Lec #23:  Nuclear Power. II.

LAST TIME:  Begin Nuclear Power (Chaps 13-15)

TODAY:  1) Fundamentals of Nuclear Physics;
        2) Reactor Technology;
        3) Prospects for Nuclear Power

NEXT:  1) Fusion Power?
       2) Introduction to Renewables
### Periodic Table of Elements

The periodic table is divided into several categories:

- **Metals**
- **Metalloids**
- **Nonmetals**

The table is organized by atomic number, with elements arranged in increasing order. Each element is represented by its atomic number, symbol, and atomic weight.

**Transition Metals** are highlighted in the middle of the table.

**Lanthanides** and **Actinides** are listed separately at the bottom of the table.

© 2006 Thomson Higher Education

---

**Lanthanides**

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Atomic Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>La</td>
<td>57</td>
<td>138.9</td>
</tr>
<tr>
<td>Ce</td>
<td>58</td>
<td>140.9</td>
</tr>
<tr>
<td>Pr</td>
<td>59</td>
<td>140.9</td>
</tr>
<tr>
<td>Nd</td>
<td>60</td>
<td>144.2</td>
</tr>
<tr>
<td>Pm</td>
<td>61</td>
<td>150.4</td>
</tr>
<tr>
<td>Sm</td>
<td>62</td>
<td>153.3</td>
</tr>
<tr>
<td>Eu</td>
<td>63</td>
<td>152.0</td>
</tr>
<tr>
<td>Gd</td>
<td>64</td>
<td>157.2</td>
</tr>
<tr>
<td>Tb</td>
<td>65</td>
<td>158.9</td>
</tr>
<tr>
<td>Dy</td>
<td>66</td>
<td>162.5</td>
</tr>
<tr>
<td>Ho</td>
<td>67</td>
<td>164.9</td>
</tr>
<tr>
<td>Er</td>
<td>68</td>
<td>167.3</td>
</tr>
<tr>
<td>Tm</td>
<td>69</td>
<td>168.9</td>
</tr>
<tr>
<td>Yb</td>
<td>70</td>
<td>173.0</td>
</tr>
</tbody>
</table>

**Actinides**

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Atomic Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ac</td>
<td>89</td>
<td>227.0</td>
</tr>
<tr>
<td>Th</td>
<td>90</td>
<td>232.0</td>
</tr>
<tr>
<td>Pa</td>
<td>91</td>
<td>231.0</td>
</tr>
<tr>
<td>U</td>
<td>92</td>
<td>238.0</td>
</tr>
<tr>
<td>Np</td>
<td>93</td>
<td>(237.0)</td>
</tr>
<tr>
<td>Pu</td>
<td>94</td>
<td>(244.1)</td>
</tr>
<tr>
<td>Am</td>
<td>95</td>
<td>(243.1)</td>
</tr>
<tr>
<td>Cm</td>
<td>96</td>
<td>(247.1)</td>
</tr>
<tr>
<td>Bk</td>
<td>97</td>
<td>(247.1)</td>
</tr>
<tr>
<td>Cf</td>
<td>98</td>
<td>(251.1)</td>
</tr>
<tr>
<td>Es</td>
<td>99</td>
<td>(252.1)</td>
</tr>
<tr>
<td>Fm</td>
<td>100</td>
<td>(257.1)</td>
</tr>
<tr>
<td>Md</td>
<td>101</td>
<td>(258.1)</td>
</tr>
<tr>
<td>No</td>
<td>102</td>
<td>(259.1)</td>
</tr>
</tbody>
</table>

© 2006 Thomson Higher Education
Fundamentals of Nuclear Physics (cont.)

3. Mass of free particles \((E=mc^2)\)
   - proton \(= 1.6726E-27 \text{ kg} = 938.3 \text{ MeV/c}^2\)
   - neutron \(= 1.6749E-27 \text{ kg} = 939.6 \text{ MeV/c}^2\)
   - electron \(= 9.1094E-31 \text{ kg} = 0.511 \text{ MeV/c}^2\)

4. Binding Energy and Mass of atom \(< m_p n_p + m_n n_n + m_e n_e\)
   - \(\Delta mc^2 = \text{binding energy}\)
   - most of this (MeV’s) is in nucleus

5. Nuclear Structure (protons + neutrons)
   - EM repulsion of protons; neutron immune to EM force
   - must be a force stronger than EM operating over tiny distances
   - more protons -> more EM; more neutrons -> some dilution
   - Atomic Number: \(Z = \# \text{ of protons}; N = \# \text{ of neutrons}\)
   - Nucleon Number: \(A = \# \text{ of nucleons} \left( A = Z + N \right)\)
   - \(\frac{A}{Z} X; \ X \text{ is chemical symbol} \quad \text{e.g.} \quad ^{238}_{92} \text{U} \ (\text{or just} \ 238\text{U})\)
Nuclear Structure

The atomic nucleus consists of positively charged protons and neutral neutrons.

**Mass number:**

Number of nucleons in the nucleus, $A = Z + N$

**Atomic number:**

Number of protons in the nucleus

$\text{Unified Mass Unit (u)}$

$1 \text{ u} = 1.6605 \times 10^{-27} \text{ kg}$ \quad \text{or} \quad 1 \text{ u} = 931.5 \text{ MeV}$

$ r \approx (1.2 \times 10^{-15} \text{ m}) A^{1/3}$

Strong Nuclear Force
Fundamentals of Nuclear Physics (cont.)

B. ISOTOPES

- same Z, therefore same chemical properties
- different N (and A), therefore
  - different mass
  - different nuclear binding energy
  - different stability
  - different behavior in nuclear reactions
- elements usually form with a mix of isotopes
- over time, this mix changes, as “unstable” isotopes “decay”
  - e.g. $^1$H = hydrogen 99.985% stable
  - .  $^2$H = deuterium 0.015% stable
  - .  $^3$H = tritium ~0.000% half-life = 12.3 years
  - e.g. $^{238}$U 99.3% half-life = 4.47 billion years
  - .  $^{235}$U 0.7% half-life = 0.70 billion years
Isotopes of Hydrogen

**ISOTOPES:** Nuclei that contain the same number of protons but a different number of neutrons.

**Protium**
- 1 proton

**Deuterium**
- 1 proton
- 1 neutron

**Tritium**
- 1 proton
- 2 neutrons

Deuterium is a stable isotope of hydrogen. Symbol: $^2\text{H}$ or D

Tritium is radioactive. Symbol: $^3\text{H}$. It decays into a proton plus electron and anti-neutrino.
C. STABILITY OF ISOTOPES

- certain combinations of neutron # and proton # hold together for a long time
- others transmute themselves to a different element by radioactive decay (alpha, beta, gamma, fission, …)
- adding neutrons to a stable nucleus generally makes it unstable
- ~400 stable nuclei known; all have $Z \leq 83$ (Bismuth)
- generally stable if $Z$ a/or $N = 2, 8, 20, 28, 50, 82, 126$
  - nuclear “shell” structure analogous to atomic shells
  - $^4\text{He}$, $^{16}\text{O}$, $^{40}\text{Ca}$, etc. are like noble gases – very stable (tightly bound)
Nuclear Reactions

A. Radioactivity

Spontaneous “decay” to a different nuclear state, or even a different type of atom, through the emission or absorption of particles or electromagnetic energy, releasing energy

1. Alpha Decay: Emission of a helium nucleus (2P, 2N)

\[ Z^AX \rightarrow Z-2^{A-4}Y + ^4He \]

Heat = \((M_x-M_Y-M_\alpha)c^2 \rightarrow K.E. \) of X, Y, \( \alpha \)

2. Beta Decay: Emission or absorption of electron or positron

\[ Z^AX \rightarrow Z+1^AY + \beta^- + \nu \]
\[ Z^AX \rightarrow Z-1^AY + \beta^+ + \nu \]
\[ Z^AX + \beta^- \rightarrow Z-1^AX + \nu \]

3. Gamma Decay: Emission of a photon (de-excitation)

\[ Z^AX^* \rightarrow Z^AX + \gamma \]
Decay Processes

Alpha decay

- The $\alpha$ decay is a nuclear transmutation: nuclei of one element change into nuclei of a lighter element.

\[
\begin{align*}
\text{Parent nucleus} & \quad \rightarrow \quad \text{Daughter nucleus} \\
^{238}_{92}\text{U} & \quad \rightarrow \quad ^{234}_{90}\text{Th} + ^{4}_{2}\text{He} \\
\text{Uranium} & \quad \rightarrow \quad \text{Thorium} + \text{He Nucleus} \\
\text{charge of } +2 & \quad \text{charge of } +2
\end{align*}
\]
Beta Decay

- During beta decay, the daughter nucleus has the same number of nucleons as the parent, but the atomic number is changed by one.

\[ ^0_1 n \rightarrow ^1_1 p + ^0_{-1} e \]

144 N
90 P

234 Th
90

143 N
91 P

\( \beta \)-particle

234 Pa
91

Thorium (parent nucleus) → Protactinium (daughter nucleus)
Gamma Decay

- Gamma rays are given off when an excited nucleus “falls” to a lower energy state.
- The de-excitation of nuclear states results from “jumps” made by a proton or neutron.
- The excited nuclear states may be the result of violent collision or more likely of an alpha or beta emission.

\[
\begin{align*}
\frac{12}{6} C^* \\
\rightarrow \frac{12}{6} C + \gamma_{ray}
\end{align*}
\]
<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha ) particles</td>
<td>a sheet of paper, a few centimeters of air, or thousands of a centimeter of biological tissue</td>
</tr>
<tr>
<td>( \beta ) particles</td>
<td>a thin aluminum plate or tenths of a centimeter of biological tissue</td>
</tr>
<tr>
<td>( \gamma ) rays</td>
<td>several centimeters of lead or meters of concrete</td>
</tr>
</tbody>
</table>

Figure 3. Radiation travelling through human tissue

© 2006 Thomson Higher Education
Nuclear Reactions (cont.)

B. Spontaneous Decay - Exponential (Half Life)

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

- Because... Rate = \( \lambda N \)
- 1 Curie = 3.7 E 10 sec\(^{-1}\) (1 g of radium)

- Half life = ln(2)/\( \lambda \) (recall rule of 70?)

- Nuclei can also be rendered unstable in nuclear reactions
C. Neutrons

• neutrons can not be accelerated, focused, etc.
• free neutrons decay (~10 min) to proton + electron
• neutrons easily pass by electron cloud and are not repelled by positively charged nucleus
• if they are traveling slowly enough, they stick; if they travel faster, they scatter
  – e.g. thermal neutrons (300 K) travel ~ 2.8 km/s
• if they are captured, they can produce an unstable isotope, which can then either DECAY or FISSION
Nuclear Fission

A. Fission and Fusion

- **Fission** - break up into 2 or more smaller pieces
- **Fusion** - combine 2 or more pieces into a bigger piece
- both involve transmutation of elements
- both can be exothermic: energy released = \( \Delta mc^2 \)
  - if \( M_{\text{big}} < \sum M_{\text{small}} \), fusion is exothermic
  - if \( M_{\text{big}} > \sum M_{\text{small}} \), fission is exothermic
- both processes occur in nature
  - fusion inside stars
  - fission e.g. OKLO
- fission of U discovered in late ‘30s
  - 1st controlled chain reaction in 1942
  - 1st uncontrolled chain reaction 1945
FUSION

FISSION

Fe

(Z=56)

Curve of Binding Energy

Binding Energy per Nucleon (MeV)

A

# of Nucleons
Nuclear Fission (cont.)

B.  Fission Example

\[ n + ^{235}\text{U} \rightarrow ^{236}\text{U} \]

\[ ^{236}\text{U} \rightarrow A^* + B^* + 3n \]

A* and B* have too many neutrons to be stable; long series of beta decays to eventually become stable

- energy released as kinetic energy of products
- neutron initiates reaction, and reaction produces neutrons
- for Uranium, only slow neutrons will cause fission, but neutrons produced by fission move very fast
- need “moderator” to slow them down
- if 1 or more of these neutrons stimulates another fission, a chain reaction can result
Nuclear Fission (cont.)

- $K =$ average # of fission inducing neutrons per fission
  - water is a moderator: it slows down neutrons
  - depends on material, moderators, shape and size of “pile”, temperature, etc.
    - if $K<1$ reaction dies out
    - if $K=1$ continuous power production
    - if $K>1$ possibly destructive chain reaction
Nuclear Fission (cont.)

C. Enrichment of Fissile Material

- Natural isotope ratio: $^{238}\text{U}/^{235}\text{U} \sim 142$
  - 99.3% $^{238}\text{U}$ [changes very slowly over time]
  - 0.7% $^{235}\text{U}$
- with water as moderator, need 3 or 4% $^{235}\text{U}$
- with heavy water, we can use natural mix
- for bombs, need 90% or more $^{235}\text{U}$ (or Plutonium)
- how do we change the isotope ratio?
  - Diffusion (ORNL)
  - Centrifuge (LBL)
  - Laser (LANL)
  - Breeder reactor (Hanford, SRS)
  - Fuel reprocessing
\[ ^{238}\text{U} + n \rightarrow ^{239}\text{U} + \gamma \]
\[ ^{239}\text{U} \rightarrow ^{239}\text{Np} + \beta^- + \bar{\nu} \]
\[ ^{239}\text{Np} \rightarrow ^{239}\text{Pu} + \beta^- + \bar{\nu} \]
\[ ^{239}\text{Pu} \rightarrow ^{235}\text{U} + \alpha \]

238U --&gt; 235U Enrichment in reactor

\((T_{1/2} = 23.5 \text{ min.})\)
\((T_{1/2} = 2.35 \text{ days})\)
\((T_{1/2} = 2.44 \times 10^4 \text{ years})\)

NUCLEAR POWER UNITS BY REACTOR TYPE, WORLDWIDE

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Units (in operation)</th>
<th>Net MWe</th>
<th>Under Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurized light-water reactors (PWR)</td>
<td>243</td>
<td>214,234</td>
<td>43</td>
</tr>
<tr>
<td>Boiling light-water reactors (BWR)</td>
<td>91</td>
<td>74,941</td>
<td>8</td>
</tr>
<tr>
<td>Gas-cooled reactors, all types</td>
<td>36</td>
<td>12,239</td>
<td>0</td>
</tr>
<tr>
<td>Heavy-water reactors, all types</td>
<td>33</td>
<td>18,645</td>
<td>16</td>
</tr>
<tr>
<td>Graphite-moderated light-water reactors (LGR)</td>
<td>15</td>
<td>14,785</td>
<td>1</td>
</tr>
<tr>
<td>Liquid-metal-cooled fast breeder reactors (LMFBR)</td>
<td>3</td>
<td>928</td>
<td>4</td>
</tr>
</tbody>
</table>
Boiling Water Reactor

Steam

$P = 1000 \text{ psi}$

$T = 540^\circ \text{F}$

Turbine

Generator

Electricity

Condenser

Cold $H_2O$

Feedwater

Pump

Hot $H_2O$

Lake or cooling tower
Pressurized Water Reactor

- Reactor vessel
- Core
- Water
- Pump
- Containment
- $P = 2200 \text{ psi}$
- $T = 600^\circ \text{F}$
- Steam
- Turbine
- Generator
- Electricity
- Condenser
- Cold $\text{H}_2\text{O}$
- Hot $\text{H}_2\text{O}$
- Lake or cooling tower
- Water
- Pump