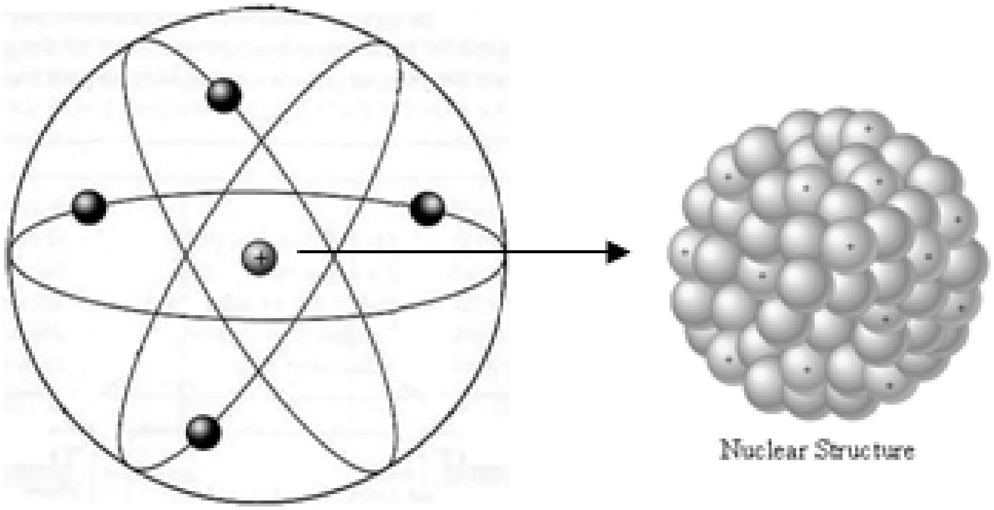
Nuclear Physics

IB Physics SL Y2
February 3, 2015



Nuclear Structure

Atomic Structure

Atomic and Nuclear Structure

13.2.1-13.2.2

Atomic Structure Review

- **Nuclide**: a particular type of nucleus
- **Nucleon**: a proton or a neutron
- **Atomic number (Z) (proton number):** number of protons in nucleus
- **Mass number (A) (nucleon number):** number of protons + neutrons
- **Neutron number (N):** number of neutrons in nucleus (N = A – Z)
- **Isotopes**: nuclei with same number of protons but different numbers of neutrons

Atomic Structure Review

- **Unified atomic mass unit (u):** 1/12th the mass of a carbon-12 nucleus
- **Atomic mass** $\approx A * u$
  - $1\ u = 1.661 \times 10^{-27}$ kg
  - 1 u = 1 g/mol
  - $1\ u = 931.5\ \mathrm{MeV}/c^2$

$^{A}_{Z}X$	$^{56}_{26}Fe$	$^{27}_{13}Al$	$^{12}_{6}C$	$^{14}_{6}C$
Atomic Number	26	13	6	6
Mass Number	56	27	12	14
Neutron Number	30	14	6	8
Atomic Mass	56 u	27u	12u	14u
Molar Mass	56 g	27g	12g	14g

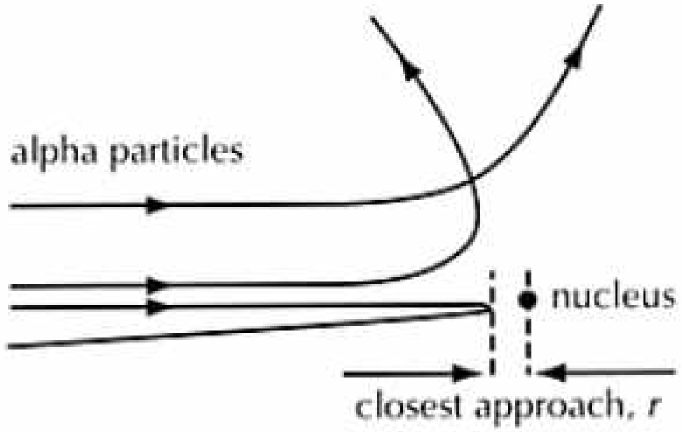
How big are atomic nuclei?

$\underline{10^{-15} \text{ to } 10^{-14}\text{ m}}$

How do we know this?

Alpha particle scattering experiment
(Geiger-Marsden)

Formulas:



$E \Rightarrow KE = \frac{1}{2}mv^2$

$E \Rightarrow E_e = \overset{(q)}{e}V$

$\therefore \frac{1}{2}mv^2 = \overset{(q)}{e}\boxed{V}$

$\Downarrow$

$\frac{1}{2}mv^2 = \overset{(q)}{e}\left(\frac{kQ}{r}\right)$

* (q) when a charged partible

* e when an electron

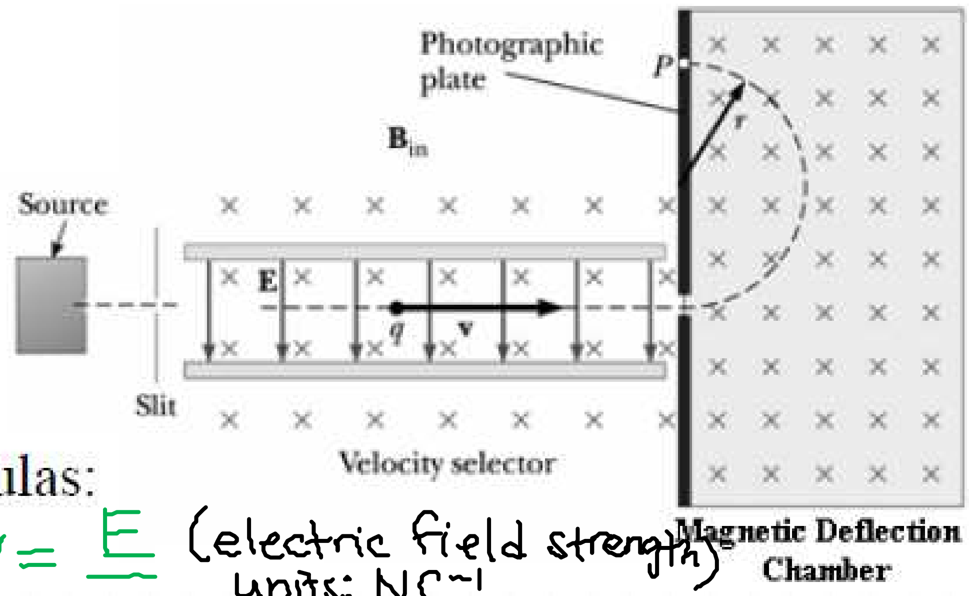
Note that most nuclei have approximately the same . . . density

How do we know that neutrons exist?

isotopes

How do we know that isotopes exist?

by measurements in mass spectrometer



$$\boxed{r = \frac{mv}{qB}}$$

Formulas:

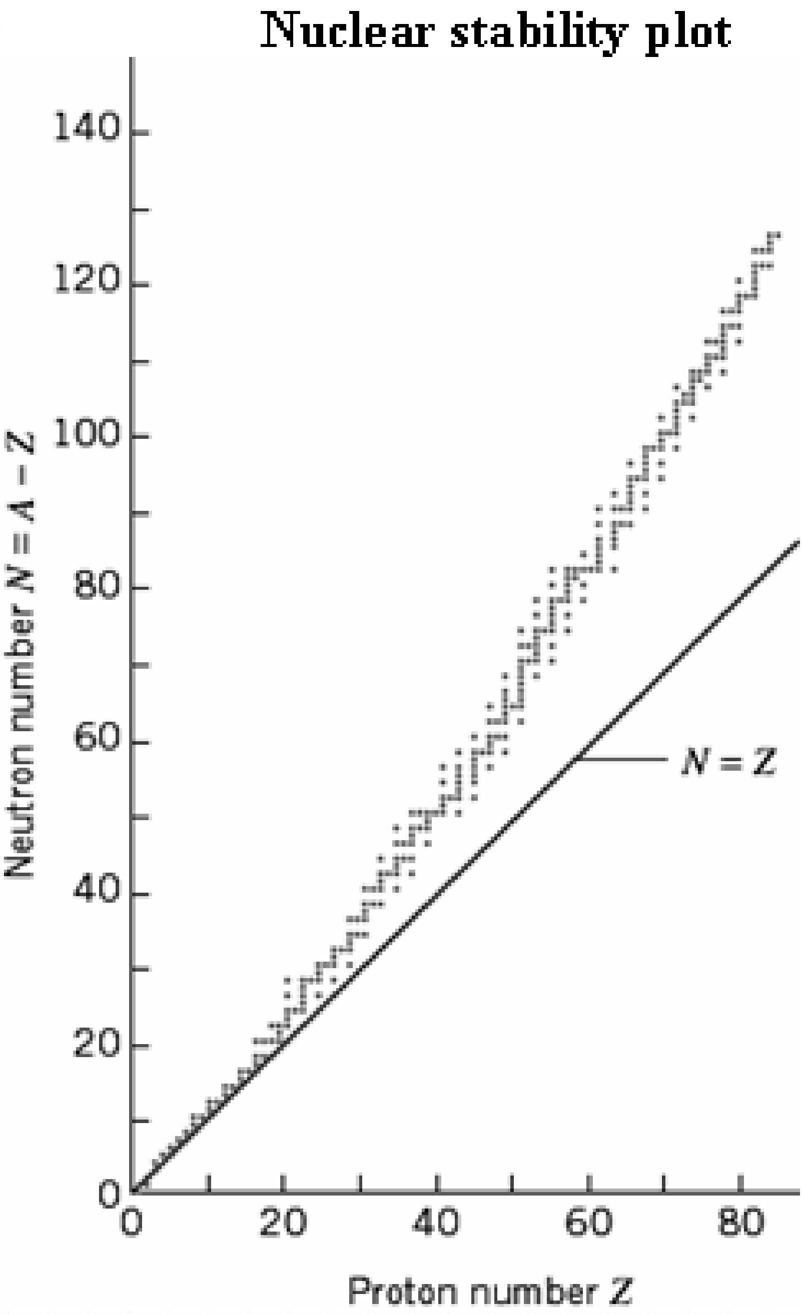
$V = \frac{E}{B}$ (electric field strength) units: NC^{-1}

B (magnetic field strength) units: Tesla (T)

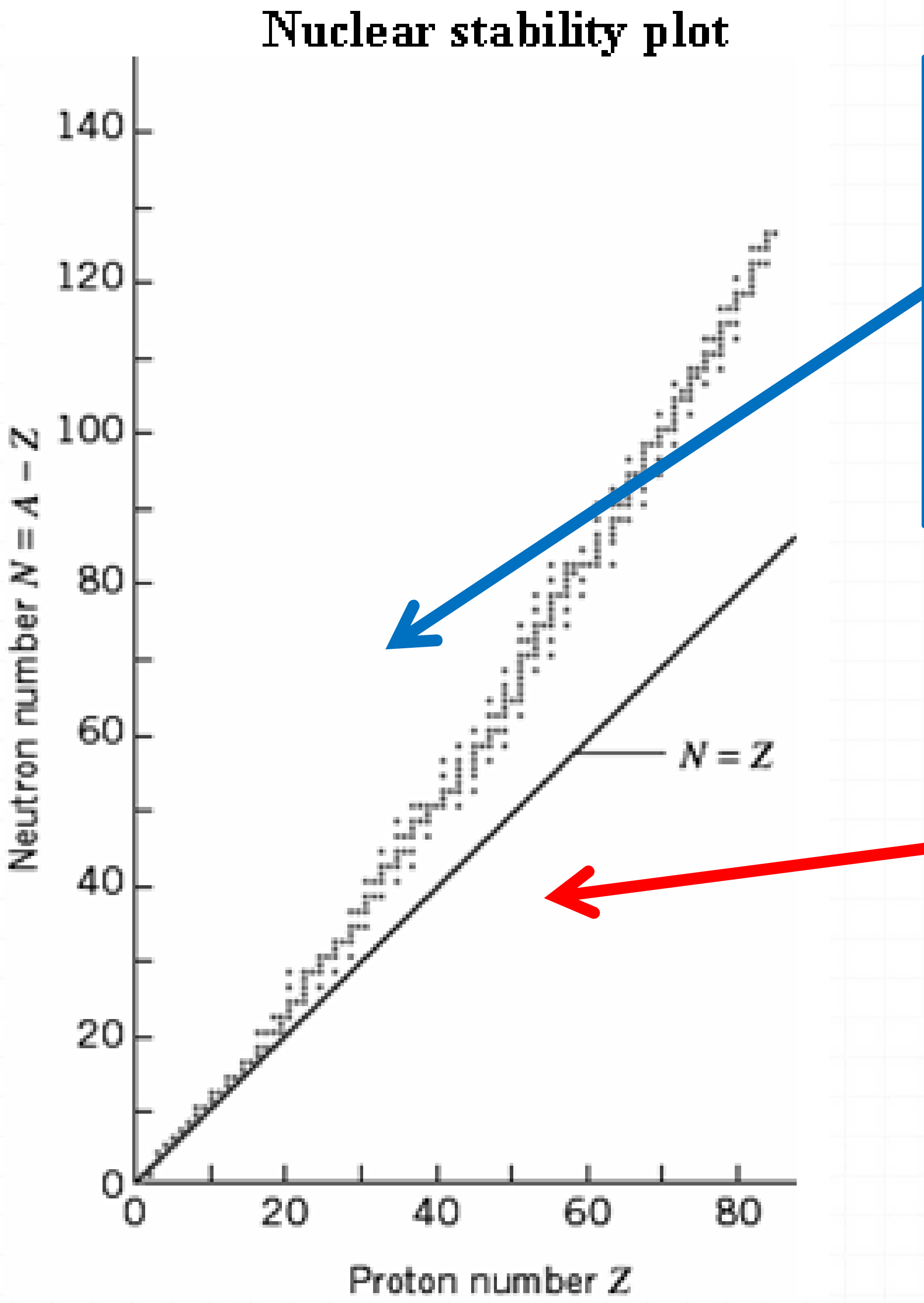
Nuclear Stability

What interactions exist in the nucleus?

- **Gravitational:** (long range) attractive but very weak/negligible
- **Coulomb or Electromagnetic:** (long range) repulsive and very strong between protons
- **Strong nuclear force:** (short range) attractive and strongest – between any two nucleons
- **Weak nuclear force:** (short range) involved in radioactive decay



Each dot in the plot at right represents a stable nuclide and the shape is known as the "band (or valley) of stability." With few exceptions, the naturally occurring stable nuclei have a number *N* of neutrons that equals or exceeds the number *Z* of protons. For small nuclei (Z < 20), number of neutrons tends to equal number of protons (N = Z).

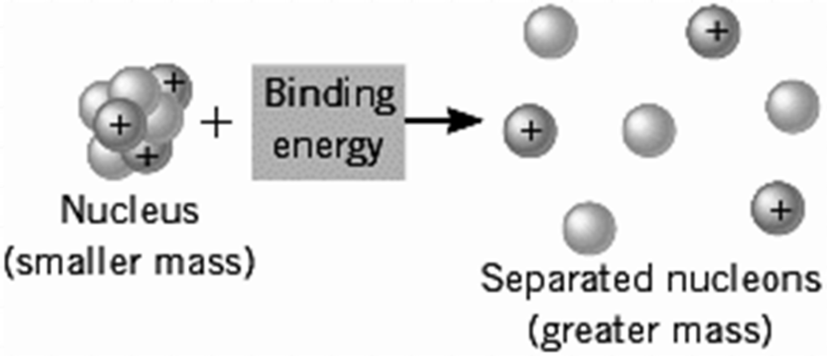


Nuclei above (to the left of) the band of stability have too many neutrons and tend to decay by alpha or beta-minus (electron) emission, both of which reduce the number of neutrons in the nucleus.

Nuclei below (to the right of) the band of stability have too few neutrons and tend to decay by beta-plus (positron) emission which increases the number of neutrons in the nucleus.

Binding Energy

- The total mass of a nucleus is always less than the sum of the masses its nucleons. Because mass is another manifestation of energy, another way of saying this is the total energy of the nucleus is less than the combined energy of the separated nucleons.



Binding Energy

- **Mass defect (mass deficit) (Δm)**

  Difference between the mass of the nucleus and the sum of the masses of its individual nucleons

- **Nuclear binding energy (ΔE)**

  1. energy **released** when a nuclide is **assembled** from its individual components

  2. energy **required** when nucleus is **separated** into its individual components

Binding Energy

- Different nuclei have different total binding energies. As a general trend, as the atomic number increases . . .

the total binding energy for the nucleus increases.

Formulas:

$$\boxed{m_{nucleus} + \Delta m = m_{nucleons}}$$

$$\boxed{\Delta E = (\Delta m) c^2}$$

Particle	Electric Charge (e)	Electric Charge (C)	Rest Mass (kg)	Rest Mass (u)	Rest Mass (MeV/c^2)
Proton	+1	$+1.60 \times 10^{-19}$	1.673×10^{-27}	1.007276	938
Neutron	0	0	1.675×10^{-27}	1.008665	940
Electron	-1	-1.60×10^{-19}	9.110×10^{-31}	0.000549	0.511

1. The most abundant isotope of helium has a ${}_{2}^{4}He$ nucleus whose mass is 6.6447×10^{-27} kg. For this nucleus, find the mass defect and the binding energy.

$m_{nucleus} + \Delta m = m_{nucleons}$

$\therefore \Delta m = m_{nucleons} - m_{nucleus}$

$\Delta m = 2m_p + 2m_n - m_{nucleus}$

$\underline{\Delta m = 5.13 \times 10^{-29}\ kg}$

$A = 4$

$Z = 2$ (2 protons)

$N = A - Z = 2$ neutrons

$\Delta E = (\Delta m)c^2$

$\underline{\Delta E = 4.62 \times 10^{-12}\ J}$

2. Calculate the binding energy and mass defect for ${}_{8}^{16}O$ whose measured mass is 15.994915 u.

$\Delta m = m_{nucleons} - m_{nucleus}$

$\Delta m = 8m_p + 8m_n - m_{nucleus}$

$\underline{\Delta m = .132613\ u}$

$A = 16$

$Z = 8$

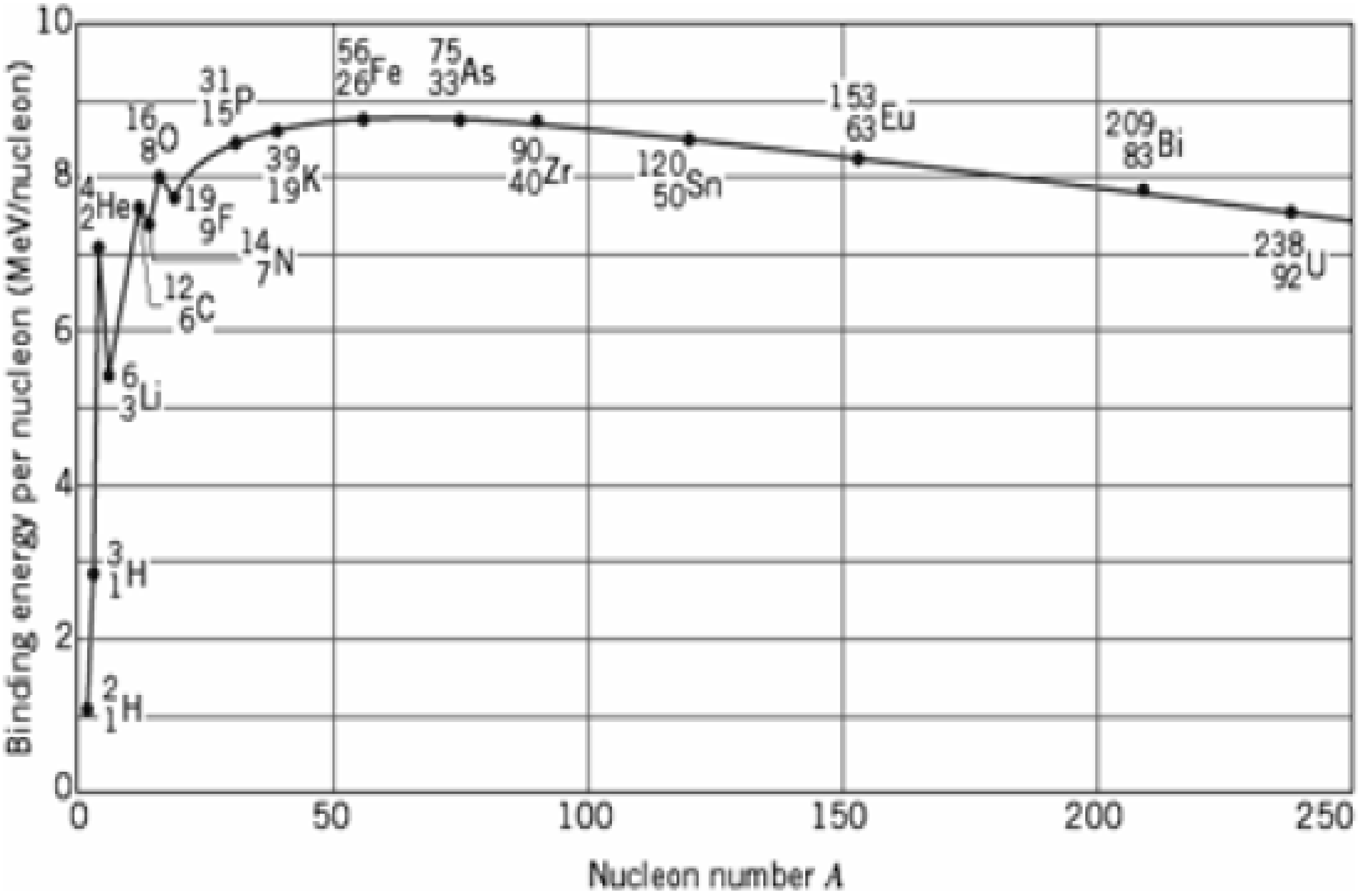
$N = 8$

$\left.\begin{matrix} \\ \\ \end{matrix}\right\}$ 8 protons
8 neutrons

$\underline{\Delta E = 123.5\ MeV}$

$(1.982 \times 10^{-11}\ J)$

Binding Energy per Nucleon



a) This graph is used to compare the energy states of different nuclides and to determine what nuclear reactions are energetically feasible. As binding energy per nucleon increases so does the stability of the nucleus. Higher binding energies represent lower energy states since more energy was released when the nucleus was assembled.

b) Binding energy per nucleon increases up to a peak at $^{56}_{26}Fe$ then decreases, so $^{56}_{26}Fe$ is the most stable nuclide. Most nuclides have a binding energy per nucleon of about 8 MeV Lighter nuclei are held less tightly than heavier nuclei.

c) Nuclear reactions, both natural (radioactive decay) and artificial/induced (fission, fusion, bombardments) occur if they increase the binding energy per nucleon ratio. Fusion occurs for light nuclei (below $_{26}^{56}$Fe) and fission occurs for heavy nuclei (above $_{26}^{56}$Fe).

d) For both natural and induced nuclear reactions, the total rest mass of the products is less than the total rest mass of the reactants since energy is released in the reaction. Also, the products are in a lower energy state since energy was released in the reaction and so the products have a greater binding energy per nucleon than the reactants.

1. Use the graph above to estimate the total binding energy of an oxygen-16 nucleus.

Total binding energy = (# nucleons)(binding energy per nucleon)

= (16)(8)

= 128 MeV

Types of Nuclear Reactions

- **Artificial (Induced) Transmutation:** A nucleus is bombarded with a nucleon, an alpha particle or another small nucleus, resulting in a nuclide with a different proton number (a different element).
- **Nuclear Fusion:** Two light nuclei combine to form a more massive nucleus with the release of energy.
- **Nuclear Fission:** A heavy nucleus splits into two smaller nuclei of roughly equal mass with the release of energy.
- **Natural Radioactivity:** When an unstable (radioactive) nucleus disintegrates spontaneously, the nucleus emits a particle of small mass and/or a photon.

Energy in Nuclear Reactions

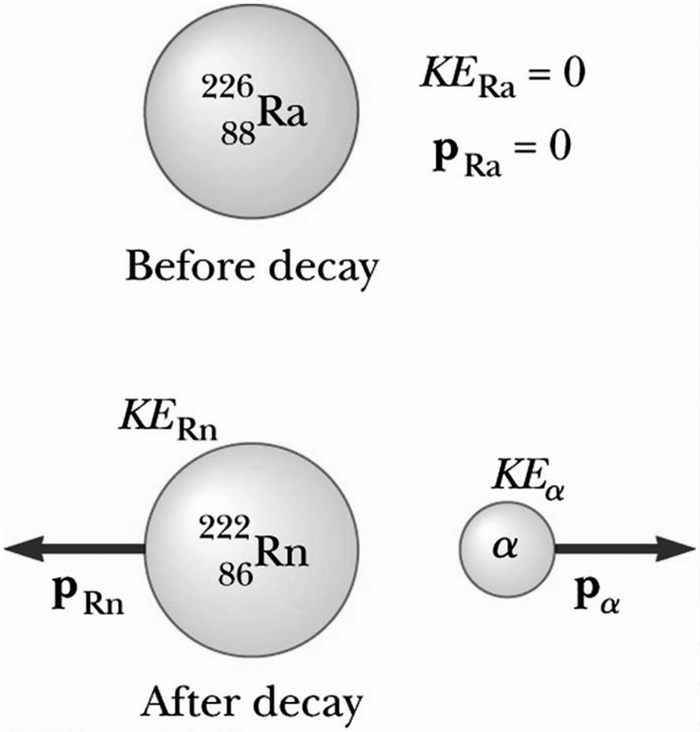
- **Release of energy in nuclear reactions**:
  - $\underset{\text{nucleons}}{m} = \underset{\text{nucleus}}{m} + \Delta m$
  - Energy is usually released in the form of kinetic energy for the products.
- **Binding energy per nucleon:**
  - greater for product nuclei than for original nuclei since energy is released

Alpha Decay

- Alpha particle:

  helium nucleus, α, ${}_2{}^4\text{He}$
- Example reaction:

$${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He + energy$$



Alpha Decay

General equation:

$${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + \text{energy}$$

Where does the kinetic energy come from?

Result: