The Promise and Problems of Nuclear Energy

Lecture #12
HNRS 228
Energy and the Environment
Chapter 6 Summary

- History of Nuclear Energy
- Radioactivity
- Nuclear Reactors
- Boiling Water Reactor
- Fuel Cycle
- Uranium Resources
- Environmental and Safety Aspects of Nuclear Energy
- Chernobyl Disaster
- Nuclear Weapons
- Storage of High-Level Radioactive Waste
- Cost of Nuclear Power
- Nuclear Fusion as a Energy Source
- Controlled Thermonuclear Reactions
- A Fusion Reactor
Recall What Is in a Nucleus

The nucleus of an atom is made up of protons and neutrons
- each is about 2000 times the mass of the electron, and thus constitutes the vast majority of the mass of a neutral atom (equal number of protons and electrons)
- proton has positive charge; mass = 1.007276 a.m.u.
- neutron has no charge; mass = 1.008665 a.m.u.
- proton by itself (hydrogen nucleus) will last forever
- neutron by itself will “decay” with half-life of ~11 min
- size of nucleus is about 0.00001 times size of atom
  ❖ Thus, an atom is mostly empty space

Remember that protons and neutrons are themselves made up of QUARKS
What holds an atom together?

- If like charges repel, and the nucleus is full of protons (positive charges), why doesn’t it fly apart?
  - repulsion is from electromagnetic force
  - at close scales, another force takes over
    - the strong nuclear force
- The strong force operates between quarks
  - Recall that both protons and neutrons are made of quarks
  - The strong force is a short-range force only
    - It is confined to nuclear sizes
  - this binding (strong force) overpowers the charge repulsion
iClicker Question

- Which is closest to the half-life of a neutron?
  - A 5 minutes
  - B 10 minutes
  - C 15 minutes
  - D 20 minutes
  - E 30 minutes
What's the deal with neutrons decaying?! 

- A neutron, which is heavier than a proton, can (and will!) decide to switch to the lower-energy state of the proton.
- Charge is conserved, so it produces an electron too.
  - and an anti-neutrino, a chargeless, nearly massless cousin to the electron.
iClicker Question

• What is the force that keeps the nucleus together?
  - A weak force
  - B strong force
  - C electromagnetic force
  - D gravitational force
Insight from the decaying neutron

• Another force, called the weak nuclear force, mediates these “flavor” changes
• Does this mean the neutron is made from an electron and proton?
  - No. But it will do you little harm to think of it this way
• Mass-energy conservation:
  - Mass of neutron is 1.008665 a.m.u.
  - Mass of proton plus electron is 1.007276 + 0.000548 = 1.007824
  - difference is 0.000841 a.m.u. (more than the electron mass)
  - in kg: $1.4 \times 10^{-30}$ kg = $1.26 \times 10^{-13}$ J = 0.783 MeV via $E = mc^2$
    ✤ 1 a.m.u. = $1.6605 \times 10^{-27}$ kg
    ✤ 1 eV = $1.602 \times 10^{-19}$ J
  - excess energy goes into kinetic energy of particles
iClicker Question

A neutron decays. It has no electric charge. If a proton (positively charged) is left behind, what other particle must come out if the net charge is conserved?

- A  No other particles are needed.
- B  A negatively charged particle must emerge as well.
- C  A positively charged particle must emerge as well.
- D  Another charge will come out, but it could be either positively charged or negatively charged.
- E  Neutrons cannot exist individually.
Counting particles

- A nucleus has a definite number of protons ($Z$), a definite number of neutrons ($N$), and a definite total number of nucleons: $A = Z + N$
- Example, the most common isotope of carbon has 6 protons and 6 neutrons (denoted $^{12}\text{C}$; 98.9% abundance)
  - $Z = 6; \ N = 6; \ A = 12$
- Another stable isotope of carbon has 6 protons and 7 neutrons (denoted $^{13}\text{C}$; 1.1% abundance)
  - $Z = 6; \ N = 7; \ A = 13$
- An unstable isotope of carbon has 6 protons and 8 neutrons (denoted $^{14}\text{C}$; half-life is 5730 years)
  - Decays via beta decay to $^{14}\text{N}$
- Isotopes of an element have same $Z$, differing $N$
Full notation

- A fully annotated nucleon symbol has the total nucleon number, $A$, the proton number, $Z$, and the neutron number, $N$ positioned around the symbol

\[
\frac{A}{Z} X_\frac{N}{A}
\]

- redundancy in that $A = Z + N$

- Examples:
  - carbon-12: $^{12}_6 C_6$
  - carbon-14: $^{14}_6 C_8$
  - uranium-235: $^{235}_{92} U_{143}$
  - uranium-238: $^{238}_{92} U_{146}$
  - plutonium-239: $^{239}_{94} Pu_{145}$
iClicker Question

- How many neutrons in U-235?
  - A 141
  - B 142
  - C 143
  - D 144
  - E 145
iClicker Question

- How many neutrons in Pu-239?
  - A 141
  - B 142
  - C 143
  - D 144
  - E 145

\[ ^{239}_{94} \text{Pu} \]
Radioactivity

Any time a nucleus spontaneously emits a particle...
- electron through beta ($\beta^-$) decay
  - increase $Z$ by 1; decrease $N$ by 1; $A$ remains the same
- positron (anti-electron) through beta ($\beta^+$) decay
  - decrease $Z$ by 1; increase $N$ by 1; $A$ remains the same
- alpha ($\alpha$) particle ($^4$He nucleus)
  - decrease $Z$ by 2; decrease $N$ by 2; decrease $A$ by 4
- gamma ($\gamma$) ray (high-energy photon of light)
  - $Z$, $N$, $A$ unchanged (stays the same nucleus, just loses energy)

...we say it underwent a radioactive transformation

Certain isotopes of nuclei are radioactively unstable
- they will eventually change flavor by a radioactive particle emission
- $\alpha$, $\beta$, $\gamma$ emission constitutes a minor change to the nucleus
  - not as dramatic as splitting the entire nucleus in two large parts
The Physicist's Periodic Table

Chart of the Nuclides

<table>
<thead>
<tr>
<th>Z</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Hydrogen</td>
<td>1.00794</td>
<td>3.01603</td>
<td>4.00301</td>
</tr>
<tr>
<td>1</td>
<td>Helium</td>
<td>4.00301</td>
<td>5.00855</td>
<td>6.01011</td>
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<tr>
<td>2</td>
<td>Lithium</td>
<td>6.94101</td>
<td>7.01068</td>
<td>8.01453</td>
</tr>
<tr>
<td>3</td>
<td>Beryllium</td>
<td>9.01227</td>
<td>10.01355</td>
<td>11.01478</td>
</tr>
<tr>
<td>4</td>
<td>Be</td>
<td>10.01250</td>
<td>11.01178</td>
<td>12.01064</td>
</tr>
<tr>
<td>5</td>
<td>Boron</td>
<td>12.01071</td>
<td>13.00359</td>
<td>14.00677</td>
</tr>
<tr>
<td>6</td>
<td>Carbon</td>
<td>13.00343</td>
<td>14.00677</td>
<td>15.00866</td>
</tr>
<tr>
<td>7</td>
<td>Nitrogen</td>
<td>14.00321</td>
<td>15.00623</td>
<td>16.00738</td>
</tr>
<tr>
<td>8</td>
<td>Oxygen</td>
<td>15.99491</td>
<td>16.99844</td>
<td>17.99863</td>
</tr>
</tbody>
</table>

Decay modes: 
- β⁺
- β⁻
- α

N → 0 1 2
iClicker Question

- If one of the neutrons in carbon-14 (carbon has 6 protons) decays into a proton, what nucleus is left?
  - A  carbon-13, with 6 protons, 7 neutrons
  - B  carbon-14, with 7 protons, 7 neutrons
  - C  boron-14, with 5 protons, 9 neutrons
  - D  nitrogen-14, with 7 protons, 7 neutrons
  - E  nitrogen-15, with 7 protons, 8 neutrons
Radioactivity Demonstration

- Have a Geiger counter that clicks whenever it detects a gamma ray, beta decay particle, or alpha particle.
  - not 100% efficient at detection, but representative of rate
- Have two sources:
  - $^{14}$C with half life of 5730 years
    - about 4000 $\beta^-$ decays per second in this sample
    - corresponds to 25 ng, or $10^{15}$ particles
  - $^{90}$Sr with half-life of 28.9 years
    - about 200 $\beta^-$ decays per second in this sample
    - contains about 40 pg (270 billion nuclei; was 450 billion in 1987)
    - produced in nuclear reactor
# Natural radioactive dose in mrem/year

<table>
<thead>
<tr>
<th>Source</th>
<th>Sea Level</th>
<th>Denver</th>
</tr>
</thead>
<tbody>
<tr>
<td>cosmic rays</td>
<td>28</td>
<td>55</td>
</tr>
<tr>
<td>terrestrial (rock)</td>
<td>46</td>
<td>90</td>
</tr>
<tr>
<td>food and water</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>air (mostly radon)</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>air travel</td>
<td>1 per 1,000 miles traveled</td>
<td></td>
</tr>
<tr>
<td>house</td>
<td>7 if made of stone/brick/concrete</td>
<td></td>
</tr>
<tr>
<td>medical X-ray</td>
<td>40 each (airport X-ray negligible)</td>
<td></td>
</tr>
<tr>
<td>nuclear med. treatment</td>
<td>14 each</td>
<td></td>
</tr>
<tr>
<td>within 50 miles of nuclear plant</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>within 50 miles of coal plant</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td><strong>total for no travel/medical</strong></td>
<td><strong>316</strong></td>
<td><strong>387</strong></td>
</tr>
</tbody>
</table>

Source: [www.epa.gov/radiation/students/calculate.html](http://www.epa.gov/radiation/students/calculate.html)
iClicker Question

- If a substance has a half-life of 30 years, how much will be left after 90 years?
  - A  one-half
  - B  one-third
  - C  one-fourth
  - D  one-sixth
  - E  one-eighth
Fission of Uranium

Figure 6.1 Three steps in the neutron-induced fission of $^{235}\text{U}$. The combination of a neutron and $^{235}\text{U}$ forms $^{236}\text{U}$ in a highly excited state, that promptly fissions into two lighter nuclei, emitting neutrons and gamma rays in the process.

Barium and Krypton represent just one of many potential outcomes
Fission

- There are only three known nuclides (arrangements of protons and neutrons) that undergo fission when introduced to a slow (thermal) neutron:
  - $^{233}\text{U}$: hardly used (hard to get/make)
  - $^{235}\text{U}$: primary fuel for reactors
  - $^{239}\text{Pu}$: popular in bombs
- Others may split if smacked hard enough by a neutron (or other energetic particle)
How much more fissile is $^{235}\text{U}$ than $^{238}\text{U}$?

**Figure 6.2** The fission probability for $^{235}\text{U}$ and $^{238}\text{U}$ as a function of neutron energy. The arrow at 0.025 eV indicates the energy of thermalized neutrons. For $^{238}\text{U}$ the fission probability becomes appreciable only above about 1 MeV neutron energy.

Bottom line: at thermal energies (arrow), $^{235}\text{U}$ is 1000 times more likely to undergo fission than $^{238}\text{U}$ even when smacked hard.
Uranium isotopes and others of interest

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Abundance (%)</th>
<th>half-life</th>
<th>decays by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{233}\text{U}$</td>
<td>0</td>
<td>159 kyr</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>$^{234}\text{U}$</td>
<td>0.0055</td>
<td>246 kyr</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>0.720</td>
<td>704 Myr</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>$^{236}\text{U}$</td>
<td>0</td>
<td>23 Myr</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>$^{237}\text{U}$</td>
<td>0</td>
<td>6.8 days</td>
<td>$\beta^-$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>99.2745</td>
<td>4.47 Gyr</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>no natural Pu</td>
<td>24 kyr</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>100</td>
<td>14 Gyr</td>
<td>$\alpha$</td>
</tr>
</tbody>
</table>
The Uranium Story

- No isotope of uranium is perfectly stable:
  - $^{235}\text{U}$ has a half-life of 704 million years
  - $^{238}\text{U}$ has a half-life of 4.5 billion years (age of earth)
- No heavy elements were made in the Big Bang (just H, He, Li, and a tiny bit of Be)
- Stars only make elements as heavy as iron (Fe) through natural thermonuclear fusion
- Heavier elements made in catastrophic supernovae
  - massive stars that explode after they're spent on fusion
- $^{235}\text{U}$ and $^{238}\text{U}$ initially had similar abundance
Uranium decay

- The natural abundance of uranium today suggests that it was created about 6 billion years ago
  - assumes $^{235}\text{U}$ and $^{238}\text{U}$ originally equally abundant
  - Now have 39.8% of original $^{238}\text{U}$ and 0.29% of original $^{235}\text{U}$
  - works out to 0.72% $^{235}\text{U}$ abundance today
- Plutonium-239 half-life is too short (24,000 yr) to have any naturally available
- Thorium-232 is very long-lived, and holds primary responsibility for geothermal heat
Why uranium?

• Why mess with “rare-earth” materials? Why not force lighter, more abundant nuclei to split?
  - only three “slow-neutron” fissile nuclei are known, what about this “smacking” business?
• Turns out, you would actually *loose* energy in splitting lighter nuclei
• Iron is about the most tightly bound of the nuclides
  - and it’s the release of binding energy that we harvest
  - so we want to drive toward iron to get the most out
iClicker Question

- Basically, what is the nature of the alpha particle?
  - A an electron
  - B a proton
  - C a helium nucleus
  - D a uranium nucleus
  - E an iron nucleus
iClicker Question

• Basically, what is the nature of the beta particle?
  - A an electron
  - B a proton
  - C a helium nucleus
  - D a uranium nucleus
  - E an iron nucleus
• Iron (Fe) is at the peak
• On the heavy side of iron, \textit{fission} delivers energy
• On the lighter side of iron, \textit{fusion} delivers energy
• This is why normal stars stop fusion after iron
• Huge energy step to be gained in going from hydrogen (H) to helium-4 via fusion
What does uranium break into?

- Uranium doesn’t break into two equal pieces
  - usually one with mass around 95 a.m.u. and one with mass around 140 a.m.u.
- The fragments are very neutron-rich, and some drip off immediately
  - these can spur additional fission events...
- Even after the neutron-drip, the fragments rapidly undergo radioactive transformations until they hit stable configurations
Chart of the nuclides

- stable nuclide
- radioactive (unstable) nuclide
Messy details summarized

• $^{235}\text{U}$ will undergo spontaneous fission if a neutron happens by, resulting in:
  - two sizable nuclear fragments flying out
  - a few extra neutrons
  - gamma rays from excited states of daughter nuclei
  - energetic electrons from beta-decay of daughters

• The net result: lots of banging around
  - generates heat locally (kinetic energy of tiny particles)
  - for every gram of $^{235}\text{U}$, get 65 trillion Joules, or about 16 million Calories
  - compare to gasoline at roughly 10 Calories per gram
    - a tank of gas could be replaced by a 1-mm pellet of $^{235}\text{U}$!!
Aside on nuclear bombs

- Since neutrons initiate fission, and each fission creates more neutrons, there is potential for a chain reaction
- Have to have enough fissile material around to intercept liberated neutrons
- Critical mass for $^{235}\text{U}$ is about 15 kg, for $^{239}\text{Pu}$ it’s about 5 kg
- Bomb is dirt-simple: separate two sub-critical masses and just put them next to each other when you want them to explode!
  - difficulty is in *enriching* natural uranium to mostly $^{235}\text{U}$