ m

Atom
Size $= 10^{-10}$ m

If this picture were drawn to the scale given by the protons and neutrons, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
Concepts from elementary mechanics

\[ \vec{F} = \frac{d\vec{p}}{dt} \]

\[ T = \frac{1}{2}mv^2 \]

\[ F = -\frac{\partial V}{\partial r} \]

\[ \vec{l} = \vec{r} \times \vec{p} \]
Relativistic mechanics

- When particle velocities approach the speed of light, there are fundamental changes in the equations we use to describe them.

To wit

\[ m = m_0 \gamma \]

where

\[ \gamma = \text{LorentzFactor} = \left( \frac{1}{\sqrt{1 - \beta^2}} \right) \]

and

\[ \beta = \frac{v}{c} \]

Thus

\[ E = mc^2 = T + m_0c^2 \]

\[ T = \text{kinetic energy} = m_0c^2(\gamma - 1) \]

\[ p = mv = \frac{E}{c^2}v \]

For massless particles, \( v = c \)

\[ p = E/c \]

\[ E = pc \]

and, in general

\[ E^2 = p^2c^2 + (m_0c^2)^2 \]
Implications of this

Table 1.4
When Does One Use Relativistic Expressions?

<table>
<thead>
<tr>
<th>Particle</th>
<th>T (MeV) when $\gamma=1.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>0</td>
</tr>
<tr>
<td>e</td>
<td>0.051</td>
</tr>
<tr>
<td>$\mu$</td>
<td>11</td>
</tr>
<tr>
<td>$\pi$</td>
<td>14</td>
</tr>
<tr>
<td>p, n</td>
<td>94</td>
</tr>
<tr>
<td>d</td>
<td>188</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>373</td>
</tr>
</tbody>
</table>
How do we use relativistic equations?

Consider the case of relativistic heavy ions. We need to know the relationship between kinetic energy, velocity, momentum and total energy.

Suppose we have $^{12}\text{C}$ ions produced by an accelerator at a kinetic energy of 2.1 GeV/nucleon.
de-Broglie Relationship

for particles

\[ \lambda = \frac{h}{p} \]

for photons

\[ \lambda = \frac{c}{\nu} = \frac{hc}{E_{\gamma}} \]

\[ E_{\gamma} = h\nu = pc \]

Table 1.5
Typical Magnitudes of De Broglie Wave lengths

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Photon (\text{cm})</th>
<th>Electron (\text{cm})</th>
<th>Proton (\text{cm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.2x10^{-9}</td>
<td>3.7x10^{-10}</td>
<td>9.0x10^{-12}</td>
</tr>
<tr>
<td>1</td>
<td>1.2x10^{-10}</td>
<td>8.7x10^{-11}</td>
<td>2.9x10^{-12}</td>
</tr>
<tr>
<td>10</td>
<td>1.2x10^{-11}</td>
<td>1.2x10^{-11}</td>
<td>0.9x10^{-12}</td>
</tr>
<tr>
<td>100</td>
<td>1.2x10^{-12}</td>
<td>1.2x10^{-12}</td>
<td>2.8x10^{-13}</td>
</tr>
<tr>
<td>1000</td>
<td>1.2x10^{-13}</td>
<td>1.2x10^{-13}</td>
<td>0.7x10^{-13}</td>
</tr>
</tbody>
</table>
Heisenberg Uncertainty Principle

\[ \Delta p_x \cdot \Delta x \geq \hbar \]
\[ \Delta p_y \cdot \Delta y \geq \hbar \]
\[ \Delta p_z \cdot \Delta z \geq \hbar \]
\[ \Delta E \cdot \Delta \Delta \geq \hbar \]
Units

\[ \frac{e^2}{4\pi \varepsilon_0} = 1.43998 \text{ MeV } \text{ fm} \]

\[ \hbar = 6.58212 \times 10^{-22} \text{ MeV s} \]

\[ c = 2.9979 \times 10^{23} \text{ fm} \text{ s}^{-1} = 29.979 \text{ cm/ns} \]

\[ \hbar c = 197.3 \text{ MeV fm} \]

1 year (sidereal) = \( 3.1558 \times 10^7 \text{ s} \approx \pi \times 10^7 \text{ s} \)
Sources of Nuclear Data

- Nuclear Wallet Cards--back of book
- National Nuclear Data Center (http://www.nndc.bnl.gov)
- Table of Isotopes Project (http://nucleardata.nuclear.lu.se/nucleardata/toi/)