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

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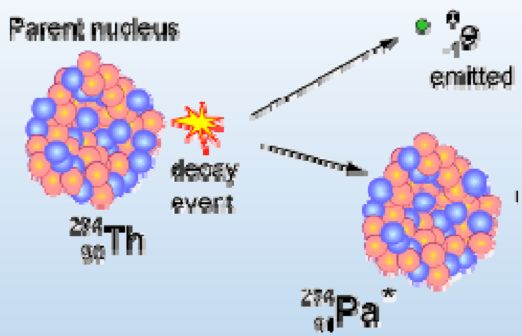

Weak

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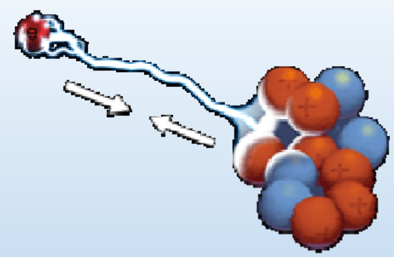

Electromagnetic

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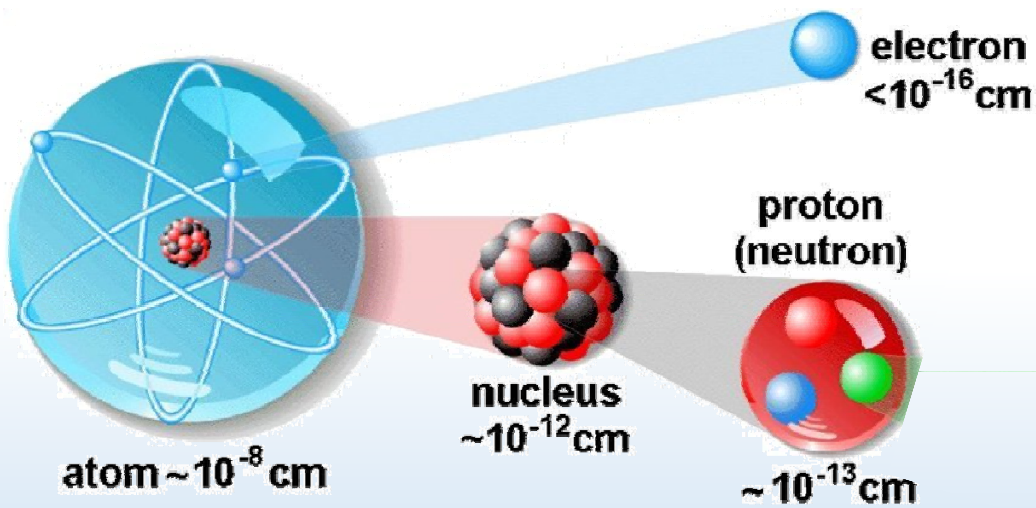
Strong

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 = "atomic mass number" → $^{A}_{Z}\mathrm{E}$ ← Element name

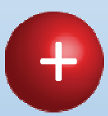
Z = "atomic number" → $^{A}_{Z}\mathrm{E}$

$$A = N + Z$$

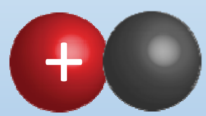
A = nucleon number (gives mass of nucleus since $m_{prot} \approx m_{neut} \gg m_{elec}$)

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

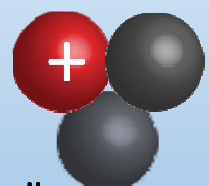
Ex: Elements with different nuclei are known as *isotopes*

$^{1}_{1}\mathrm{H}$ 

"protium"

$^{2}_{1}\mathrm{H}$ 

"deuterium"

$^{3}_{1}\mathrm{H}$ 

"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

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

$$r \approx A^{1/3} \cdot 1.2 \times 10^{-15}\,\mathrm{m}$$

fm "femtometer"

Ex: deuterium (1 proton + 1 neutron)

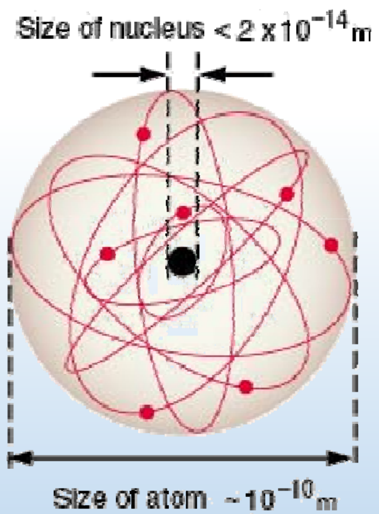
Ex: $^{27}_{13}\mathrm{Al}$

$$r_{nucleus} \approx 3.6 \times 10^{-15}\,\mathrm{m}$$

$$r_{atom} \approx 1.4 \times 10^{-10}\,\mathrm{m}$$

$10^4 - 10^5$

Compared to size of atom (outer e^- shell)

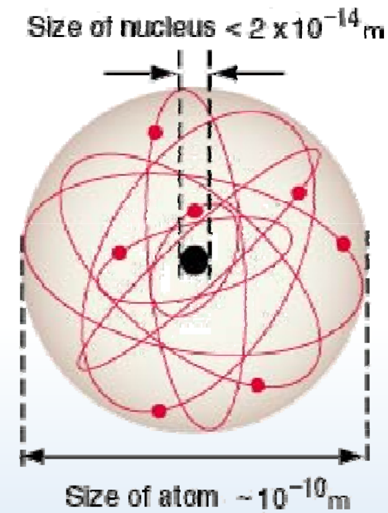


How do protons not repel each other inside nucleus?

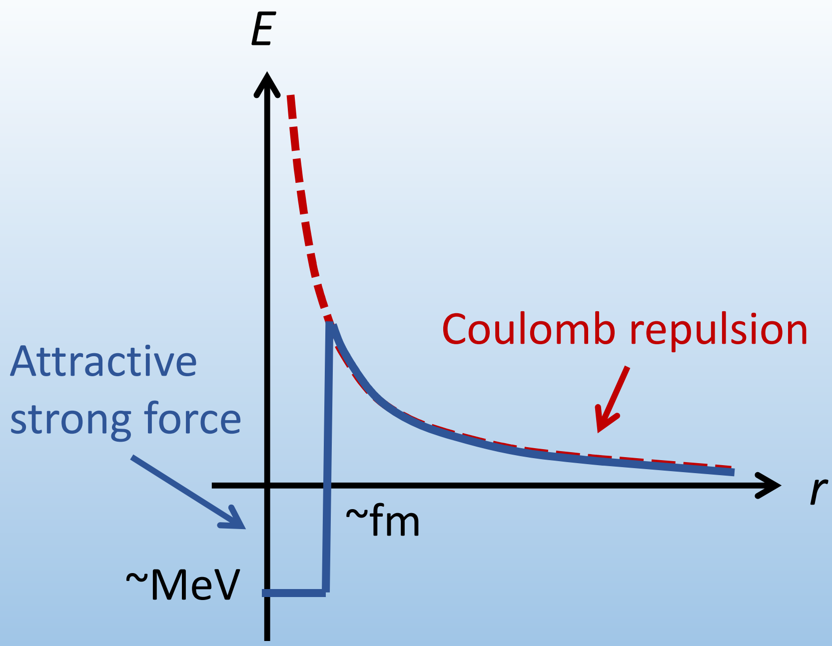
Strong nuclear force

Electric potential energy of two protons in 1 fm nucleus:

$$U_{p-p} = +\frac{ke^2}{r} = \frac{1.44\,\text{eV}\cdot\text{nm}}{1\times10^{-6}\,\text{nm}} = 1.44\,\text{MeV}$$



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



Ex: deuterium (1 proton + 1 neutron)

$$E_{deuteron} \approx 2.2\text{MeV}$$
$$E_{atom} \approx 13.6\,\text{eV}$$

10^5

DEMO

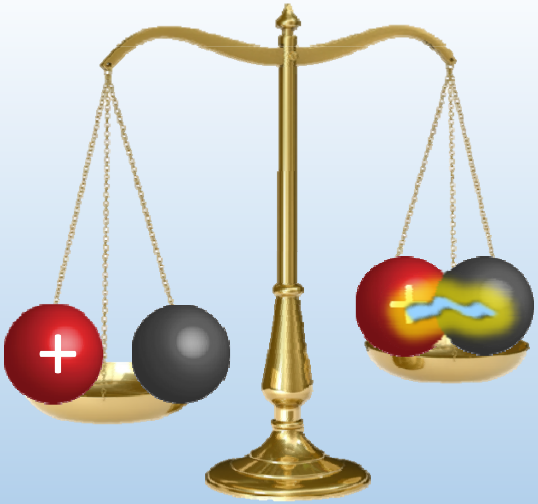
Binding energy & mass defect

Nuclear binding energy decreases mass of nucleus

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

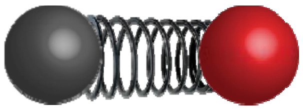
$$m_{nucleus} = Zm_{prot} + Nm_{neut} - \frac{|E_{bind}|}{c^2}$$ "Mass defect"

Ex: deuteron = 1 proton + 1 neutron



ACT: Binding Energy

Which system “weighs” more?

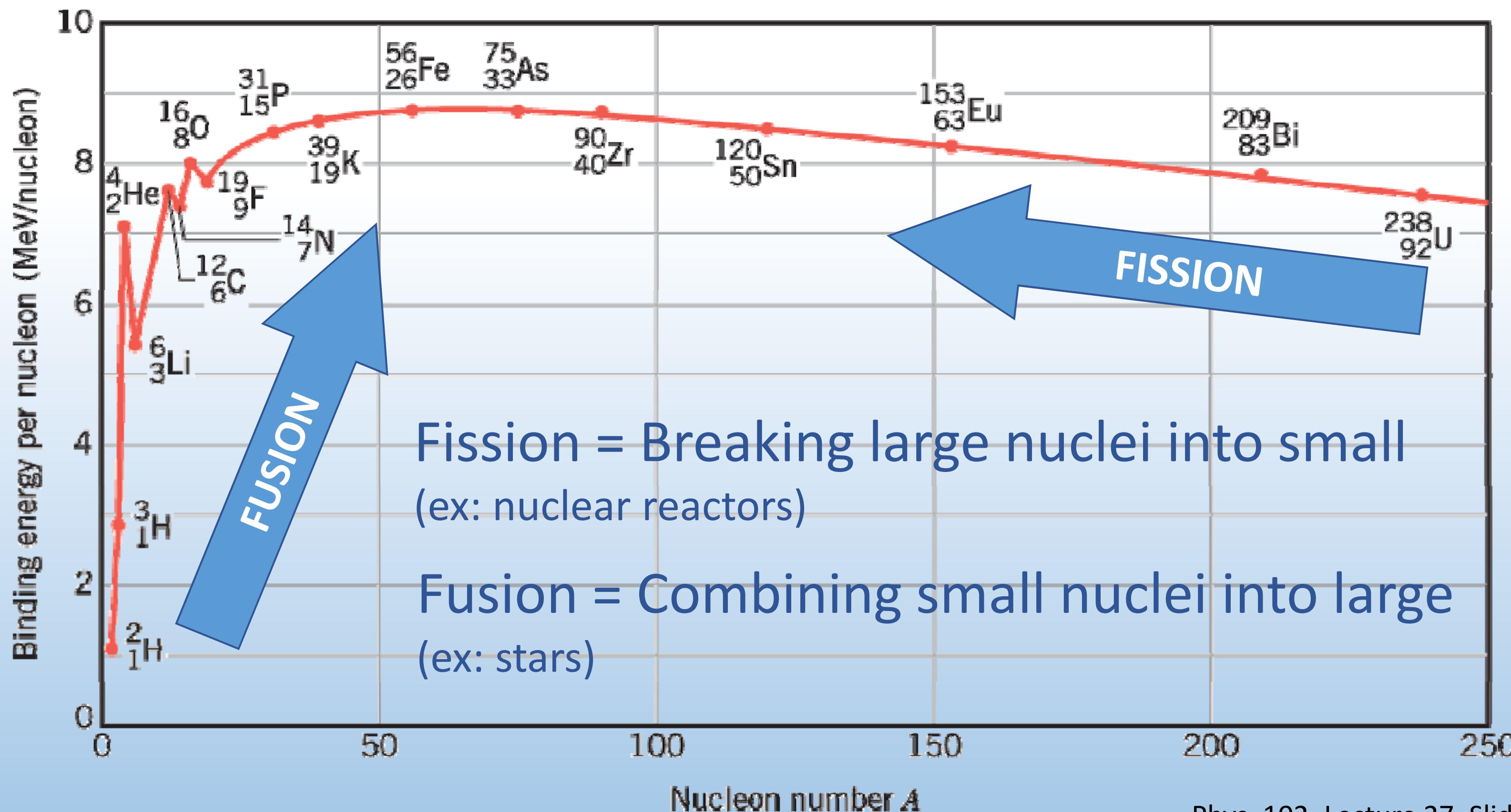
A  B 

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

$$\frac{E_{bind}}{A}$$



Fission = Breaking large nuclei into small

(ex: nuclear reactors)

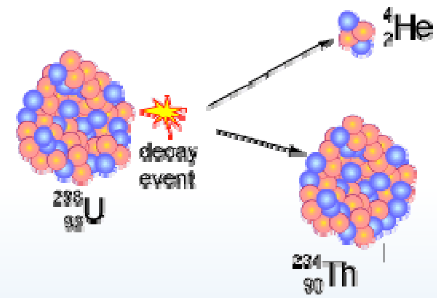
Fusion = Combining small nuclei into large

(ex: stars)

ACT: Uranium mass

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

$$^{238}_{92}\mathrm{U} \rightarrow \, ^{234}_{90}\mathrm{Th} + \, ^{4}_{2}\mathrm{He} + \text{energy}$$



What must be true about the masses of the nuclei?

A. $m_U > m_{Th} + m_{He}$

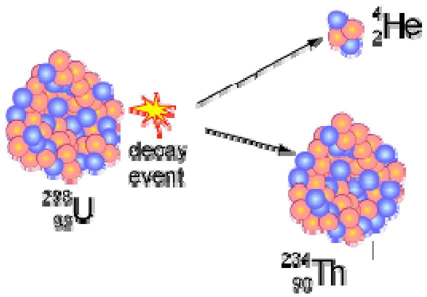
B. $m_U = m_{Th} + m_{He}$

C. $m_U < m_{Th} + m_{He}$

Calculation: Uranium decay

Calculate the energy released in this fission reaction:

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



Initial energy:

$$m_U c^2 = 92 m_p c^2 + 146 m_n c^2 - |E_U|$$

Final energy:

$$m_{Th} c^2 = 90 m_p c^2 + 144 m_n c^2 - |E_{Th}|$$

$$+ m_{He} c^2 = 2 m_p c^2 + 2 m_n c^2 - |E_{He}|$$

$$+ E_{released}$$

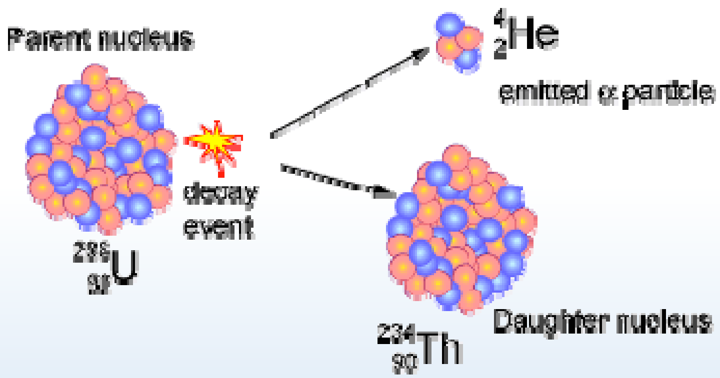
Released energy is difference in binding energies:

$$E_{released} = E_{Th} + E_{He} - E_U$$

Radioactive decay

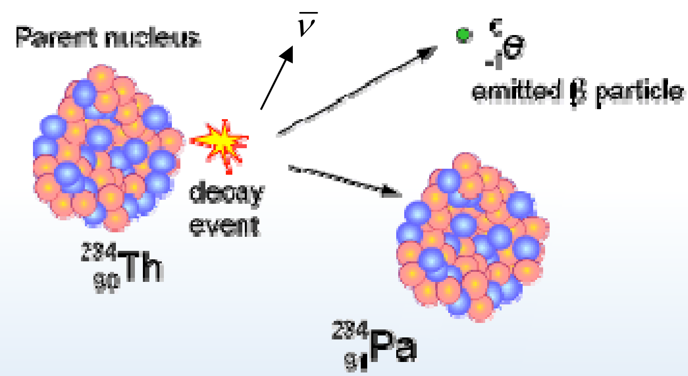
There are 3 types of radioactive decay:

α particle: ${}^{4}_{2}\mathrm{He}$ nucleus



Easily stopped

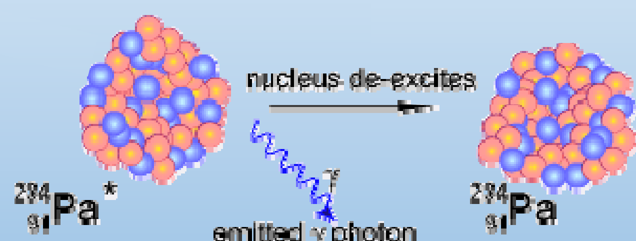
β⁻ particle: electron

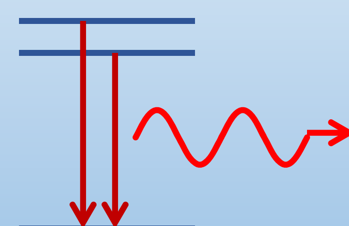


Stopped by metal

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

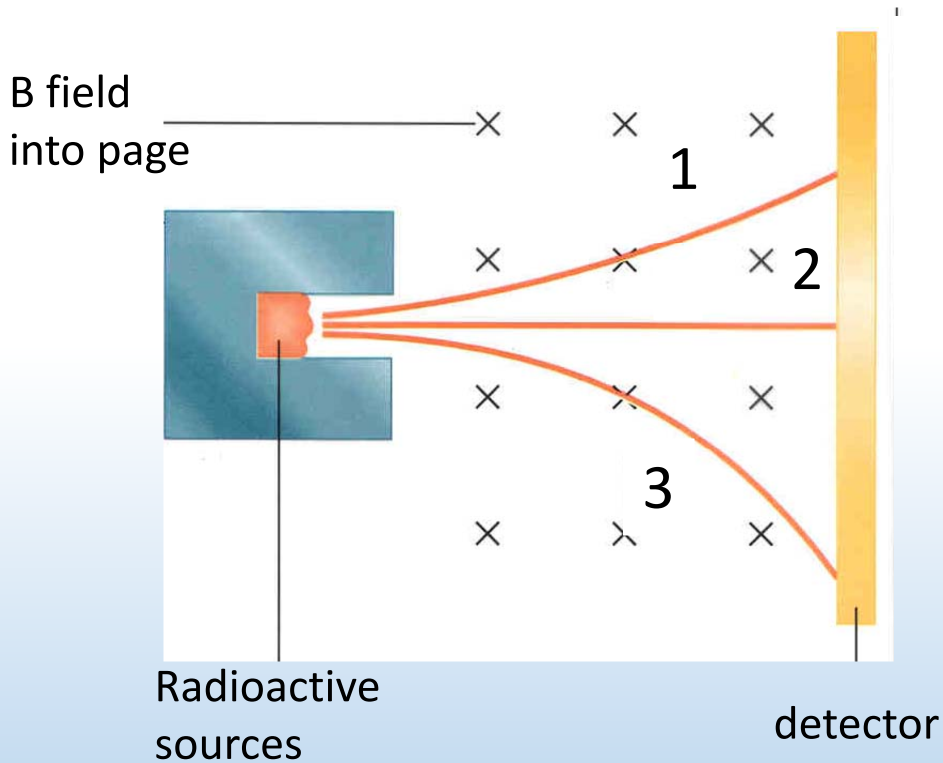
Penetrate





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.

α decay: $^{A}_{Z}\mathrm{P} \rightarrow {}^{A-4}_{Z-2}\mathrm{D} + {}^{4}_{2}\mathrm{He}$

α particle has 2 protons, 2 neutrons: A = 4
Charge is +2e: Z = +2

β⁻ decay: $^{A}_{Z}\mathrm{P} \rightarrow {}^{A}_{Z+1}\mathrm{D} + {}^{0}_{-1}e$

Electron is not a nucleon: A = 0
Charge is –1e: Z = –1

γ decay: $^{A}_{Z}\mathrm{P}^{*} \rightarrow {}^{A}_{Z}\mathrm{P} + {}^{0}_{0}\gamma$

Photon is not a nucleon: A = 0
Charge is 0: Z = 0

"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 ${}^{234}_{90}\mathrm{Th}$ 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?

A. $^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + \alpha$

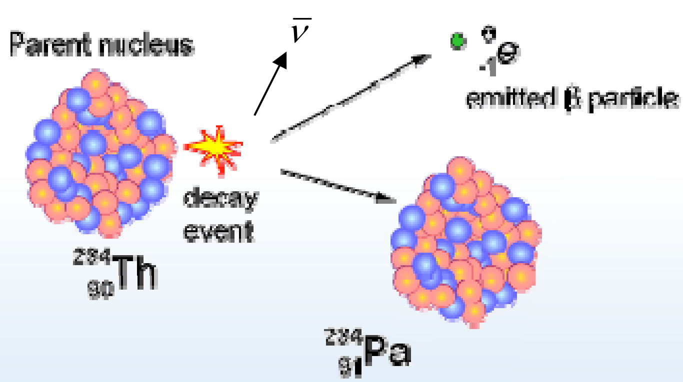
B. $^{214}_{84}\mathrm{Po} \rightarrow {}^{210}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$

C. $^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \gamma$

D. $^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{20}\mathrm{Ca} + {}^{0}_{-1}\mathrm{e}^{-} + {}^{0}_{0}\overline{\nu}$

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:



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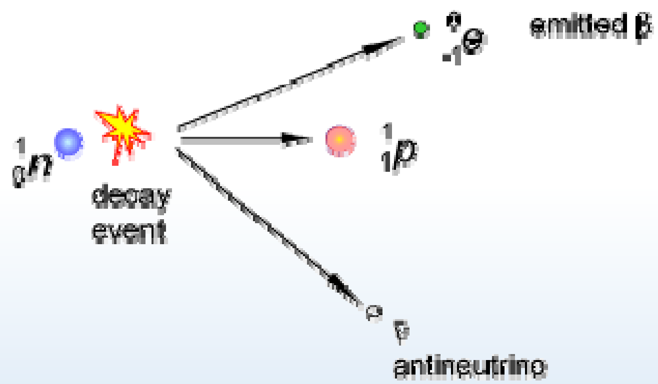


$$^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}e^{-} + {}^{0}_{0}\overline{\nu} \qquad {}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}e^{-} + {}^{0}_{0}\overline{\nu}$$

"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

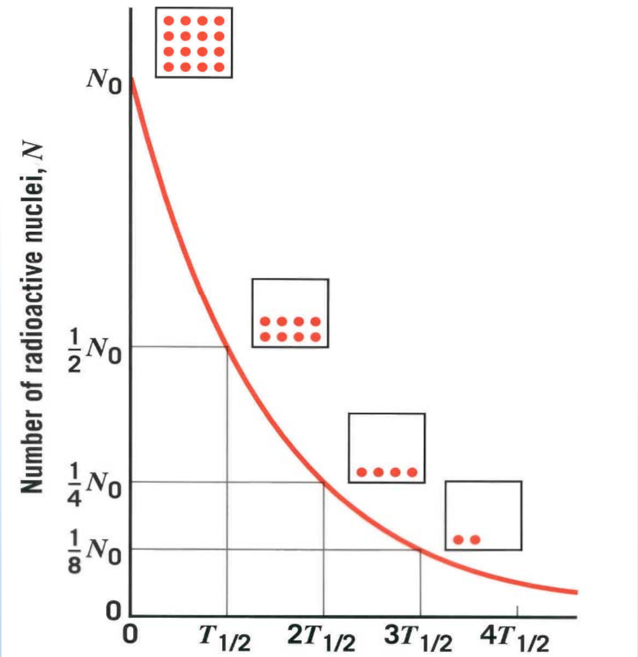
$$\frac{\Delta N}{\Delta t} = -\lambda N$$

"Activity" or rate of decay

Number of un-decayed nuclei

Decay constant

Units: "Becquerel"
(1 Bq ≡ 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 ½ of the nuclei to decay

Ex: At $t = T_{1/2}$, ½ the nuclei survived & the activity decreased by ½
At $t = 2T_{1/2}$, ¼ the nuclei survived & the activity decreased by ¼

Calculation: carbon dating

1 in ~8 × 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.

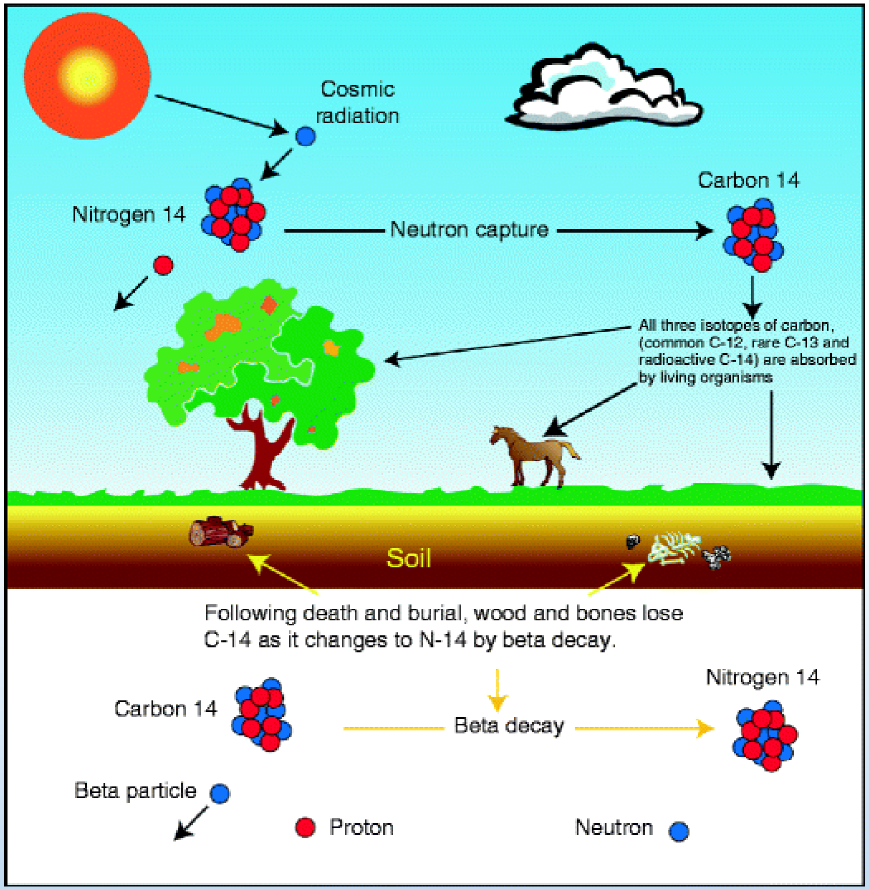
$$\frac{\Delta N}{\Delta t} = -\lambda N$$

Decay constant:

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

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

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



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 ~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 ½ of nuclei to decay & for activity to decrease by ½

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