



Phys 102 – Lecture 27

The strong & weak nuclear forces

4 Fundamental forces of Nature

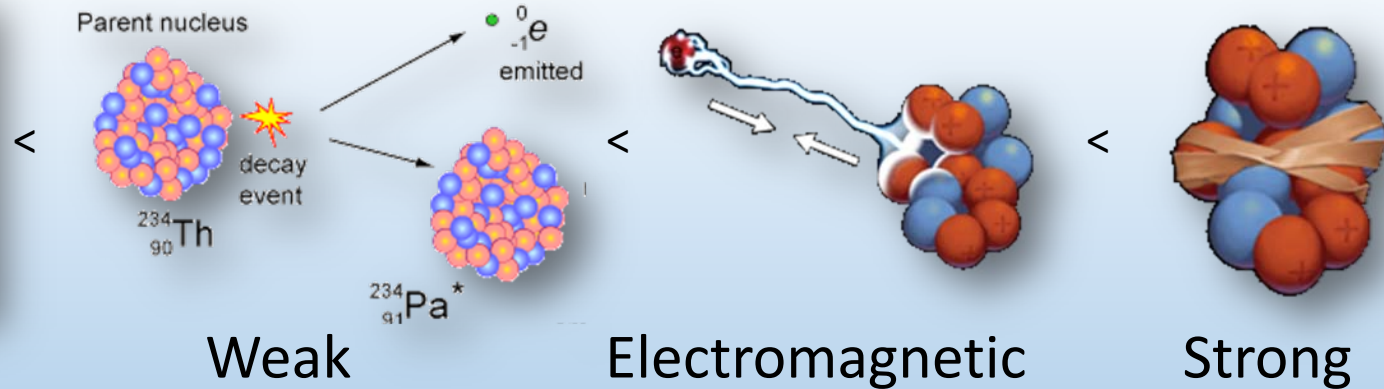
Gravitational force (solar system, galaxies)

Electromagnetic force (atoms, molecules)

Today {
Strong force (atomic nuclei)
Weak force (radioactive decay)



Gravitational

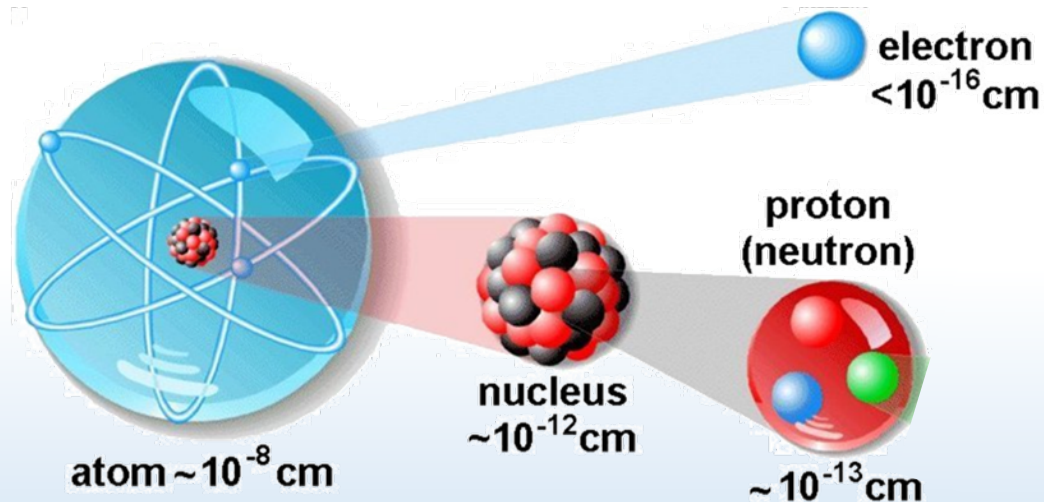


weakest

strongest

The nucleus

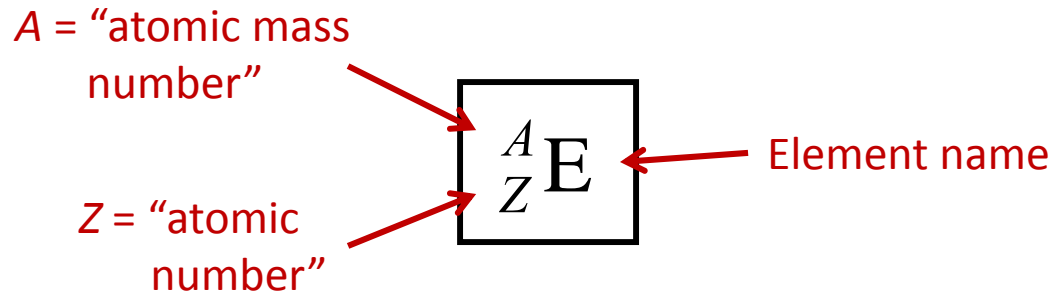
All + charge of the atom is inside a small *nucleus*, which is made up of *protons* and *neutrons* (“nucleons”)



Particle	Mass (MeV/c ²)	Charge
electron	0.511	-e
proton	938.3	+e
neutron	939.5	0

Nuclear nomenclature

A nucleus is composed of Z *protons* and N *neutrons* (“nucleons”)



$$A = N + Z$$

A = nucleon number (gives mass of nucleus since $m_{\text{prot}} \approx m_{\text{neut}} \gg m_{\text{elec}}$)

Z = proton number = electron number (gives element name & chemical properties)

Ex: Elements with different nuclei are known as *isotopes*



“protium”



“deuterium”



“tritium”



ACT: CheckPoint 1.1

A material is known to be made from an isotope of lead (Pb).

Based on this information which of the following can you specify?

- A. The atomic mass number
- B. The neutron number
- C. The proton number

Nucleus size

Mass densities of nuclei are approximately the same

$$\rho_{nucleus} = \frac{M_{nucleus}}{V_{nucleus}} \quad \text{and} \quad M_{nucleus} \propto A \quad \text{so} \quad V_{nucleus} = \frac{4\pi}{3} r^3 \propto A$$

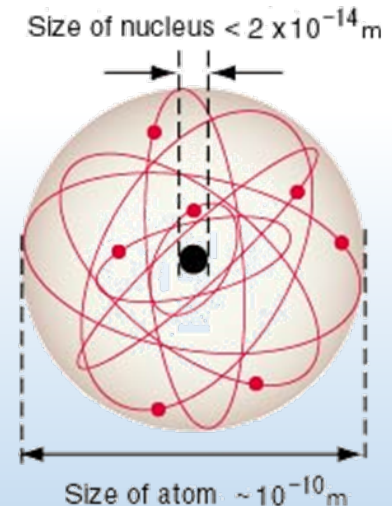
$$r \approx A^{1/3} \cdot 1.2 \times 10^{-15} \text{ m} \quad \text{fm "femtometer"}$$

Ex: deuterium (1 proton + 1 neutron)

$$\text{Ex: } \left. \begin{array}{l} {}_{13}^{27}\text{Al} \quad r_{nucleus} \approx 3.6 \times 10^{-15} \text{ m} \\ r_{atom} \approx 1.4 \times 10^{-10} \text{ m} \end{array} \right\} 10^4 - 10^5$$

Compared to size of atom (outer e⁻ shell)

How do protons not repel each other inside nucleus?

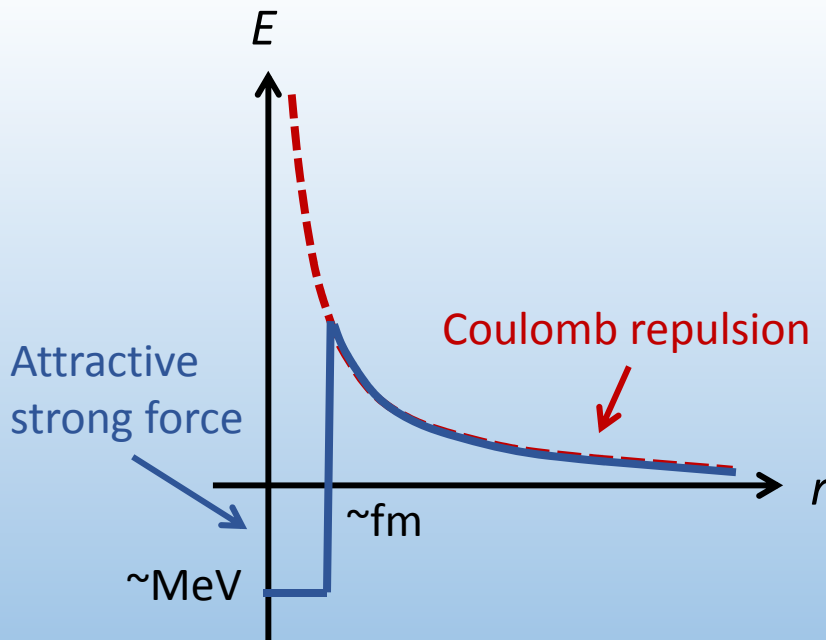
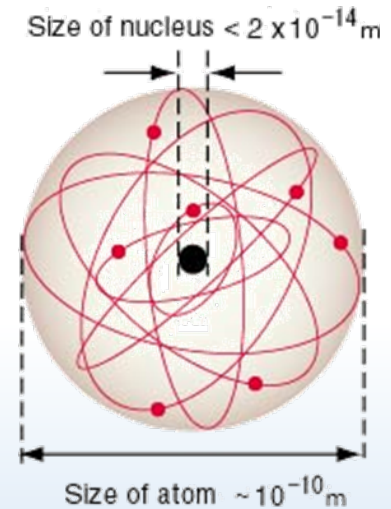


Strong nuclear force

Electric potential energy of two protons in 1 fm nucleus:

$$U_{p-p} = +\frac{ke^2}{r} = \frac{1.44 \text{ eV} \cdot \text{nm}}{1 \times 10^{-6} \text{ nm}} = 1.44 \text{ MeV}$$

Strong nuclear force binds nucleons together, overcomes Coulomb repulsion at fm distances



Ex: deuterium (1 proton + 1 neutron)

$$\left. \begin{array}{l} E_{\text{deuteron}} \approx 2.2 \text{ MeV} \\ E_{\text{atom}} \approx 13.6 \text{ eV} \end{array} \right\} 10^5$$

DEMO

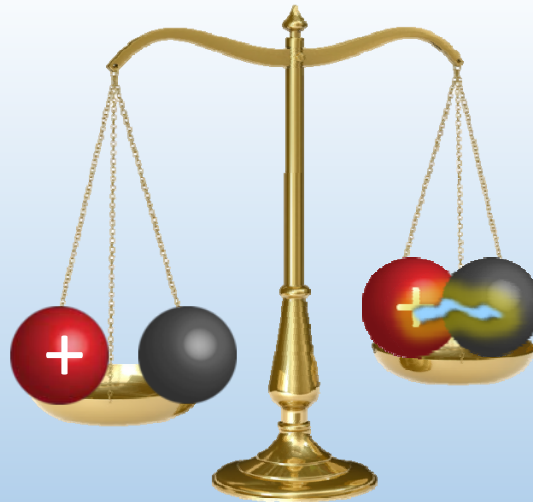
Binding energy & mass defect

Nuclear binding energy decreases mass of nucleus

Einstein's equation: $E_0 = mc^2$ Equivalence of mass and energy

$$m_{\text{nucleus}} = Zm_{\text{prot}} + Nm_{\text{neut}} - \frac{|E_{\text{bind}}|}{c^2} \quad \text{"Mass defect"}$$

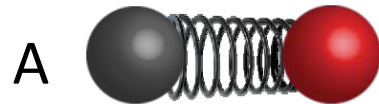
Ex: deuteron = 1 proton + 1 neutron





ACT: Binding Energy

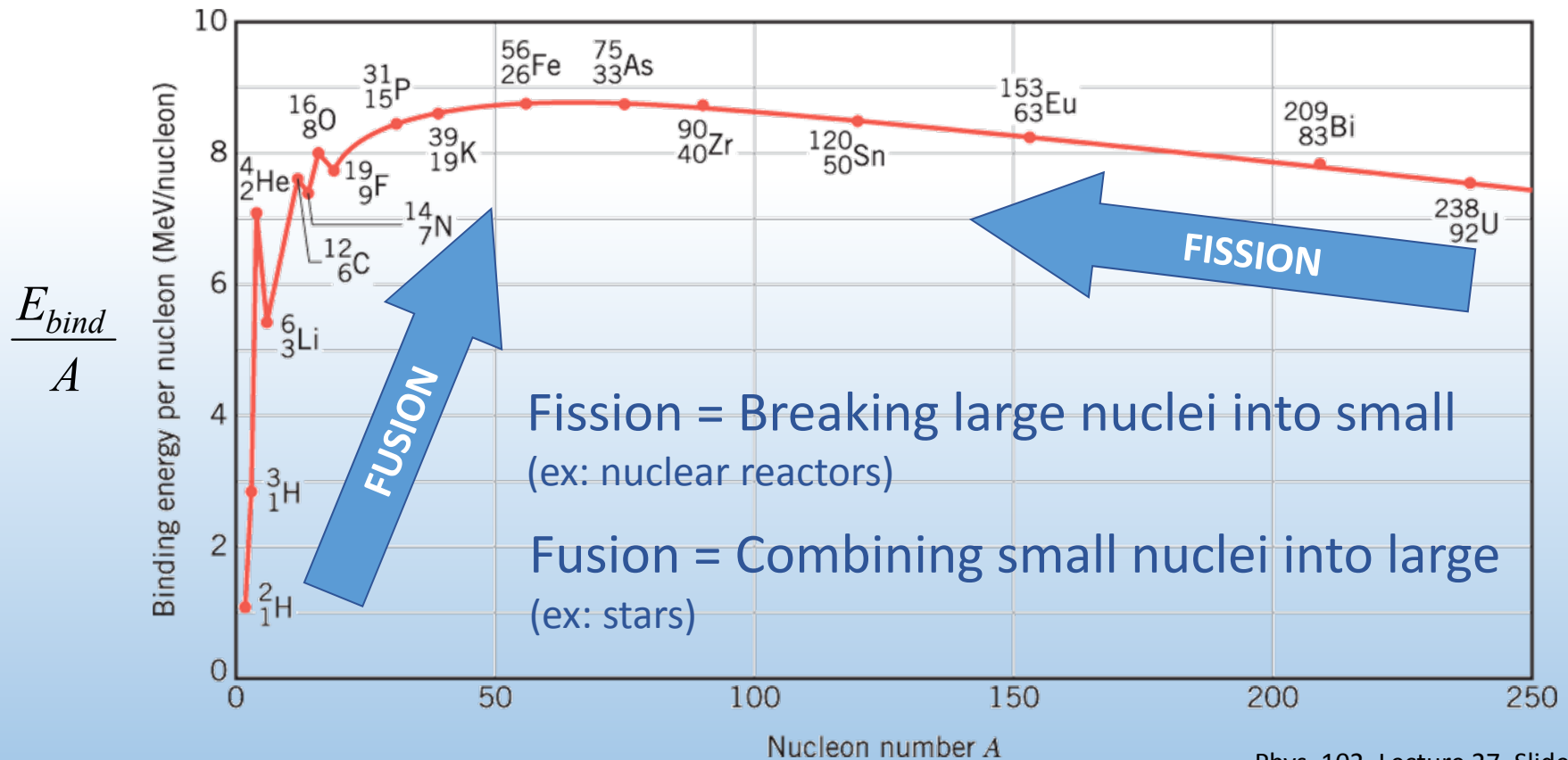
Which system “weighs” more?



- A. Two balls attached by a relaxed spring
- B. Two balls attached by a stretched spring
- C. They have the same weight

Binding energy plot

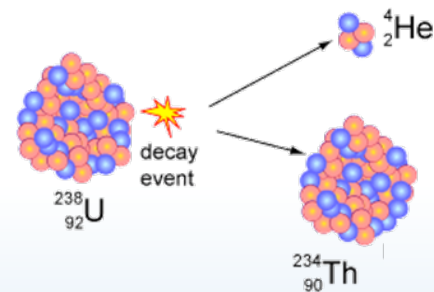
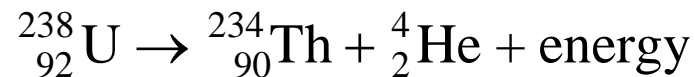
Binding energy per nucleon increases with A due to higher strong force, then decreases due to Coulomb repulsion





ACT: Uranium mass

^{238}U is long-lived but ultimately unstable. Eventually, it will spontaneously break into a ^4He and ^{234}Th nucleus, and release a tremendous amount of energy:



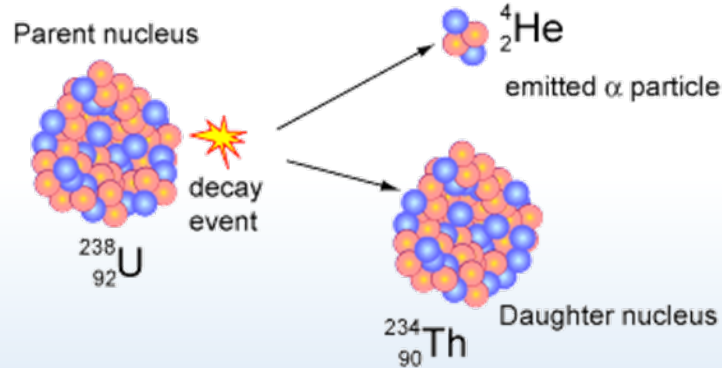
What must be true about the masses of the nuclei?

- A. $m_U > m_{\text{Th}} + m_{\text{He}}$
- B. $m_U = m_{\text{Th}} + m_{\text{He}}$
- C. $m_U < m_{\text{Th}} + m_{\text{He}}$

Radioactive decay

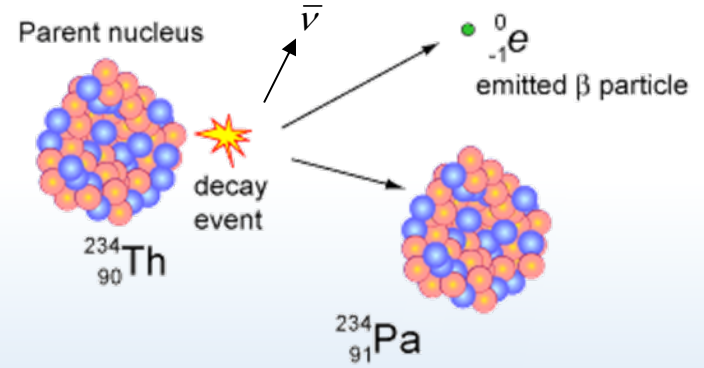
There are 3 types of radioactive decay:

α particle: ${}^4_2\text{He}$ nucleus



Easily stopped

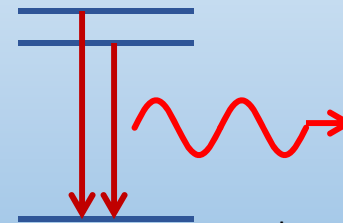
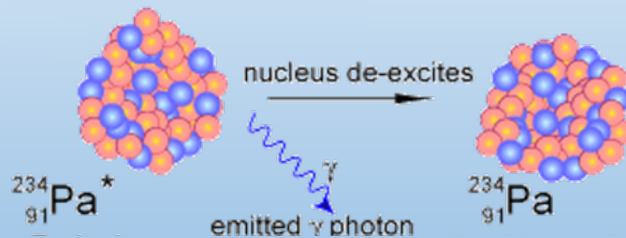
β^- particle: electron



Stopped by metal

γ radiation: photon (more energetic than x-rays)

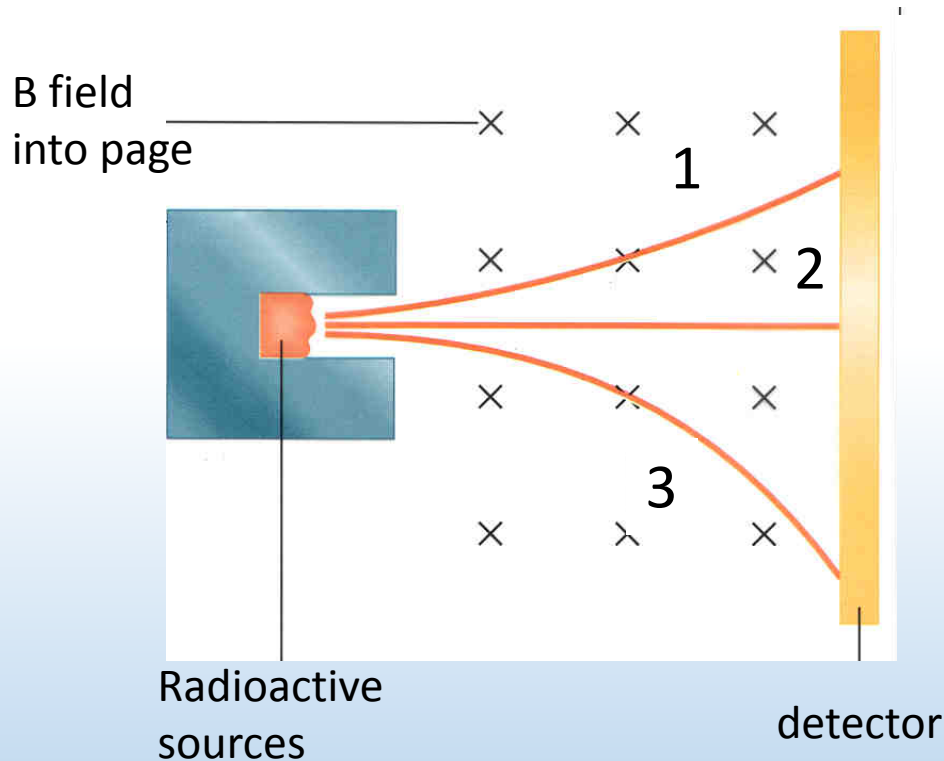
Penetrate





ACT: Types of radioactivity

Consider the following trajectories from α , β^- , and γ sources



Which of the trajectories must belong to an α particle?

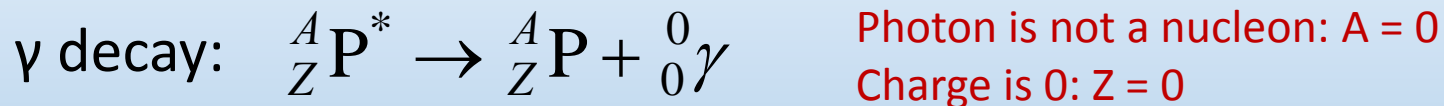
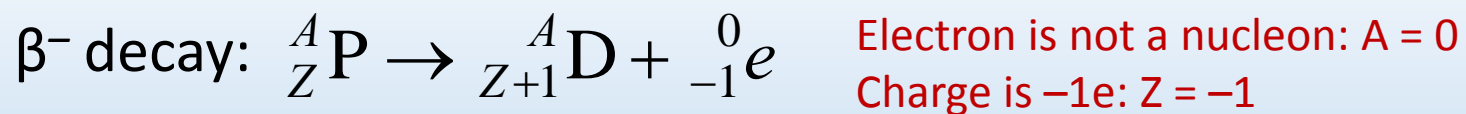
A. 1

B. 2

C. 3

Radioactive decay rules

- 1) Nucleon Number (A) is conserved.
- 2) Atomic Number (Z) is conserved.
- 3) Energy and momentum are conserved.



“nuclear isomer”
excited state



ACT: Checkpoint 2.1

A nucleus undergoes α decay. Which of the following is FALSE?

- A. Nucleon number decreases by 4
- B. Neutron number decreases by 2
- C. Charge on nucleus increases by 2



ACT: Checkpoint 2.2

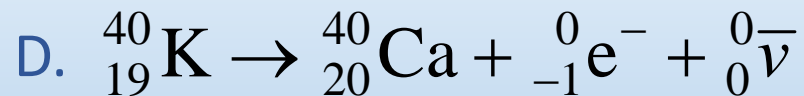
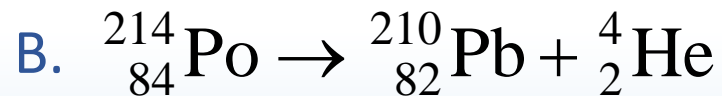
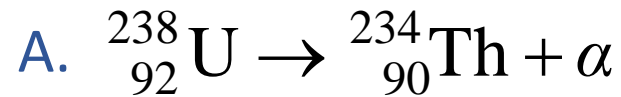
The nucleus ${}_{90}^{234}\text{Th}$ undergoes β^- decay. Which of the following is true?

- A. The number of protons in the daughter nucleus increases by one.
- B. The number of neutrons in the daughter nucleus increases by one



ACT: Decay reactions

Which of the following decays is NOT allowed?

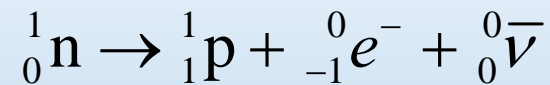
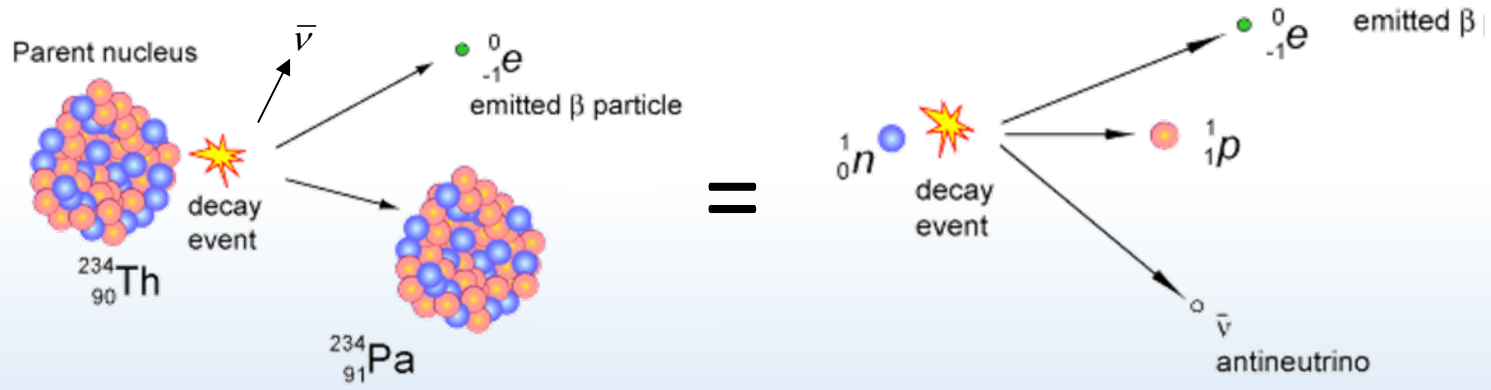


Weak nuclear interaction

α decay is a fission reaction (strong force vs. Coulomb repulsion)

γ decay is transition between nuclear energy levels

β^- decay converts a neutron into a proton:



“Weak” interaction is mechanism behind this decay process

Range only 10^{-18} m and $10^{-6}\times$ weaker than strong interaction!

Radioactive decay rates

Decay reactions are probabilistic

“Activity” or rate of decay

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

Number of un-decayed nuclei

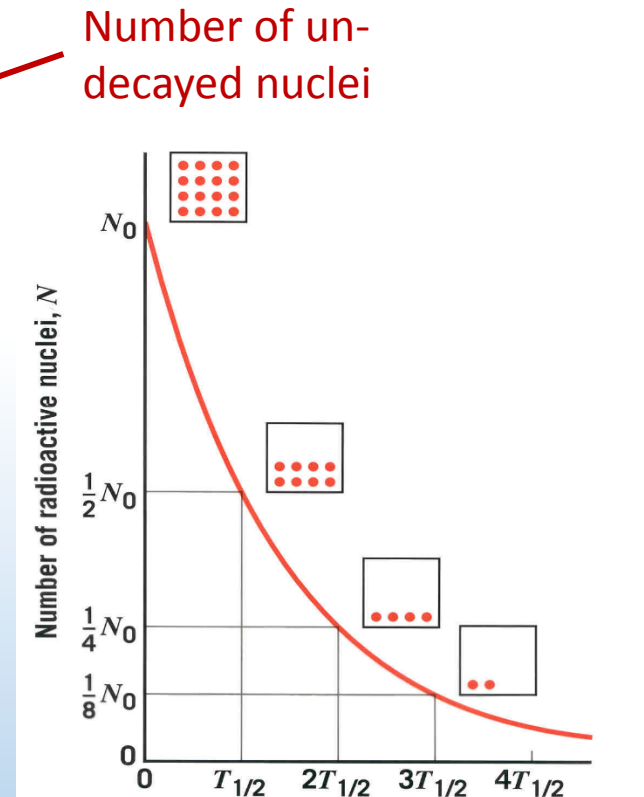
Decay constant

Units: “Becquerel”
(1 Bq \equiv 1 decay/s)

$$N(t) = N_0 e^{-\lambda t} = N_0 2^{-t/T_{1/2}}$$

$$T_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda}$$

“Half-life” = time for $\frac{1}{2}$ of the nuclei to decay



Ex: At $t = T_{1/2}$, $\frac{1}{2}$ the nuclei survived & the activity decreased by $\frac{1}{2}$
At $t = 2T_{1/2}$, $\frac{1}{4}$ the nuclei survived & the activity decreased by $\frac{1}{4}$

Calculation: carbon dating

1 in $\sim 8 \times 10^{11}$ C atoms is ^{14}C and β^- decays with a $T_{1/2}$ of 5730 years. Determine how many decays/s per gram of carbon occur in a living organism.

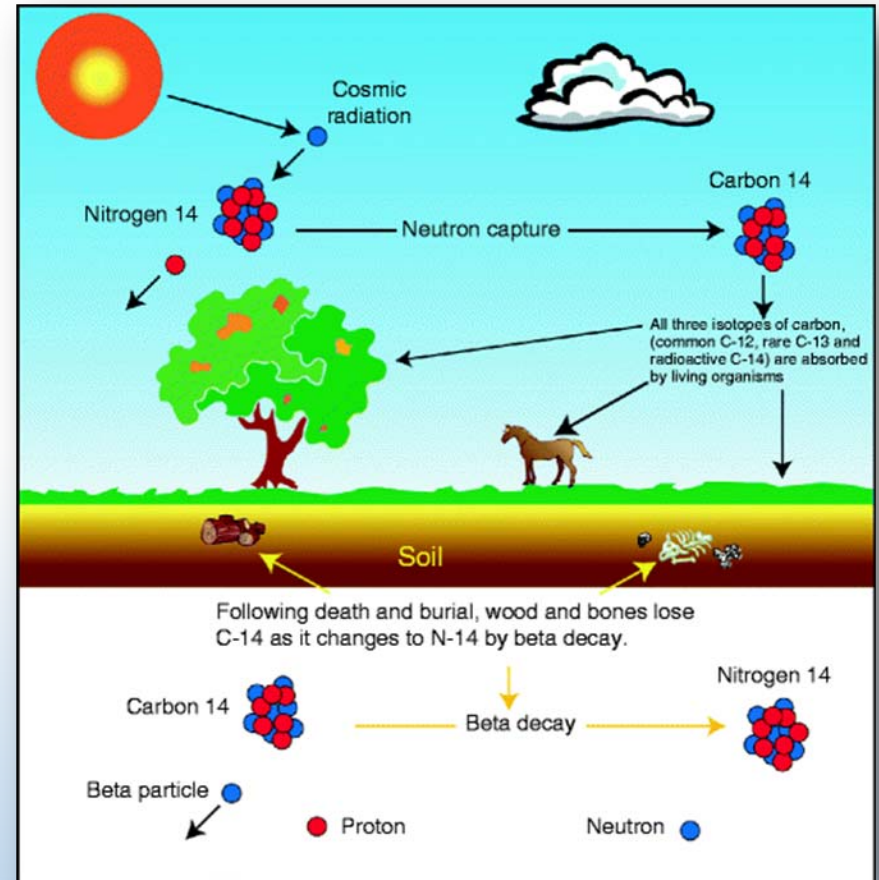
$$\frac{\Delta N}{\Delta t} = -\lambda N$$

Decay constant:

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

Number N of ^{14}C atoms per gm:

$$N = \left(\frac{\# \text{ } ^{12}\text{C atoms/gm}}{8.3 \times 10^{11}} \right)$$





ACT: Carbon dating

In the previous example we found that the ^{14}C activity in living organisms is 0.24 Bq per gram of sample.

The half-life for β^- decay of ^{14}C is $\sim 6,000$ years. You test a fossil and find that its activity is 0.06 Bq/gm. How old is the fossil?



- A. 3,000 years
- B. 6,000 years
- C. 12,000 years

Summary of today's lecture

- Nuclear atom

Nuclei composed of neutrons & protons (nucleons)

Strong force binds nucleons together -> “mass defect”

- Radioactive decay

Three types: α (He nucleus), β^- (electron), γ (photon)

Nucleon number, charge, energy/momentum conserved

- Decay rate

$T_{1/2}$ is time for $\frac{1}{2}$ of nuclei to decay & for activity to decrease by $\frac{1}{2}$

$$\frac{\Delta N}{\Delta t} = -\lambda N \quad N(t) = N_0 2^{-t/T_{1/2}}$$