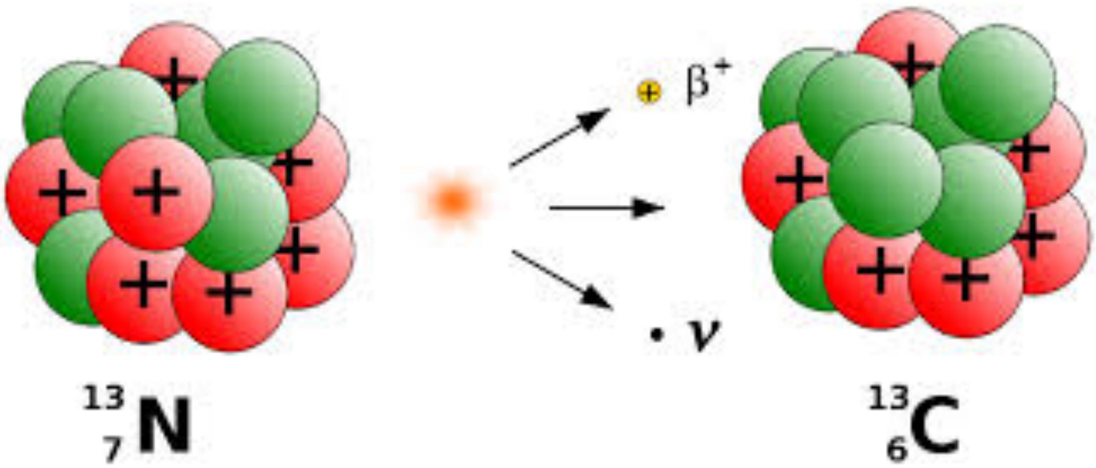
PHY20004 Nuclear Physics Class 3: Radioactivity

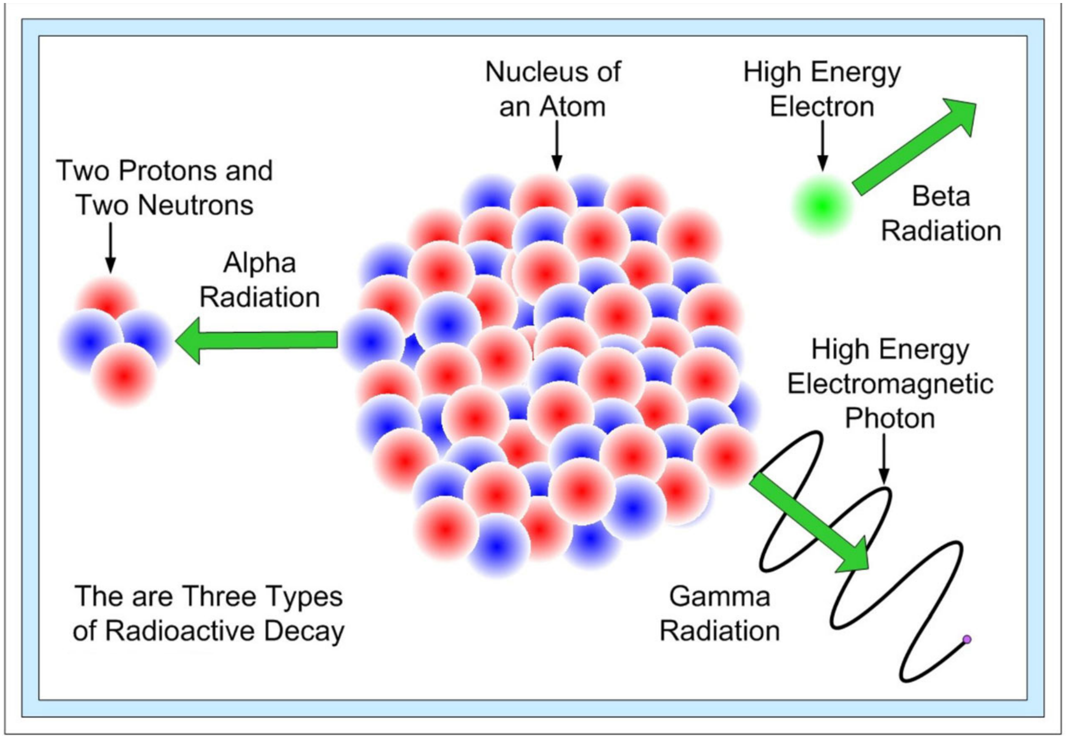
In this class we will describe the basic types of nuclear radioactive decay, that produce α, β and γ particles



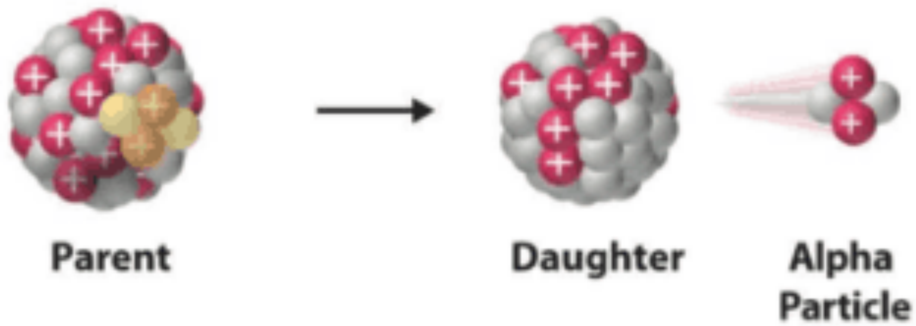
Introducing radioactivity

- Radioactivity is the **spontaneous transformation of an unstable nucleus**, involving the emission of radiation
- Radioactive decay can occur if the nucleons are arrange-able in a **lower energy state** than their current configuration

We will discuss the three common types of nuclear radioactive decay, which are labelled α, β, γ decays



α decays



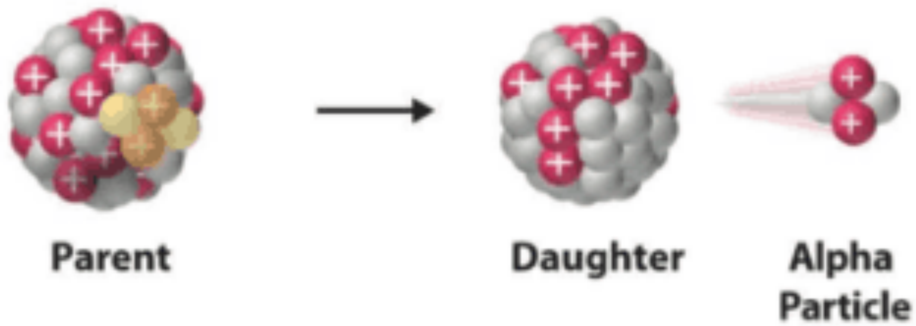
Helium nucleus consists of 2 protons and 2 neutrons

$$^{A}_{Z}X \quad \rightarrow \quad ^{A-4}_{Z-2}Y + {}^{4}_{2}He \quad (+\text{ energy } Q)$$

- α-decay occurs when a nucleus is too large to be stable, and disintegrates to a lower-energy state by **ejecting a helium nucleus**, which is also known as an α-particle

- α-decay requires the parent to have **mass number $\boldsymbol{A \gtrsim 150}$** in order that the decay is spontaneous (i.e. energy $Q > 0$)

α decays



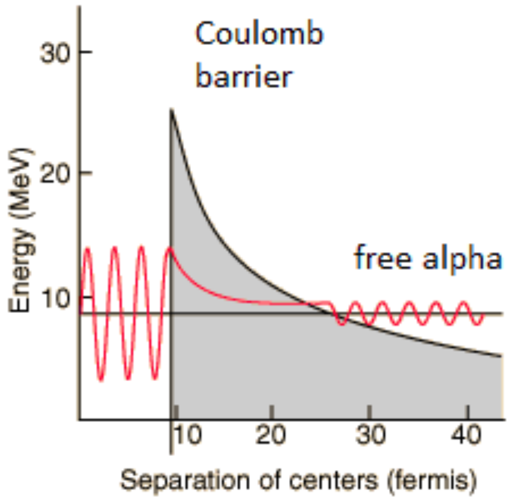
$$^{A}_{Z}X \quad \rightarrow \quad ^{A-4}_{Z-2}Y + {}^{4}_{2}He \quad (\text{+ energy } Q)$$

- Although other types of fission are possible, α-decay is dominant because $^{4}_{2}\mathrm{He}$ is **very tightly bound** (doubly magic!)
- Consider the energy released from the following decays of ^{232}U : the only spontaneous decay (with $Q > 0$) is ^{4}He

	n	p	^{2}H	^{3}H	^{3}He	^{4}He	^{5}He	^{6}Li	^{7}Li
Q/MeV	-7.26	-6.12	-10.70	-10.24	-9.92	+5.41	-2.59	-3.79	-1.94

α decays

- The escape of an α-particle from the nucleus is an example of **quantum tunneling**



Credit: https://www.nuclear-power.net/

- Tunneling is a quantum phenomenon which allows the α-particle to violate energy conservation for a brief period of time, owing to the **quantum uncertainty principle**

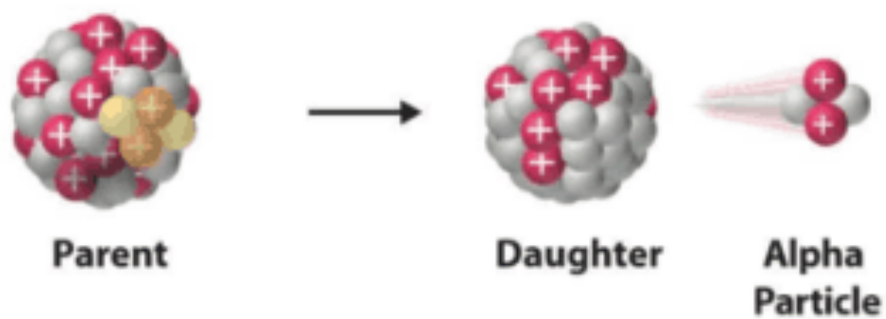
- Having tunneled out of the nucleus, the α-particle is ejected by **Coulomb repulsion**

- The mean lifetime of the unstable nucleus is *highly sensitive to the height of the potential barrier* and can vary between 10^{-7} s and 10^{+10} yr! (see: the **Geiger-Nuttall law**)

Calculating the energy released

- As the nucleus disintegrates to a lower energy configuration, α-decay releases energy Q which takes the form of the **kinetic energy of the decay products**

- Q can be calculated as the **difference in the binding energy** B between the decay products and the initial nucleus



$$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}Y + \, ^{4}_{2}He$$

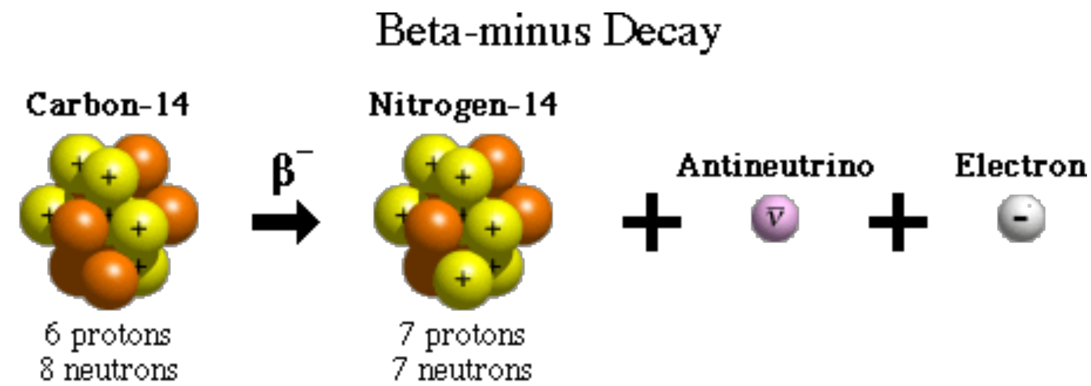
Binding energy of α-particle is $B(\alpha) = 28.3\ MeV$

$$Q = B(\alpha) + B(A-4, Z-2) - B(A, Z)$$

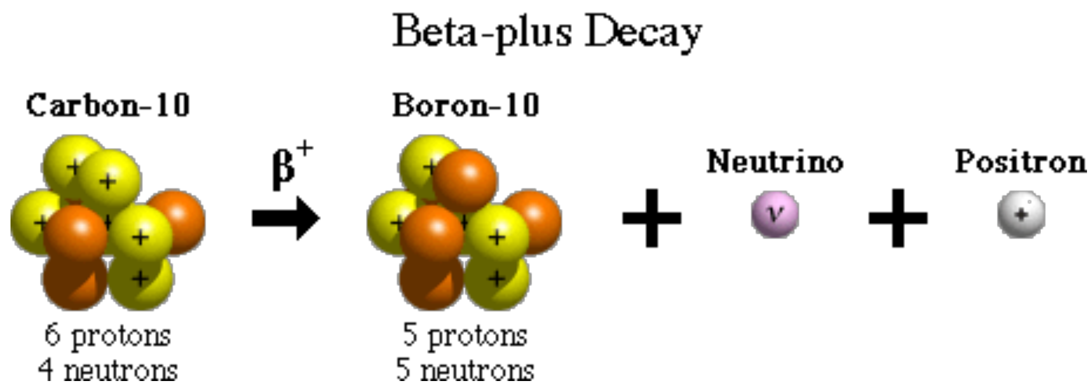
β decays

- β-decay is the transformation of a neutron-rich (or proton-rich) nucleus by the **direct conversion of a neutron into a proton** (or vice versa)

Neutron transforms into proton



Proton transforms into neutron



Credit: https://education.jlab.org

β decays

- β-decay transforms the number of protons Z and neutrons N in a nucleus closer to the **line of stability** $Z \sim N$

- There are 3 forms of β-decay:
  - **β^- decay**: N is too large for stability, and a neutron becomes a proton involving the emission of an electron and anti-neutrino

    $$n \to p + e^- + \bar{\nu}_e \qquad {}^{A}_{Z}X \to {}_{Z+1}^{\;\;A}Y^+ + {}_{-1}^{\;0}e^- + \bar{\nu}_e$$

  - **β^+ decay**: Z is too large for stability, and a proton becomes a neutron involving the emission of a positron and a neutrino

    $$p \to n + e^+ + \nu_e \qquad {}^{A}_{Z}X \to {}_{Z-1}^{\;\;A}Y^- + {}_{+1}^{\;0}e^+ + \nu_e$$

  - **Electron capture**: Z is too large for stability, and an atomic electron strays too close to the nucleus and reacts with a proton, producing a neutron (within the nucleus) and a neutrino

    $$p + e^- \to n + \nu_e \qquad {}^{A}_{Z}X + {}_{-1}^{\;0}e^- \to {}_{Z-1}^{\;\;A}Y^- + \nu_e$$

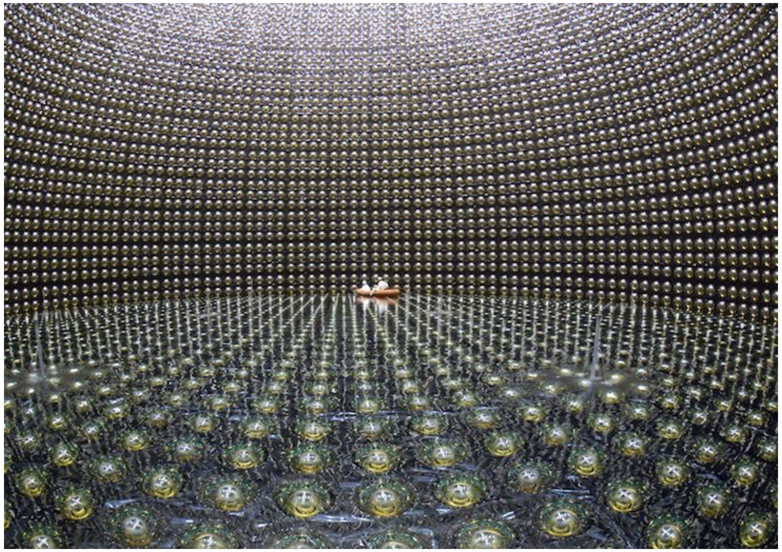
Neutrinos

- The production of new particles called **neutrinos** is an interesting feature of β-decay

- Neutrinos are weakly-interacting, electrically-neutral particles with near-zero mass

- Their existence is required to **ensure energy and momentum conservation** during β-decay

- *We'll hear much more about neutrinos later in the course!*

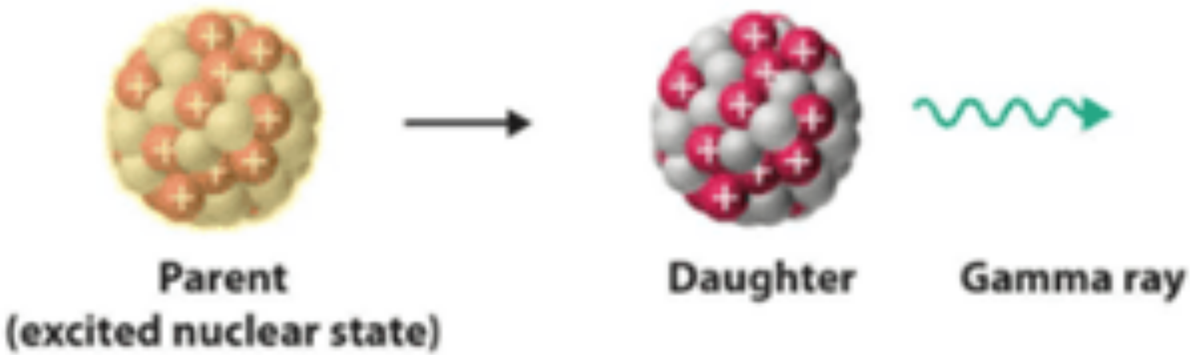


The Super-Kamiokande detector in Japan, an underground neutrino detector

Note: a proton cannot decay in free space (since it's the lightest baryon), but inside a nucleus it can decay by borrowing some energy from the binding energy

γ decays

- γ-decay occurs when a nucleus is in an excited state – often following α- or β-decay – and reverts to the ground state, **emitting a photon** (also known as a γ-ray)



$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + {}^{0}_{0}\gamma$$

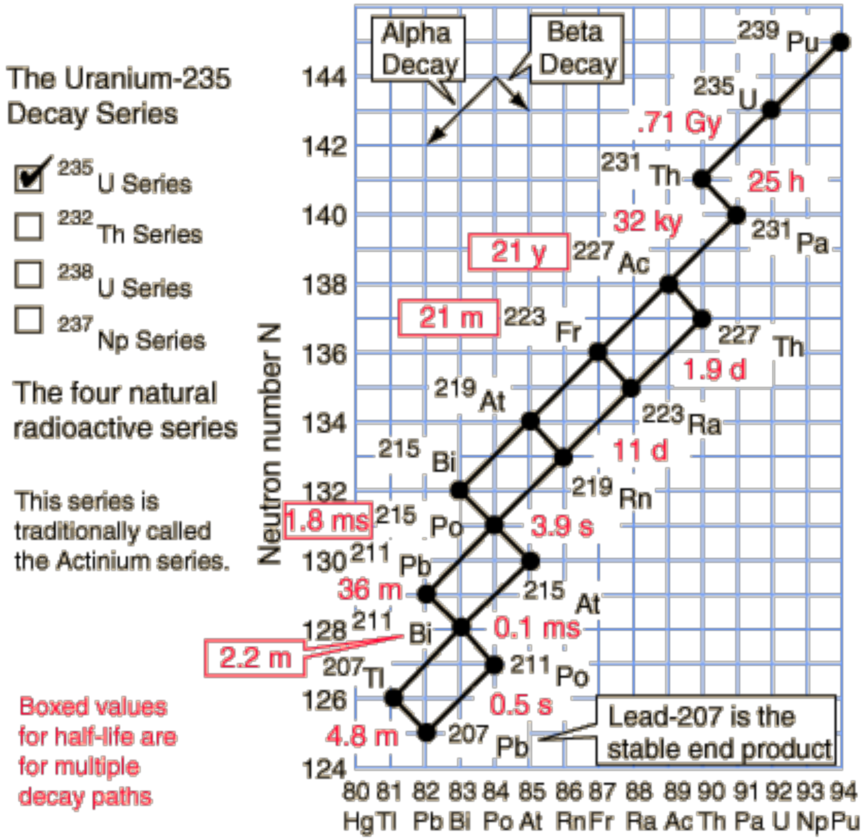
- γ-decay is similar to atomic de-excitation, but occurs at much higher energy ($\sim$ MeV vs. $\sim$ eV)

Radioactive decay chains

- The products of radioactive decay may themselves be unstable to decay – creating a **decay chain**

- Here's the decay chain for **Uranium-235** – notice the very different half-lives of different steps!

- *We'll discuss this in more detail in the next class*



Credit: http://hyperphysics.phy-astr.gsu.edu/

Key take-aways

- Radioactive decay is a **spontaneous process** which occurs when nucleons re-arrange themselves into a lower-energy configuration

- We can distinguish **three main cases**:

- **α-decay**: transformation of a large nucleus ($A \gtrsim 150$) by the emission of a ${}^{4}_{2}He$ particle, via quantum tunneling

- **β-decay**: transformation of a neutron into a proton (or vice versa), emitting an electron (or positron) and neutrino

- **γ-decay**: de-excitation of a nucleus, involving the emission of a photon