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, radioactive 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.

Radioactive decay
- Said last time that some nuclei are more stable than others.
- Unstable nuclei can 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).

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)
- Heavy nucleus spontaneously emits alpha particle

A new element
- When a nucleus emits an alpha-particle, it loses two neutrons and two protons.
- It becomes a different element.
- Example:
  \[
  ^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^{4}_2\text{He}
  \]
  - 92 protons
  - 146 neutrons
  - 2 protons
  - 2 neutrons
  - 90 protons
  - 144 neutrons
A random process

- This is a quantum-mechanical process
  - It has some probability for occurring.
- For every second of time, there is a probability that the nucleus will decay by emitting an alpha-particle.
- The alpha-particle quantum-mechanically tunnels out of the nucleus.

Radioactive half-life

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

![Decay sequence of 238U](image)

![Radioactive half-life](image)

More physical half-life

- $^{232}$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.

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

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
**Radon**

- One of the daughters in the $^{226}$Ra decay series is radon.
- Radon is an alpha emitter that presents an environmental hazard.
- Inhalation of radon and its daughters can ionize lung cells enough to increase the risk of lung cancer.
- Health risk depends on radon concentration, which depends on concentration of uranium and other radioactive elements.

**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.

**Other radioactive decay**

- Beta decay
  - 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

**Not just neutrons & protons**

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

**Quarks**

- Six quarks (also six antiquarks)
- All have electrical charge, spin,
- Also have other quantum numbers...

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<th>d</th>
<th>s</th>
<th>c</th>
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Quark structure of nucleons

- Proton = up+up+down
- Charge = 2/3+2/3-1/3=+1
- Proton is a composite object, as are many other particles.
- Neutron = up+down+down= 2/3-1/3-1/3=0

Neutron into proton

- Think about this in terms of quarks.
- Neutron becomes proton by changing 1 quark.

Neutron decay

- Can be clearer to visualize this diagrammatically.

Example of beta decay

- $^{14}\text{C}$, radioactive form of carbon, decays by beta decay (electron emission).
- Carbon has 6 electrons, so six protons.
- $^{12}\text{C}$ has (12-6)=6 neutrons.
- $^{14}\text{C}$ has (14-6)=8 neutrons.
- Beta decay:
  
  \[ ^{14}\text{C} \rightarrow ^{7}\text{N} + \text{e}^{-} \]

Carbon dating

- This decay is used to time since biological substance has died.
- $^{14}\text{C}$ naturally present in the atmosphere as a result of transmutation of $^{14}\text{N}$.
- Cosmic ray proton shatters atmospheric gas nucleus, producing atmospheric neutrons.
- Neutron knocks proton out of $^{14}\text{N}$ nucleus, becoming $^{14}\text{C}$

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

- $^{14}\text{C}$ 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 of 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 $^{14}\text{C}$ decays.
Other isotopes of carbon

- Lighter forms of carbon are observed to emit a particle that looks 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?

- $^{14}$C has more neutrons than the most stable form $^{12}$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.

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

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

60CoBalt

- Is radioactive by measurement, half-life 5.3 yr.
- By what mechanism will this decay?
- From the periodic table, Co has 27 electrons.
  - Stable form of Co is $^{59}$Co, with 32 neutrons
  - $^{60}$Co has 33 neutrons, one more than most stable form
- Likely to decay by changing one of the neutrons into a proton
  - Charge conservation says electron must be emitted
  - One more proton means it becomes Nickel ($^{60}$Ni)
  - $^{60}$Ni is a stable isotope, with 26% natural abundance.
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: $^{198}\text{Pt} + \text{neutron} \rightarrow ^{199}\text{Pt}$
  - second: $^{199}\text{Pt} \rightarrow ^{199}\text{Au} + \text{subatomic particle}$

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

Nuclear Fusion
- ‘Opposite’ process also occurs, where nuclei are fused to produce a heavier nucleus, but requires large initial energy input.
- Called nuclear fusion.