The Nucleus

• Z, N, A, isotopes
• Nucleons, mass
• Radius $R = r_o A^{1/3}$
• Nuclear density
• Nuclear magnetic moments
Nuclear Stability

Up to A~40, N ~ Z

Beyond that N>Z

shielding Coulomb repulsion

$^{238}\text{U}$ is largest naturally occurring nuclide
Binding Energy per Nucleon

- For X splitting to R + S:
  \[ B = [m(R) + m(S) - m(X)]c^2 \]
Proton & Neutron E levels

\[ ^{12}_6\text{C} \]
Stable

\[ ^{13}_6\text{C} \]
Stable

\[ ^{15}_7\text{N} \]
Unstable

\[ ^{16}_6\text{C} \]
Unstable

\[ ^{14}_7\text{N} \]
Stable

\[ ^{15}_7\text{N} \]
Stable

\[ ^{15}_8\text{O} \]
Unstable

\[ ^{16}_8\text{O} \]
Stable
Activity & Half Life

• Activity = \( R = -\frac{dN}{dt} \)
• Unit = 1 decay/s = 1 becquerel (Bq)
  also 1 Curie (Ci) = \( 3.7 \times 10^{10} \) Bq
• \( R = \lambda N(t) = -\frac{dN}{dt} \), so \( \frac{dN}{N} = -\lambda dt \)
  or \( N(t) = N_0 e^{-\lambda t} = N_0 e^{-t/\tau} \), where \( \tau = \frac{1}{\lambda} \) --
  also \( R(t) = R_0 e^{-\lambda t} \), where \( R_0 = \lambda N_0 \)
• \( N(t = t_{1/2}) = N_0 / 2 = N_0 e^{-\lambda t_{1/2}} \)
  so \( t_{1/2} = \ln(2)/\lambda = 0.693/\lambda = 0.693\tau \)
Half Life and Radioactive Decay

\[ N(t) = N_0 e^{-\lambda t} \]
Alpher, Bethe, Gamow

- Radioactivity reactions must satisfy all conservation laws (E, p, L, etc., plus, all lower E (<100MeV) conservation of nucleons (A)
- Parent nuclide $\rightarrow$ Daughter + small fragment
  Cons of E: $M(X) = M(D) + M_y + \frac{Q}{c^2}$
  where $Q =$ disintegration energy; $Q = -B$; $Q > 0$ unstable
- Three types of radiation: $\alpha, \beta, \gamma$
- Alpha decay: $^A_ZX \rightarrow ^{A-4}_{Z-2}D + \alpha$ where $\alpha = ^4_2He$
  $\alpha$ gets most of the KE since it is so much lighter
Tunneling

- Higher $E$ means shorter lifetime
Half-lives for alpha decay
Beta Decay

Beta decay: \( n \rightarrow p + \beta^- + \text{neutrino} \)

e.g. \( ^{14}\text{C} \rightarrow ^{14}\text{N} + \beta^- + \text{neutrino} \)

- Neutrino not detected, but conservation laws demanded it – first predicted by Pauli in 1930, but not detected till 1956

- Also positron decay: \( ^A_ZX \rightarrow ^A_{Z-1}D + \beta^+ + \nu \)
Example decay scheme

- Alpha decay shifts N,Z and often ends up further off line of stability – resulting in beta decay
### Table 12.3 The Four Radioactive Series

<table>
<thead>
<tr>
<th>Mass Numbers</th>
<th>Series Name</th>
<th>Parent</th>
<th>$t_{1/2}$ (y)</th>
<th>End Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4n$</td>
<td>Thorium</td>
<td>$^{232}_{90}\text{Th}$</td>
<td>$1.40 \times 10^{10}$</td>
<td>$^{208}_{82}\text{Pb}$</td>
</tr>
<tr>
<td>$4n + 1$</td>
<td>Neptunium</td>
<td>$^{237}_{93}\text{Np}$</td>
<td>$2.14 \times 10^{6}$</td>
<td>$^{209}_{83}\text{Bi}$</td>
</tr>
<tr>
<td>$4n + 2$</td>
<td>Uranium</td>
<td>$^{238}_{92}\text{U}$</td>
<td>$4.47 \times 10^{9}$</td>
<td>$^{206}_{82}\text{Pb}$</td>
</tr>
<tr>
<td>$4n + 3$</td>
<td>Actinium</td>
<td>$^{235}_{92}\text{U}$</td>
<td>$7.04 \times 10^{8}$</td>
<td>$^{207}_{82}\text{Pb}$</td>
</tr>
</tbody>
</table>
$^{14}$C decay & Radioactive Dating

- $n + ^{14}N \rightarrow ^{14}C + p$

---

**Cosmic rays produce neutrons**

**Neutrons interact with $^{14}N$ to produce $^{14}C$**

**$^{14}C$ makes CO$_2$ with two $^{16}O$ atoms**

**Plants and animals use or breathe CO$_2$**

When an organism dies, the ratio of $^{13}C/^{12}C$ decreases.

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## Fuels & Power Plants

### Table 13.1 Energy Content of Fuels

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
<th>Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1 kg</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>Oil</td>
<td>1 barrel (0.16 m$^3$)</td>
<td>$6 \times 10^9$</td>
</tr>
<tr>
<td>Natural gas</td>
<td>1 ft$^3$ (0.028 m$^3$)</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Wood</td>
<td>1 kg</td>
<td>$10^7$</td>
</tr>
<tr>
<td>Gasoline</td>
<td>1 gallon (0.0038 m$^3$)</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>Uranium (fission)</td>
<td>1 kg</td>
<td>$10^{14}$</td>
</tr>
<tr>
<td>Uranium (fusion)</td>
<td>1 kg</td>
<td>$2 \times 10^{14}$</td>
</tr>
</tbody>
</table>

### Table 13.2 Daily Fuel Requirements for 1000-MWe Power Plant

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>$8 \times 10^6$ kg</td>
</tr>
<tr>
<td>Oil</td>
<td>40,000 barrels (6400 m$^3$)</td>
</tr>
<tr>
<td>Natural gas</td>
<td>$2.5 \times 10^6$ ft$^3$ (7.1 $\times 10^4$ m$^3$)</td>
</tr>
<tr>
<td>Uranium</td>
<td>3 kg</td>
</tr>
</tbody>
</table>
Binding Energy per Nucleon

- Review
Fission

- Liquid drop model of nucleus – as sphere distorts, larger surface energy – less well shielded Coulomb repulsion – overcomes fission barrier – spontaneous fission if $Z^2/A \geq 49$
- To be useful, fission must be induced – usually by slow neutron absorption (use moderator [water, graphite or beryllium] to slow n) to a highly excited compound nucleus – products have a $N/Z$ ratio that is too high and 2 – 3 neutrons are emitted during fission
- These can be used to produce a self-sustaining chain reaction – if just 1 n on average then critical (vs. sub-critical or super-critical = bomb)
- Neutron control via control rods [cadmium] that absorb n
- $^{235}\text{U}$ absorbs thermal n better – need to enrich it (0.7% natural)
• BWR (Boiling Water Reactor) – danger that water can become contaminated
Alternate PWR

• Pressurized Water Reactor –
• Highest use of nuclear power: Lithuania (82%), France (77%), Belgium (60%) – in US (20%)
Progress on Fusion

• Stellar process
• Best reaction is $^{2}\text{H} + ^{3}\text{H} \rightarrow \text{n} + ^{4}\text{He}$
  $Q=17.6\text{MeV}$
• Enough $^{2}\text{H}$ for billions of years in sea water

3 Requirements for Fusion:

1. High $T$ – 1-200 million K
2. High Density – 2-3x10$^{20}$ ions/m$^3$
3. Sufficient confinement time – 1-2 s

Lawson criterion:
$nt \geq 3x10^{20} \text{ s/m}^3$

Two schemes: MCF & ICF
MCF - Tokamaks
MC Fusion Power Plant of the Future?
Laser Fusion

- NIF (National Ignition Facility – Livermore)
Advertisement

• April 23 – 24 (Friday/Saturday) at Union – meeting of the NY State and New England Sections of the American Physical Society
Modern Nuclear Applications: Medicine, Power and non-Proliferation
Help out at meeting and hear about the latest