From Last Time...

- Nucleus is small, tightly bound system of protons & neutrons.
- Proton number determines the element.
- Different isotopes have different # neutrons.
- Some isotopes unstable, radioactively decay
- Nucleus held together by the strong nuclear force
  - Stronger than coulomb force,
  - But much shorter range than coulomb force.
- Strong force actually between quarks, internal constituents of the neutron/proton.
  ‘Leaks’ out to appear as an attractive force.

Proton and Neutron states

- Various quantum states for nucleons in the nucleus
- Proton and neutron can be in the same state

Populating nucleon states

- Various quantum states for nucleons in the nucleus
- Similar to the hydrogen atom: one electron in each quantum state.
- Two states at each energy (spin up & spin down)

[Diagram of helium isotopes]

This is \(^{4}\)He, with 2 neutrons and 2 protons in the nucleus

Other helium isotopes

- Too few neutrons, -> protons too close together.
  High Coulomb repulsion energy
- Too many neutrons, requires higher energy states.

Radioactivity

- Most stable nuclei have about same number of protons as neutrons.
- If the energy gets too high, nucleus will spontaneously try to change to lower energy configuration.
- Does this by changing nucleons inside the nucleus.
- These nuclei are unstable, and are said to decay.
- They are called radioactive nuclei.
Radioactive decay

- Decay usually involves emitting some particle from the nucleus.
- Generically refer to this as radiation.
- Not necessarily electromagnetic radiation, but in some cases it can be.
- The radiation often has enough energy to strip electrons from atoms, or to sometimes break apart chemical bonds in living cells.

Discovery of radioactivity

- Accidental discovery in 1896
- Henri Becquerel was trying to discover x-rays (discovered in 1895 by Roentgen).
- Exposed uranium compound to sunlight, then placed it on photographic plates.
- Believed uranium absorbed sun’s energy and then emitted it as x-rays.
- On the 26th-27th February, experiment “failed” because it was overcast in Paris.
- Becquerel developed plates anyway, finding strong images.
- Proved uranium emitted radiation without an external source of energy.

Detecting radiation

- A Geiger counter
- Radiation ionizes (removes electrons) atoms in the counter

Leaves negative electrons and positive ions.
Ions attracted to anode/cathode, current flow is measured

A random process

- The particle emission is a random process
  - It has some probability of occurring.
- For every second of time, there is a probability that the nucleus will decay by emitting a particle.
- If we wait long enough, all the radioactive atoms will have decayed.

Radioactive half-life

- Example of random decay.
- Start with 8,000 identical radioactive nuclei
- Suppose probability of decaying in one second is 50%.

<table>
<thead>
<tr>
<th>Undecayed nuclei</th>
<th>Every second, half the atoms decay</th>
<th>The half-life is one second</th>
</tr>
</thead>
<tbody>
<tr>
<td>t=0 sec</td>
<td>t=1 sec</td>
<td>t=2 sec</td>
</tr>
</tbody>
</table>

Radioactive decay question

A piece of radioactive material is initially observed to have 1,000 decays/sec.
Three hours later, you measure 125 decays / second.
The half-life is

A. 1/2 hour
B. 1 hour
C. 3 hours
D. 8 hours

In each half-life, the number of radioactive nuclei, and hence the number of decays / second, drops by a factor of two.

After 1 half life, the decays/sec drop to 500.
After 2 half lives it is 250 decays/sec.
After 3 half lives there are 125 decays/sec.
Another example

- $^{232}$Th has a half-life of 14 billion years
- Sample initially contains 1 million $^{232}$Th atoms
- Every 14 billion years, the number of $^{232}$Th nuclei goes down by a factor of two.

Different types of radioactivity

Unstable nuclei decay by emitting some form of energy,

- Three different types of decay observed:
  - Alpha decay
  - Beta decay
  - Gamma decay

(First three letters of Greek alphabet).

Ernest Rutherford (1899): “These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation - one that is very readily absorbed, which will be termed for convenience the alpha-radiation, and the other of more penetrative character which will be termed the beta-radiation.”

Penetrating power of radiation

- Alpha radiation very weak
- Beta radiation penetrates farther
- Gamma radiation hardest to stop

Is the radiation charged?

- Alpha radiation positively charged
- Beta radiation negatively charged
- Gamma radiation uncharged

Detecting radiation

- A Geiger counter
- Radiation ionizes (removes electrons) atoms in the counter

Leaves negative electrons and positive ions.

These are attracted to the anode/cathode, current flow is measured
Alpha radiation
- Alpha radiation now known to be a helium nucleus (2 protons, 2 neutrons)

Piece of atom (alpha particle) is broken from heavy nucleus and ejected

A new element
- When a nucleus emits an alpha-particle, it loses two neutrons and two protons.
- It becomes a different element (the number of protons in the nucleus has changed).
- Example:

\[
^{238}_{92}\text{U} \rightarrow ^{4}_{2}\text{He} + ^{234}_{90}\text{Th}
\]

Thorium is the element with 90 electrons (and hence 90 protons in the nucleus)

Why?
- Why does a piece come out of the atom?
  - All nucleons (neutrons & protons) attracted by short-range strong force
  - Protons forced apart by long-range Coulomb force.
  - Smaller nuclei will be more stable
- Why is the ejected piece an alpha-particle, and not something else?
  - Helium nucleus is much more stable than other light nuclei

Decay question
- Radium was isolated by Marie Curie in 1898.
- It has a half-life of 1,600 years and decays by alpha-emission.
- The resulting element is
  A. Polonium (84 electrons)
  B. Thorium (90 electrons)
  C. Radon (86 electrons)

Decay chain originates at $^{238}\text{U}$

Radon
- One of the daughters in the $^{238}\text{U}$ decay series.
- Radon is an alpha emitter that presents environmental hazard
- Inhalation of radon can ionize lung cells, increasing risk of lung cancer.
- Risk depends on radon concentration, which depends on concentration of uranium and other radioactive elements.
**A use for alpha-decay**

- Smoke detectors contain radioactive americium-241 (half-life 432 yrs)
- $^{241}\text{Am}$ decays by alpha emission.
- Alpha particles from the americium collide with oxygen and nitrogen particles in the air creating charged ions.
- An electrical current is applied across the chamber in order to collect these ions (just like a geiger counter!)
- When smoke is in chamber, smoke absorbs alpha particles.
- Current decreases, detected by electronics

**Decay sequence of $^{238}\text{U}$**

<table>
<thead>
<tr>
<th>Number of neutrons</th>
<th>Number of protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>92</td>
</tr>
<tr>
<td>141</td>
<td>92</td>
</tr>
<tr>
<td>142</td>
<td>92</td>
</tr>
<tr>
<td>143</td>
<td>92</td>
</tr>
<tr>
<td>144</td>
<td>92</td>
</tr>
<tr>
<td>145</td>
<td>92</td>
</tr>
<tr>
<td>146</td>
<td>92</td>
</tr>
</tbody>
</table>

**Beta decay**

- Beta radiation...
  - Now know to be an electron.
  - Radioactive nucleus emits an electron
- How can this be?
  - There are no electrons in the nucleus!
  - Has only neutrons and protons.
- Particles are not forever!
  - Charge is forever, energy/mass is forever
  - But particles can appear and disappear

**A different kind of decay**

Number of neutrons decreases by one
Number of protons increases by one
How could this happen?

**How can this be?**

- Nucleons have an internal structure.
- Made up of different types of quarks.
- In this sense, neutrons and protons not so different.
Quark structure of nucleons

- Proton = up+up+down
- Charge = $2/3 + 2/3 - 1/3 = +1$

- Neutron = up+down+down
  charge = $2/3 - 1/3 - 1/3 = 0$

Neutron decay

- Can be clearer to visualize this diagrammatically.
- One of the down quarks changed to an up quark.
- We identify this new combination of quarks as a proton.

Example of beta decay

- $^{14}$C (radioactive form of carbon) decays by beta decay (electron emission).
- Carbon has 6 electrons, so six protons.
- $^{14}$C has $(14-6)=8$ neutrons.

Now have a new element (one more proton)
Element with 7 protons in nucleus is Nitrogen

$\begin{align*}
^{14}\text{C} & \rightarrow ^{14}\text{N} + e^- \\
\text{Beta decay} & \text{number of nucleons stays fixed, but} \\
& \text{one of the neutrons changes into a proton} \\
& \text{one additional proton -> different element!}
\end{align*}$

Radioactive carbon

- $^{14}$C naturally present in the atmosphere
  as a result of transmutation of $^{14}$N.

Cosmic ray proton shatters nucleus
of atmospheric gas atom.
This produces neutrons.
Neutron knocks proton out of $^{14}$N nucleus.

$^{14}$N becomes $^{14}$C after losing neutron

Natural atmospheric abundance

- $^{14}$C is produced at a particular rate from transmutation of $^{14}$N in upper atmosphere.
- $^{14}$C is radioactive with half-life of 5,730 yrs
  - Decays at rate set by half-life
- Balance of these results in an equilibrium
  ratio $\frac{^{14}\text{C}}{^{12}\text{C}} = 1.3 \times 10^{-12}$ in the atmosphere
- One radioactive $^{14}$C atom for every $\sim 10^{12}$ non-radioactive $^{12}$C atom.

$^{14}$C to $^{12}$C ratio

- $^{14}$C has a half-life of ~6,000 years,
  continually decaying back into $^{14}$N.
- Steady-state achieved in atmosphere,
  with $^{14}$C:$^{12}$C ratio ~ 1:1 trillion (1 part in $10^{12}$)

As long as biological material alive,
atmospheric carbon mix ingested (as CO$_2$),
ratio stays fixed.

After death, no exchange
with atmosphere. Ratio starts to change
as $^{14}$C decays
Carbon-dating question
The $^{14}\text{C}:^{12}\text{C}$ ratio in a fossil bone is found to be 1/8 that of the ratio in the bone of a living animal. The half-life of $^{14}\text{C}$ is 5,730 years.

What is the approximate age of the fossil?

A. 7,640 years
B. 17,200 years
C. 22,900 years
D. 45,800 years

Since the ratio has been reduced by a factor of 8, three half-lives have passed.

$3 \times 5,730 = 17,190$ years

Other carbon decays
- Lightest isotopes of carbon are observed to emit a particle like an electron, but has a positive charge!
- This is the antiparticle of the electron.
- Called the positron.

Antimatter
- Every particle now known to have an antiparticle.
- Even antimatter has been generated.

Matter and antimatter annihilate when in close proximity.
Photons are created so that energy is conserved.

What is going on?
- $^{14}\text{C}$ has more neutrons than the most stable form $^{12}\text{C}$.
  - So it decays by electron emission, changing neutron into a proton.
- Other isotopes of carbon have fewer neutrons.
  - Decays by emitting positron, changing proton into neutron.

Decay question
$^{20}\text{Na}$ decays into $^{20}\text{Ne}$, a particle is emitted?
What particle is it?
Na atomic number = 11
Ne atomic number = 10

A. Alpha
B. Electron beta
C. Positron beta
D. Gamma

$^{20}\text{Na}$ has 11 protons, 9 neutrons
$^{20}\text{Ne}$ has 10 protons, 10 neutrons
So one a proton (+ charge) changed to a neutron (0 charge) in this decay. A positive particle had to be emitted.

Gamma decay
- So far
  - Alpha decay: alpha particle emitted from nucleus
  - Beta decay: electron or positron emitted
- Both can leave the nucleus in excited state
  - Just like a hydrogen atom can be in an excited state
  - Hydrogen emits photon as it drops to lower state.

Nucleus also emits photon as it drops to ground state
This is gamma radiation
But energies much larger, so extremely high energy photons.
Guessing the decay route

- Can often make good guesses regarding decay route
- Only heavy nuclei decay via alpha emission
- Nuclei decay in a way that produces a more stable nucleus

Light elements:

Excess neutrons -> change neutron to proton by electron emission

Too few neutrons -> change proton to neutrons by positron emission

Half-lives of alpha-decay

- Nucleus emits a helium nucleus (2 neutrons, 2 protons).
- Only heavy nuclei will alpha-decay.
- Decay is by quantum mechanical tunneling.

- Tunneling is sensitive to the nuclear barrier.
- Decay probability (and hence half-life) varies dramatically.
- Can vary 20 orders of magnitude.

Tunneling is sensitive to the nuclear barrier.
Decay probability (and hence half-life) varies dramatically.
Can vary 20 orders of magnitude.

Turning lead into gold

Radioactive decay changes one element into another by changing the number of protons in a nucleus.

This can also be done artificially by neutron bombardment.

- The transmutation of platinum into gold accomplished by a sequence of two nuclear reactions
- first: $^{198}\text{Pt} +$ neutron $\rightarrow^{199}\text{Pt}$
- second: $^{199}\text{Pt} \rightarrow^{199}\text{Au} +$ subatomic particle

Nuclear fission

- In some cases, the effect of neutron bombardment is more dramatic.
- Leads to nuclear fission, where a heavy nucleus is split apart into two smaller ones.

Fission chain reaction

- Neutrons are released in this process, leading to more fission events
- Chain reaction can result