Introduction

• Nuclear power is made possible by energy emitted from either nuclear fission or nuclear fusion.

• Current nuclear power plants utilize fission to produce thermal energy that is converted to mechanical energy to do useful work i.e. turn a generator to produce electricity.

• Understanding the atom and the stability of the atom is the focus of this presentation
Atom

• An atom is the basic building block of matter that is chemically unique.
• Each atom consists of an equal number of protons and an electrons.
  – Net charge is neutral
  – Neutrons may also be present
  – Each atom is classified according to the number of protons (chemical element) and neutrons (isotope)
• An ion consists of an atom with 1 or more missing electrons
Although the electron and the proton have the same magnitude of electrical charge, the masses and size of each particle differ.

<table>
<thead>
<tr>
<th></th>
<th>Charge (C)</th>
<th>Mass (amu)</th>
<th>Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>-1</td>
<td>5.4858x10^{-4}</td>
<td>~10^{-22}**</td>
</tr>
<tr>
<td>Proton</td>
<td>+1</td>
<td>1.0073</td>
<td>10^{-15}</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
<td>1.0087</td>
<td>10^{-15}</td>
</tr>
</tbody>
</table>
Atom

- The atom is made up of a nucleus consisting of protons and neutrons with electrons orbiting.
- The nucleus is quite small compared to the size of the atom.

Simple Representation of a Lithium Atom
Atomic Forces

• The nucleus of an atom consists of protons with zero or more neutrons

• Electrostatic repulsion of positive charged protons must be balanced by an equal force holding the nucleus together

• The nuclear force that acts at short range between nucleons (proton – proton , proton – neutron, and neutron – neutron - neutron)

• The nuclear force acts on adjacent nucleons while coulombic forces (electrostatic repulsion) act over the entire nucleus
Classification

ISOTOPES OF OXYGEN

16
8
8 protons
8 neutrons

17
8
8 protons
9 neutrons

18
8
8 protons
10 neutrons
Classification

- $A$: atomic mass number - number of nucleons
- $X$: chemical symbol of the element
- $Z$: represents atomic number — number of protons
# Classification

<table>
<thead>
<tr>
<th>Elements</th>
<th>Mass Number</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boron</td>
<td>5</td>
<td>B</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>C</td>
</tr>
<tr>
<td>Helium</td>
<td>4</td>
<td>He</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1</td>
<td>H</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>7</td>
<td>N</td>
</tr>
<tr>
<td>Oxygen</td>
<td>8</td>
<td>O</td>
</tr>
<tr>
<td>Plutonium</td>
<td>94</td>
<td>Pu</td>
</tr>
<tr>
<td>Uranium</td>
<td>92</td>
<td>U</td>
</tr>
</tbody>
</table>
Chart of Nuclides

**SYMBOLS**

**RADIATIONS AND DECAY**
- $\alpha$: alpha particle
- $\beta^-$: negative electron
- $\beta^+$: positron
- $\gamma$: gamma ray
- $n$: neutron
- $p$: proton
- $d$: deuterium
- $t$: triton
- $e^-$: electron capture
- $\text{IT}$: isomeric transition
- $D$: delayed radiation
- $\text{SF}$: spontaneous fission
- $e^-$: disintegration energy
- $\beta^-$: conversion electron
- $\beta^-$: double beta decay
- $\beta^-$: particle emission
- $\text{Ne}$: particle emission

**TIME**
- $\mu$: microseconds (1.0E-6 sec.)
- $\text{ms}$: milliseconds (1.0E-3 sec.)
- $s$: seconds
- $m$: minutes
- $h$: hours
- $d$: days
- $y$: years

**OTHER SYMBOLS**
- $<1\%$: absolute abundance less than 1%
- $\leq1\%$: absolute abundance less than 10E-3%
- $<10E-6%$: absolute abundance less than 10E-6%
- $\text{E}$: indicates exponential format, e.g., 1.0E11 is 1.0 x 10^{11} years
- $\leftrightarrow$: indicates assignment to metastable (m) and ground (g) state states inconclusive
- $\uparrow$: indicates assignment of $m_g$ and $m_h$
- $x$: unspecified number of particles of a given type emitted, e.g., $\gamma p$

**COLORS USED FOR HALF LIVES**
- 1 DAY TO 10 DAYS
- 10 DAYS TO 100 DAYS
- 100 DAYS TO 10 YEARS
- 10 YEARS TO 500 YEARS
- > 500 YEARS OR STABLE

**COLORS USED FOR NEUTRON ABSORPTION PROPERTIES**
- 10 BARS TO 100 BARS
- 100 BARS TO 500 BARS
- 500 BARS TO 1000 BARS
- > 1000 BARS
Classification

- Elemental Lithium has an atomic weight of 6.941 amu
- Lithium has 3 protons but can have a varying number of neutrons
Mass

- This is the weighted average of two naturally occurring isotopes of Lithium, $^6\text{Li}$ and $^7\text{Li}$.

- Referring to the chart of nuclides the isotopic abundance of each isotope and the corresponding atomic masses are the following:
Mass

- The mass of elemental Lithium

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Abundance (%)</th>
<th>Atomic Mass (amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6_3\text{Li}$</td>
<td>7.5</td>
<td>6.015122</td>
</tr>
<tr>
<td>$^7_3\text{Li}$</td>
<td>92.5</td>
<td>7.016003</td>
</tr>
</tbody>
</table>

\[
[\% \cdot \text{mass}]^6_3\text{Li} + [\% \cdot \text{mass}]^7_3\text{Li} = \\
[0.075 \cdot 6.015122] + [0.925 \cdot 7.016003] = 6.940937
\]
Nuclear Stability

- Nuclear stability is defined as the ability of an atom to maintain its atomic structure or energy.
- Factors affecting stability are complex but one may consider the balance of nuclear and coulomb forces within the nucleus.
- Adding more protons to the nucleus increases the repulsive forces that must be balanced by the addition of neutrons and the corresponding increase in nuclear forces.
- Since nuclear forces act on adjacent nucleons and coulombic forces act over the entire nucleus, additional neutrons are needed for larger nuclei.
Nuclear Stability

- Stability curve – plot of nuclei as a function of the number of protons (Z) and number of neutrons (N = A-Z)
- Vertical lines correspond to isotopes or nuclides having the same number of protons (Z) (\(^6\) Li and \(^7\) Li)
- Horizontal lines correspond to isotones or nuclides with the same number of neutrons (N) (\(^6\) Li and \(^7\) Be)
- Diagonal lines correspond isobars or nuclides with the same mass number (A) (\(^6\) Li and \(^6\) Be)
- The divergence from the line of equal number of protons and neutrons (N=Z) is based on the requirement to have more neutrons in the nucleus to overcome the longer range coulombic forces
- No known stable nuclide above Bismuth
Binding Energy

• Binding energy represents the amount of energy that must be supplied to separate a nucleus into individual protons and neutrons.
• The greater the binding energy, the more tightly bound the nucleus.
• When an atom is assembled, the resulting mass is lower than the total mass of the protons, neutrons and electrons. This difference is referred to as the mass defect and is defined as:

\[
\Delta M = Z \cdot (mass_{proton} + mass_{electron}) + (A - Z)(mass_{neutron}) - M
\]

\[
\Delta M = Z \cdot (mass_{hydrogen}) + (A - Z)(mass_{neutron}) - M
\]
Binding Energy

- Example – Determine the Mass Defect of $^{238}_{92}$U

\[ \Delta M = Z \cdot (\text{mass}_{\text{hydrogen}}) + (A - Z)(\text{mass}_{\text{neutron}}) - M \]

\[ \Delta M = 92 \cdot (1.0079) + (238 - 92)(1.0087) - 238.0508 \]

\[ \Delta M = 92.7268 + 147.2702 - 238.0508 \]

\[ \Delta M = 1.9462 \text{amu} \]

- To convert to Energy

\[ E = \Delta m \cdot c^2 = 931.5016 \frac{\text{MeV}}{\text{amu}} \]

\[ E = \left(931.5016 \frac{\text{MeV}}{\text{amu}}\right) \cdot 1.9462 \text{amu} = 1812.9 \text{MeV} \]
# Binding Energy

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>BE MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2\text{D}$</td>
<td>2.226</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>28.296</td>
</tr>
<tr>
<td>$^{14}\text{N}$</td>
<td>104.659</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>127.619</td>
</tr>
<tr>
<td>$^{40}\text{Ca}$</td>
<td>342.052</td>
</tr>
<tr>
<td>$^{58}\text{Fe}$</td>
<td>509.945</td>
</tr>
<tr>
<td>$^{206}\text{Pb}$</td>
<td>1622.340</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>1812.888</td>
</tr>
</tbody>
</table>

Binding energy increases with increasing $Z$. 
Binding Energy

- Another Example – Consider the thermal fission of $^{235}_{92}U$

\[ {^{235}_{92}U + ^{1}_{0}n \rightarrow ^{94}_{38}Sr + ^{139}_{54}Xe + 3^{1}_{0}n + \gamma} \]

- Determine the mass defect

\[
\begin{align*}
(235.0439 + 1.0087) &= (93.9152 + 138.9178 + 3(1.0087)) \\
\Delta m &= 236.0526 - 235.8591 \\
\Delta m &= 0.1935 \text{amu} \\
E &= 0.1935 \text{amu} \left( 931.5016 \frac{\text{MeV}}{\text{amu}} \right) \\
E &= 180.2 \text{MeV}
\end{align*}
\]
Binding Energy

• The more nucleons packed into a nucleus, the more energy is released, and thus the higher the binding energy. Therefore binding energy is not a good indicator of nuclide stability.

• The binding energy per nucleon provides insight into how tightly the nucleus of the atom is bound or how much energy on average is required to remove a nucleon from a given nucleus.

• It is the binding energy (BE) divided by the number of nucleons (A).

• Taking our example of $^{238}_{92}$U

$$\frac{BE}{A} = \frac{1812.9\text{MeV}}{238} \approx 7.6\text{MeV}$$
Binding Energy

Iron is the most tightly bound nucleus. $^{56}_{26}\text{Fe}$ has 8.8 MeV per nucleon binding energy.

Elements heavier than iron can yield energy by nuclear fission.

Average mass of fission fragments is about 118.

Mass Number, $A$
Binding Energy

• Light elements from hydrogen up to sodium generally exhibit increasing binding energy per nucleon as the atomic mass increases.
  – This increase is generated by increasing forces per nucleon in the nucleus, as each additional nucleon is attracted by all of the other nucleons, and thus more tightly bound to the whole.
  – Nuclear fusion is possible in this region where the resulting

• The sequence of elements of magnesium through xenon exhibit a plateau of binding energy per nucleon
  – the nucleus has become large enough that nuclear forces no longer completely extend efficiently across its width. Attractive nuclear forces in this region, as atomic mass increases, are nearly balanced by repellent electromagnetic forces between protons, as atomic number increases.

• The binding energy per nucleon of heavy nuclei decrease as atomic number increases.
  – In this region of nuclear size, electromagnetic repulsive forces are beginning to gain against the strong nuclear force.
Nuclear Stability

- Nuclei tend to move toward greater binding energy or stability.
- Nuclides outside the “valley of stability” undergo nuclear process known as radioactive decay to become more stable.
- Nuclei that are neutron rich (N/Z >> 1) typically decay by Beta\(^-\) decay or through the ejection of a neutron from the nucleus.
- Nuclei that are neutron poor (N/Z < 1) typically decay by Beta\(^+\) decay, electron capture, or through the ejection of a proton from the nucleus.
- Heavy nuclei that are unstable may decay a number of ways depending on their N/Z ratio but may also decay through the ejection of a Helium nucleus known as an alpha particle.
As A increases, a larger proportion of neutrons are required in order to overcome the mutual electrostatic forces of opposition of the protons.
Nuclear Stability

Relative Locations of the Products of Various Nuclear Processes

Note the change in the axes
Conclusion

• The Atom
• How elements are classified through the number of protons (Z) and number of neutrons (N = A-Z)
• How the nucleus is held together through the balance of the nuclear force and the coulombic force
• The stability of nuclides and the ratio of neutrons to protons (N/Z)
• Understanding of the concept of Binding energy (BE) and the binding energy per nucleon (BE/A)
• The regions where nuclear fusion and nuclear fission can occur
• Understanding the concept of nuclear decay with respect to the line of stability and the preferred type of radioactive decay for a nucleus to become more stable