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

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 an Energy Source
- Controlled Thermonuclear Reactions
- A Fusion Reactor
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. 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
  - Mass-energy difference is 0.000841 a.m.u. (more than the electron mass)
  - in kg: 4.41 x 10^-26 kg = 1.26 x 10^-19 J = 0.783 MeV via $E = mc^2$
  - 1 a.m.u. = 1.6605 x 10^-27 kg
  - 1 eV = 1.602 x 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
  - redundancy in that $A = Z + N$
- Examples:
  - carbon-12: $^{12}\text{C}_6$
  - carbon-14: $^{14}\text{C}_7$
  - uranium-235: $^{235}\text{U}_{92}$
  - uranium-238: $^{238}\text{U}_{92}$
  - plutonium-239: $^{239}\text{Pu}_{94}$

iClicker Question

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

Any time a nucleus spontaneously emits a particle...
- electron through beta (β⁻) decay
  * increase Z by 1; decrease N by 1; A remains the same
- positron (anti-electron) through beta (β⁺) decay
  * decrease Z by 1; increase N by 1; A remains the same
- alpha (α) particle (4He nucleus)
  * decrease Z by 2; decrease N by 2; decrease A by 4
- gamma (γ) 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
  * α, β, γ 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

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:
  - ¹⁴C with half life of 5730 years
    * about 4000 β⁻ decays per second in this sample
    * corresponds to 25 ng, or 10¹⁵ particles
  - ⁹⁰Sr with half-life of 28.9 years
    * about 200 α⁻ decays per second in this sample
    * contains about 40 pg (70 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>40</td>
<td></td>
</tr>
<tr>
<td>air (mostly radon)</td>
<td>203</td>
<td></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>total for no travel/medical</td>
<td>316</td>
<td>387</td>
</tr>
</tbody>
</table>

source: 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 \( ^{236}\text{U} \), 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 \( ^{238}\text{U} \)?

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 lose 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

Binding energy per nucleon
- Iron ($^{56}\text{Fe}$) is at the peak
  - On the heavy side of iron, fusion delivers energy
  - On the lighter side of iron, fusion delivers energy
  - This is why normal stars stop fusion after iron
  - Huge energy step to be gained in going from hydrogen ($^{1}\text{H}$) 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
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 $^{235}\text{U}$