From Last Time...

- Nucleus is small, tightly bound system of protons & neutrons.
- Proton number determines the element.
- Different isotopes have different # neutrons.
- Nucleus held together by the strong nuclear force:
  - Stronger than coulomb force,
  - But much shorter range than coulomb force.
- Some isotopes unstable, radioactively decay.

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)

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 nuclear are unstable, and are said to decay.
- They are called radioactive nuclei.

Radioactive nuclei

- Equal # neutrons and protons

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.
Detect ionizing radiation

- Ionizing radiation strips electrons from atoms.
- Makes free charges that can neutralize existing charges.
- Can discharge an electroscope.

Radioactive tracers

- Worked on radioactivity as student with Ernest Rutherford.
- Lodged in nearby boarding home.
- Suspected his landlady was serving meals later in the week “recycled” from the Sunday meat pie. His landlady denied this!
- deHevesy described his first foray into nuclear medicine:

  “The coming Sunday in an unguarded moment I added some radioactive deposit [lead-212] to the freshly prepared pie and on the following Wednesday, with the aid of an electroscope, I demonstrated to the landlady the presence of the active deposit in the soufflé.”

Geiger counter

- 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>
</tr>
</thead>
<tbody>
<tr>
<td>t=0 sec</td>
<td>t=1 sec</td>
</tr>
</tbody>
</table>

- The half-life is one second.
- 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, 5000 are left undecayed.
- After 2 half lives, 1/2 of these are left: 2,500
- After 3 half lives there are 1,250 left.

Radioactive decay question

A piece of radioactive material is initially observed to have 10,000 radioactive nuclei.
3 hours later, you measure 1,250 radioactive nuclei.
The half-life is

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

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

Radioactive decay question

A piece of radioactive material is initially observed to have 1,000 decays/sec.

It’s half life is 2 days.

Four days later, you measure

A. 1,000 decays/sec
B. 500 decays/sec
C. 250 decays/sec
D. 125 decays/sec

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
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 \(^{226}_{88}\text{Ra}\) 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)
- $^{241}$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 $^{238}$U

<table>
<thead>
<tr>
<th>Number of neutrons</th>
<th>Number of protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>decreases by one</td>
<td>increases by one</td>
</tr>
</tbody>
</table>

How could this happen?

- 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

Beta decay

- Nucleus emits an electron (negative charge)
- Must be balanced by a positive charge appearing in the nucleus.

This occurs as a neutron changing into a proton

- 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 = \( \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1 \)
- Neutron = up+down+down
- Charge = \( \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0 \)

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

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

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

\[ ^{14}\text{C} \rightarrow ^{14}\text{N} + e^- \]

\( ^{14}\text{C} \) to \( ^{12}\text{C} \) ratio

- \(^{14}\text{C}\) naturally present in the atmosphere as a result of transmutation of \(^{14}\text{N}\).

Cosmic ray proton shatters nucleus of atmospheric gas atom.
This produces neutrons.
Neutron knocks proton out of \(^{14}\text{N}\) nucleus.
\(^{14}\text{N}\) becomes \(^{14}\text{C}\) after losing neutron

Natural atmospheric abundance

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

Radioactive carbon

- \(^{14}\text{C}\) has a half-life of \(~6,000\) years, continually decaying back into \(^{14}\text{N}\).
- Steady-state achieved in atmosphere, with \(^{14}\text{C} : ^{12}\text{C}\) ratio \(
  \sim 1:1 \text{ trillion} \) \( (1 \text{ part in } 10^{12})\)
- After death, no exchange with atmosphere. Ratio starts to change as \(^{14}\text{C}\) decays

As long as biological material alive, atmospheric carbon mix ingested (as \(\text{CO}_2\)), ratio stays fixed.