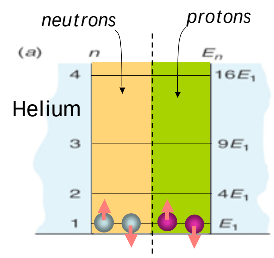
From the Last Time

- Nucleus:
  - System of protons and neutrons bound by the strong force
- Proton number determines the element.
- Different isotopes have different # neutrons.
  - Stable isotopes generally have similar number of protons and neutrons.
  - Too many of either results in a higher energy state: either nuclear energy state or coulomb energy state
- Some isotopes unstable, radioactively decay

Today: Radioactivity

Populating nucleon states

- 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)

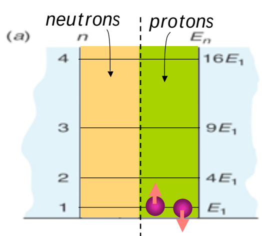


This is ^{4}He, with 2 neutrons and 2 protons in the nucleus

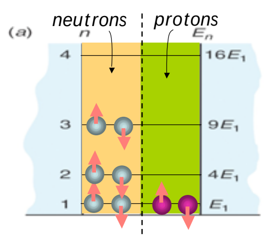
In the lowest possible energy state

Other(less stable) helium isotopes

Too few neutrons, -> protons too close together. High Coulomb repulsion energy



Too many neutrons, requires higher energy states.

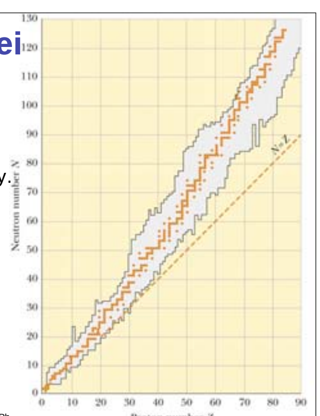


Radioactivity

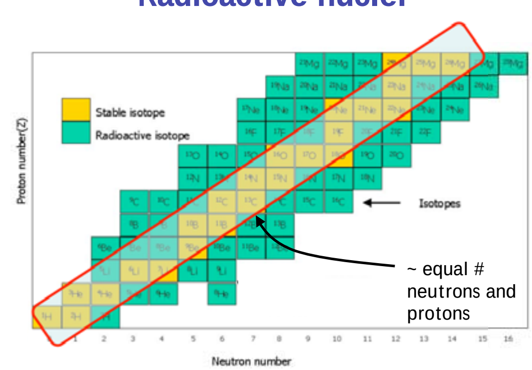
- Most stable nuclei have about same number of protons as neutrons.
- If the energy gets too high, nucleus will spontaneously try to change to lower energy configuration.
- These nuclear are unstable, and are said to decay.
- They are called radioactive nuclei.

Stability of nuclei

- Dots are naturally occurring isotopes.
- Larger region is isotopes created in the laboratory.
- Observed nuclei have ~ $N=Z$
- Slightly fewer protons because they cost Coulomb repulsion energy.



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

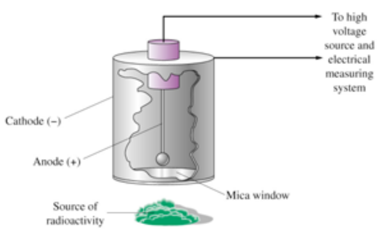
- Accidental discovery in 1896
- Henri Becquerel was trying to investigate x-rays (discovered in 1895 by Roentgen).
- Exposed uranium compound to sunlight, then placed it on photographic plates
- Believed uranium absorbed sun's energy and then emitted it as x-rays.
- On the 26th-27th February, experiment "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



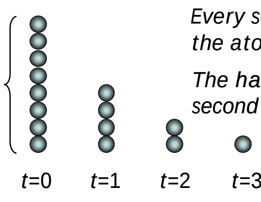
A random process

- 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%.

Undecayed nuclei



Every second, half the atoms decay

The half-life is one second

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

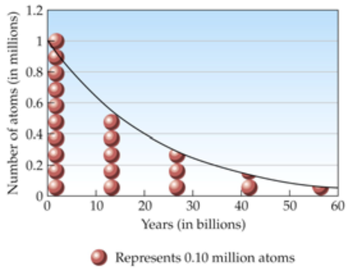
A. 1/2 hour
B. 1 hour
C. 3 hours
D. 8 hours

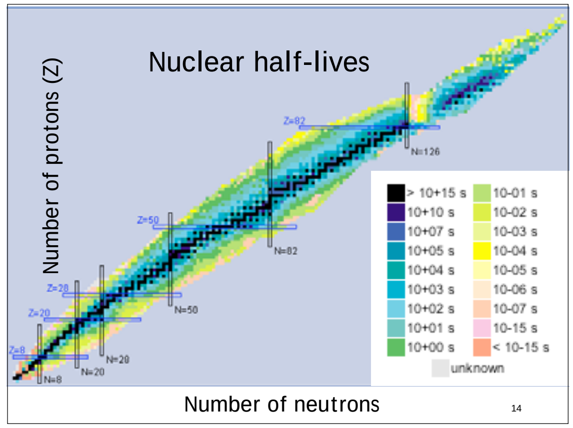
In each half-life, the number of radioactive nuclei, and hence the number of decays / second, drops by a factor of two.

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

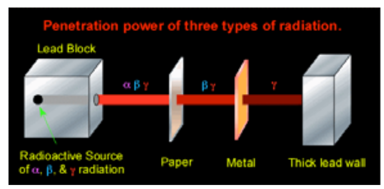
Unstable nuclei **decay** by emitting some form of energy,

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

(First three letters of Greek alphabet).

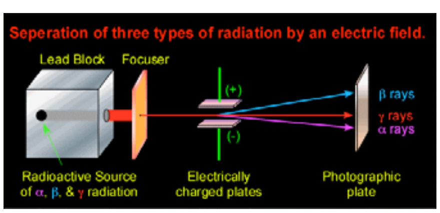
Ernest Rutherford (1899): "These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation - one that is very readily absorbed, which will be termed for convenience the alpha-radiation, and the other of more penetrative character which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

Penetrating power of radiation



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

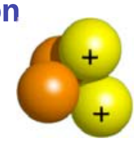
Is the radiation charged?



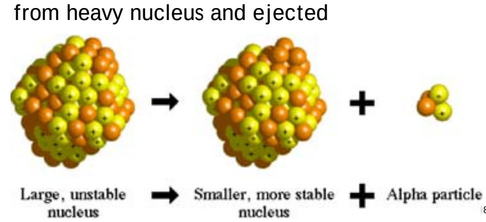
- Alpha radiation positively charged
- Beta radiation negatively charged
- Gamma radiation uncharged

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:

Alpha particle

$$^{238}_{92}U \rightarrow \boxed{^{4}_{2}He} + {}^{234}_{90}Th$$

92 protons 146 neutrons	2 protons 2 neutrons	90 protons 144 neutrons

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
  - Smaller Thorium nucleus more stable as well
  - Overall energy state is less

Decay question

Radium $^{226}_{88}Ra$ was isolated by Marie Curie in 1898. It has a half-life of 1,600 years and decays by alpha-emission.

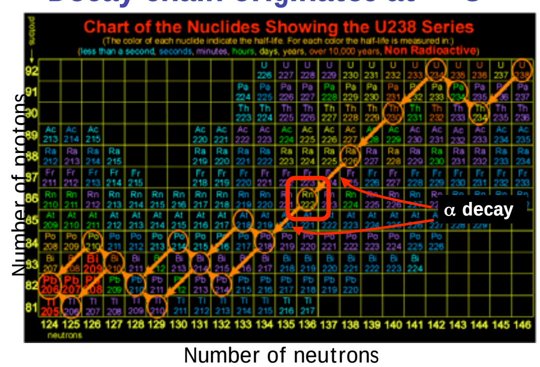
The resulting element is

A. Polonium (84 electrons)

B. Thorium (90 electrons)

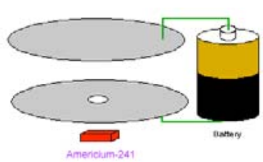
C. Radon (86 electrons)

Decay chain originates at ^{238}U

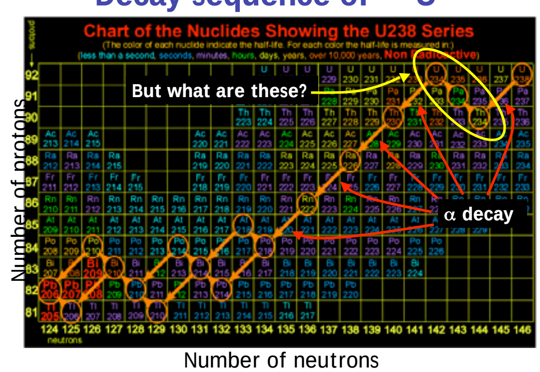


A use for alpha-decay

- 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 geiger counter!)
- When smoke is in chamber, smoke absorbs alpha particles.
- Current decreases, detected by electronics



Decay sequence of ^{238}U

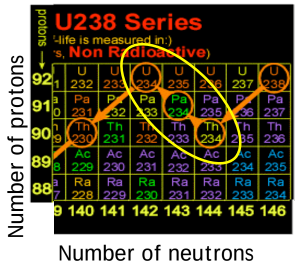


A different kind of decay

Number of neutrons decreases by one

Number of protons increases by one

How could this happen?



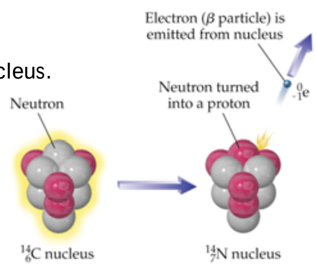
Beta decay

- 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 or be changed

Beta decay

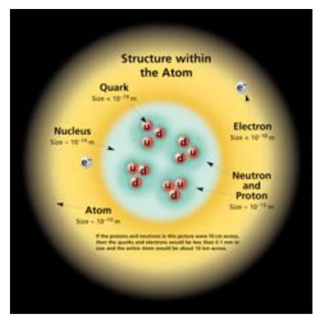
- Nucleus emits an electron (negative charge)
- Must be balanced by a positive charge appearing in the nucleus.

This occurs as a neutron changing into a proton



How can this be?

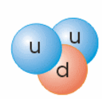
- Nucleons have an internal structure.
- Made up of different types of quarks.
- In this sense, neutrons and protons not so different.



Quark structure of nucleons

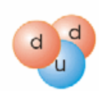
- Proton = up+up+down
- Charge = 2/3+2/3-1/3 = +1

The Proton



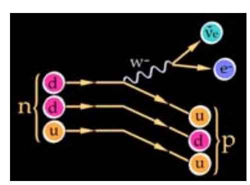
- Neutron = up+down+down charge = 2/3-1/3-1/3 = 0

The Neutron



Neutron decay

- Can be clearer to visualize this diagramatically.
- One of the down quarks changed to an up quark.
- We identify this new combination of quarks as a proton.
- A new process unlike any other we've seen: The Weak Force



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

$$^{14}_{6}C \rightarrow ^{14}_{7}N + e^{-}$$

Beta decay

number of nucleons stays fixed, but
one of the neutrons changes into a proton
one additional proton -> different element!

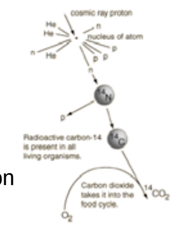
Radioactive carbon

- ^{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 $\frac{^{14}C}{^{12}C} = 1.3 \times 10^{-12}$ in the atmosphere

- One radioactive ^{14}C atom for every ~ 10^{12} non-radiocative ^{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 $^{14}CO_2$), ratio stays fixed.

After death, no exchange with atmosphere. Ratio starts to change as ^{14}C decays

Carbon-dating question

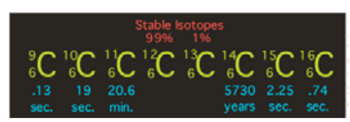
The ^{14}C:^{12}C ratio in a fossil bone is found to be 1/8 that of the ratio in the bone of a living animal.
The half-life of ^{14}C is 5,730 years.
What is the approximate age of the fossil?

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

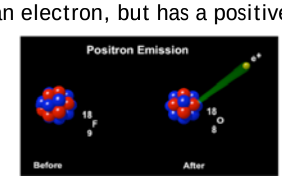
Since the ratio has been reduced by a factor of 8, three half-lives have passed.

3 x 5,730 years = 17,190 years

Other carbon decays



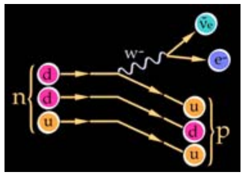
- Lightest isotopes of carbon are observed to emit a particle like an electron, but has a positive charge!

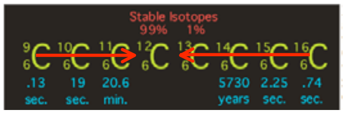


- This is the **antiparticle** of the electron.
- Called the **positron**.

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.



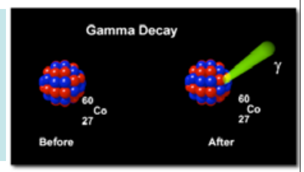


Gamma decay

- 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.



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}Pt + neutron --> ^{199}Pt
- second: ^{199}Pt --> ^{199}Au + subatomic particle