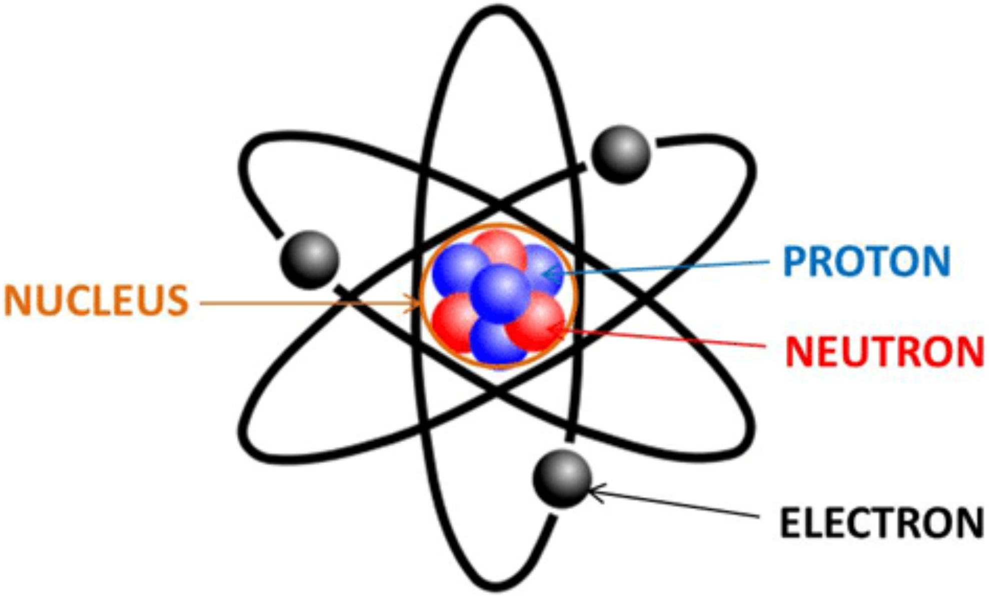
PHY20004 Nuclear Physics Class 1:

Introducing the Nucleus

In this class we will summarize the basic properties of the nucleus: composition, size, nuclear forces and binding energy

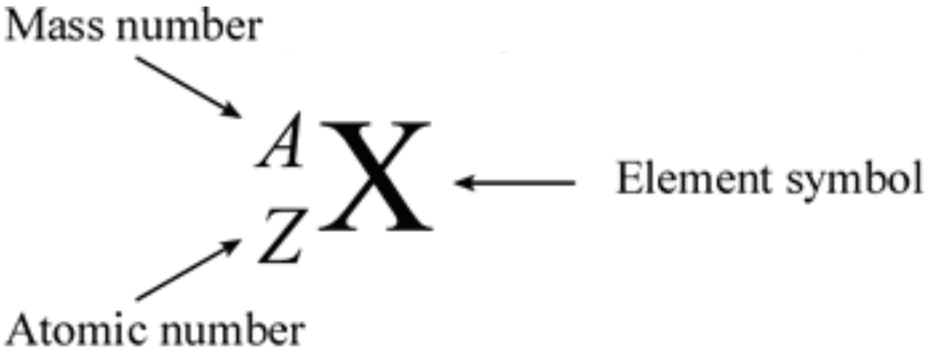


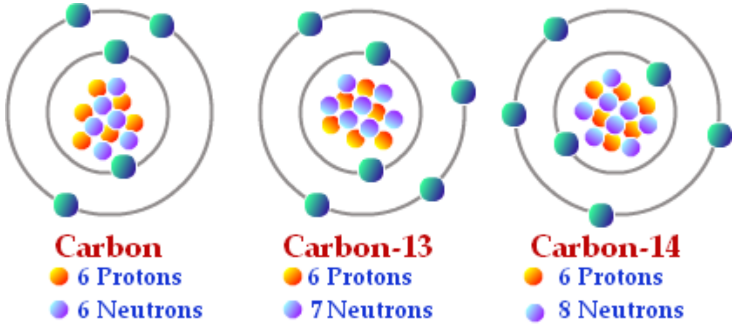
Describing the nucleus

- The nucleus is a **bound assembly of neutrons and protons** at the centre of an atom

- **Atomic number** Z = number of protons → nuclear charge $= +Ze$
- **Neutron number** N = number of neutrons
- **Mass number** $A = Z + N$ = total number of nucleons

This information is written as:



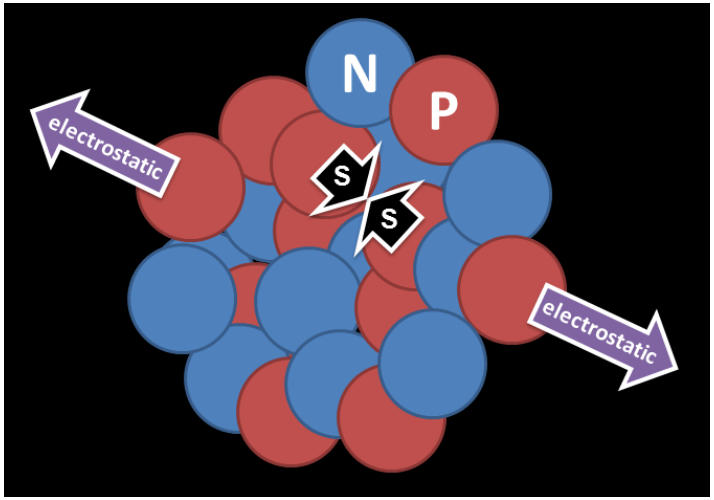


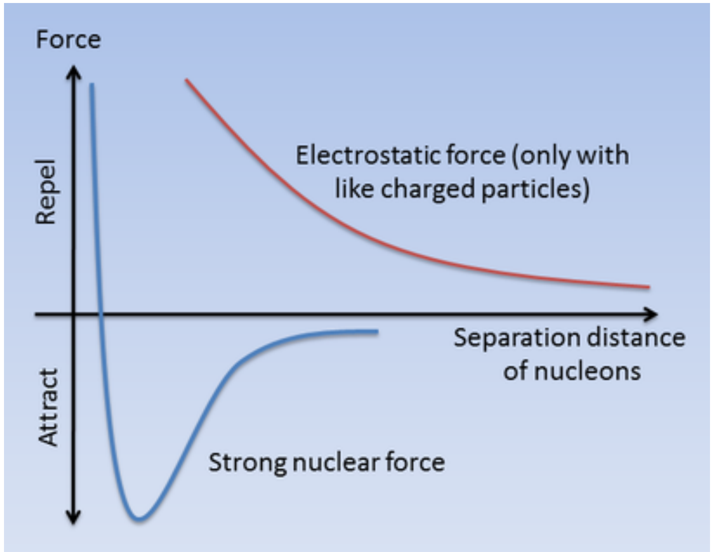
$${}^{12}_{6}C \qquad {}^{13}_{6}C \qquad {}^{14}_{6}C$$

- This can also be written as ${}^{A}X$, since Z can be deduced from X!

Nuclear forces

- The existence of the nucleus is interesting, because **protons should repel each other** by Coulomb's Law!
- The electrostatic force is overcome by the **strong nuclear force**, which binds nucleons together
- The strong nuclear force is a **short-range force** which falls to zero after a few femtometres $(1\ \mathrm{fm} = 10^{-15}\ \mathrm{m})$

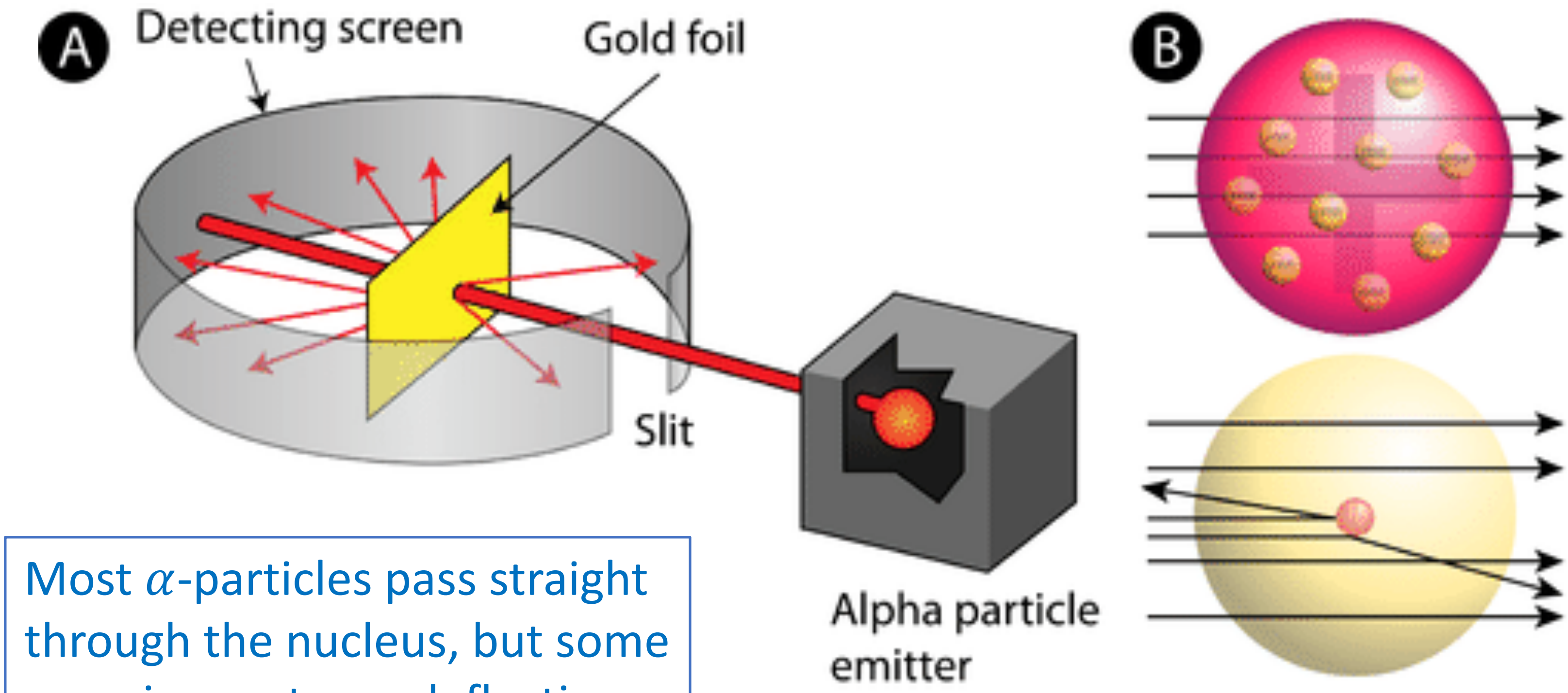




Credit:http://www.physbot.co.uk/particle-physics.html

How big is the nucleus?

- Rutherford's famous "gold foil" scattering experiments showed that the **size of the nucleus** ($\sim 10^{-15}$ m) **is much smaller than the size of the atom** ($\sim 10^{-10}$ m)

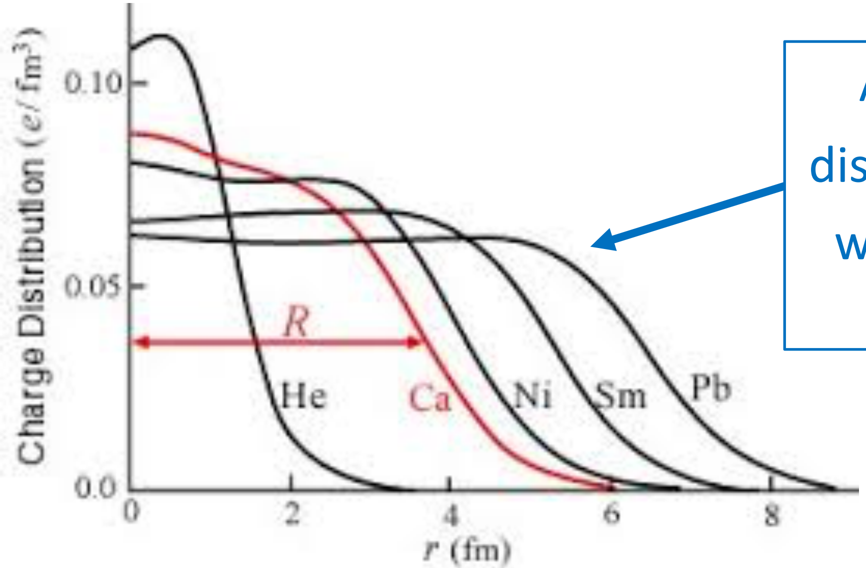


Most α-particles pass straight through the nucleus, but some experience strong deflections

Credit: https://flexbooks.ck12.org/cbook

How big is the nucleus?

- The results of electron scattering experiments show nuclei have a **fairly constant charge density out to the surface**



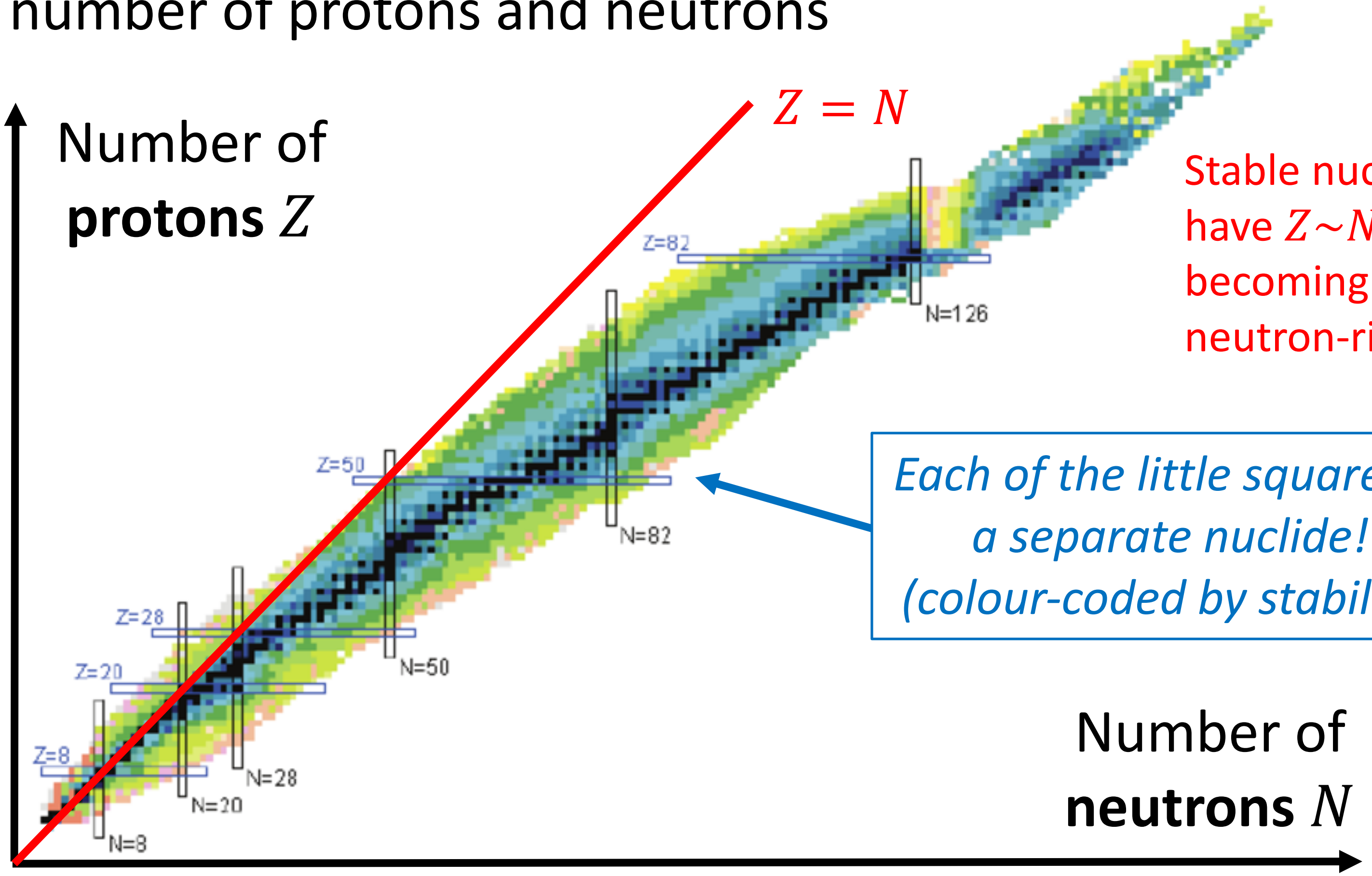
A good model for the charge distribution is $\rho(r) = \frac{\rho(0)}{1+e^{(r-R)/s}}$, where $s \approx 2$ fm is the range of the strong force!

Credit: http://ne.phys.kyushu-u.ac.jp

- A constant charge density implies $\frac{A}{\frac{4}{3}\pi R^3} \approx \text{constant}$ hence **radius $\boldsymbol{R \approx R_0\, A^{1/3}}$** where $R_0 \approx 1.2\times10^{-15}\ \mathrm{m} = 1.2\ \mathrm{fm}$

All the nuclides!

- A **nuclide** is a distinct atom characterized by a specific number of protons and neutrons



Number of **protons** Z

$Z = N$

Stable nuclei tend to have $Z \sim N$, although becoming a more neutron-rich at high A

Each of the little squares is a separate nuclide! (colour-coded by stability)

Number of **neutrons** N

See https://www.nndc.bnl.gov/nudat2/ for the full interactive chart

All the nuclides!

- A **nuclide** is a distinct atom characterized by a specific number of protons and neutrons

- *Some nuclide terminology:*

- **Isotopes** are nuclides with the same atomic number Z, but different numbers of neutrons (different N, A)

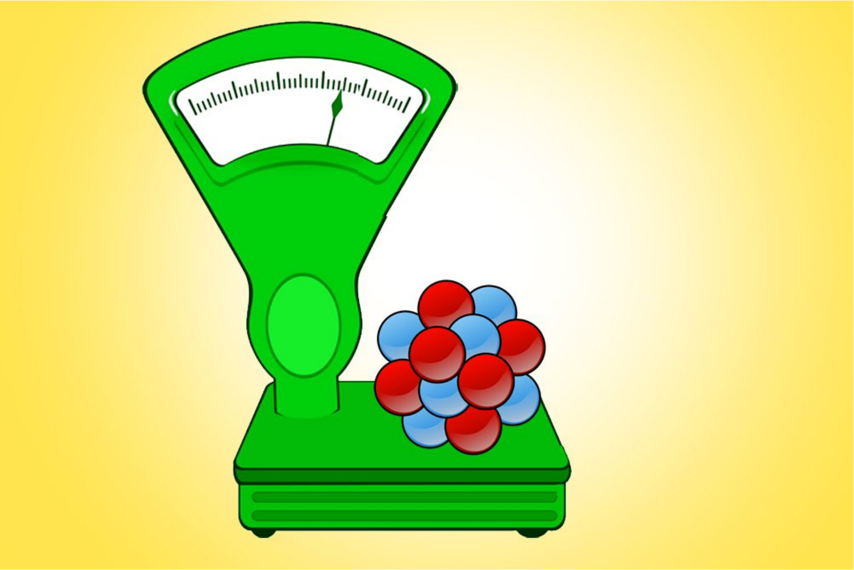
- **Isobars** are nuclides with the same mass number A, but different atomic numbers (different Z, N)

- **Isotones** are nuclides with the same neutron number N, but different atomic numbers (different Z, A)

Atomic mass units

- It’s awkward to use the kg mass unit for atoms, so masses are typically expressed in **atomic mass units** (u)
- $1\ \mathrm{u} = \frac{1}{12}$th the mass of one ${}^{12}_{6}C$ atom $= \frac{1}{12} \times \frac{12\ \mathrm{g}}{6.023\times10^{23}} = 1.66054\times10^{-27}\ \mathrm{kg} = 931.5\ \mathrm{MeV}/c^2$

Avogadro’s number



Credit: http://www.scienceabc.com

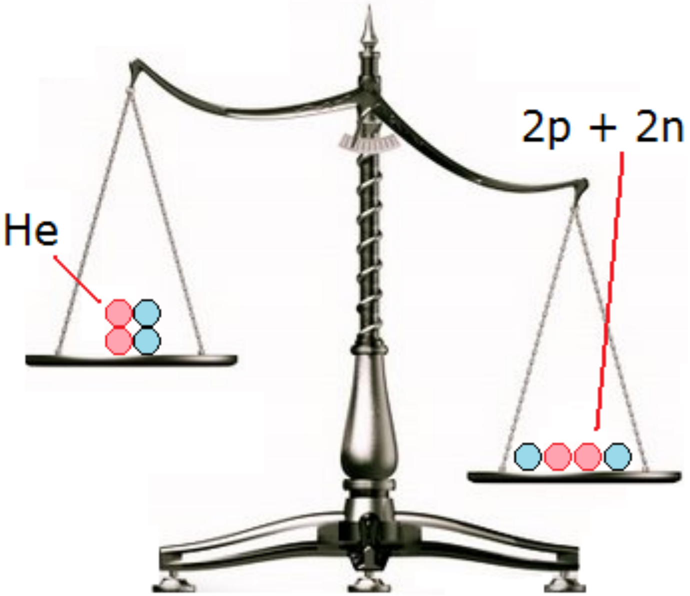
$1u \approx$ the mass per nucleon inside the nucleus

Object	*Mass* [u]
Proton	1.00728
Neutron	1.00866
Electron	0.00055
Hydrogen atom	1.00783

The mass defect

- The key fact of nuclear physics is the **total mass of a nucleus is less than the sum of the mass of its constituents** – this is known as the **mass defect** ΔM

$$\boxed{M_{nucleus} = Zm_P + Nm_N - \Delta M}$$



Credit: https://chemistryonline.guru

- This mass defect is equivalent to the **binding energy** of the nucleus, $B = \Delta M\, c^2$
- This is the energy needed to break the nucleus apart
- Binding energy can also be **released by nuclear reactions**

The mass defect

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$$\boxed{M_{nucleus} = Zm_P + Nm_N - \Delta M}$$

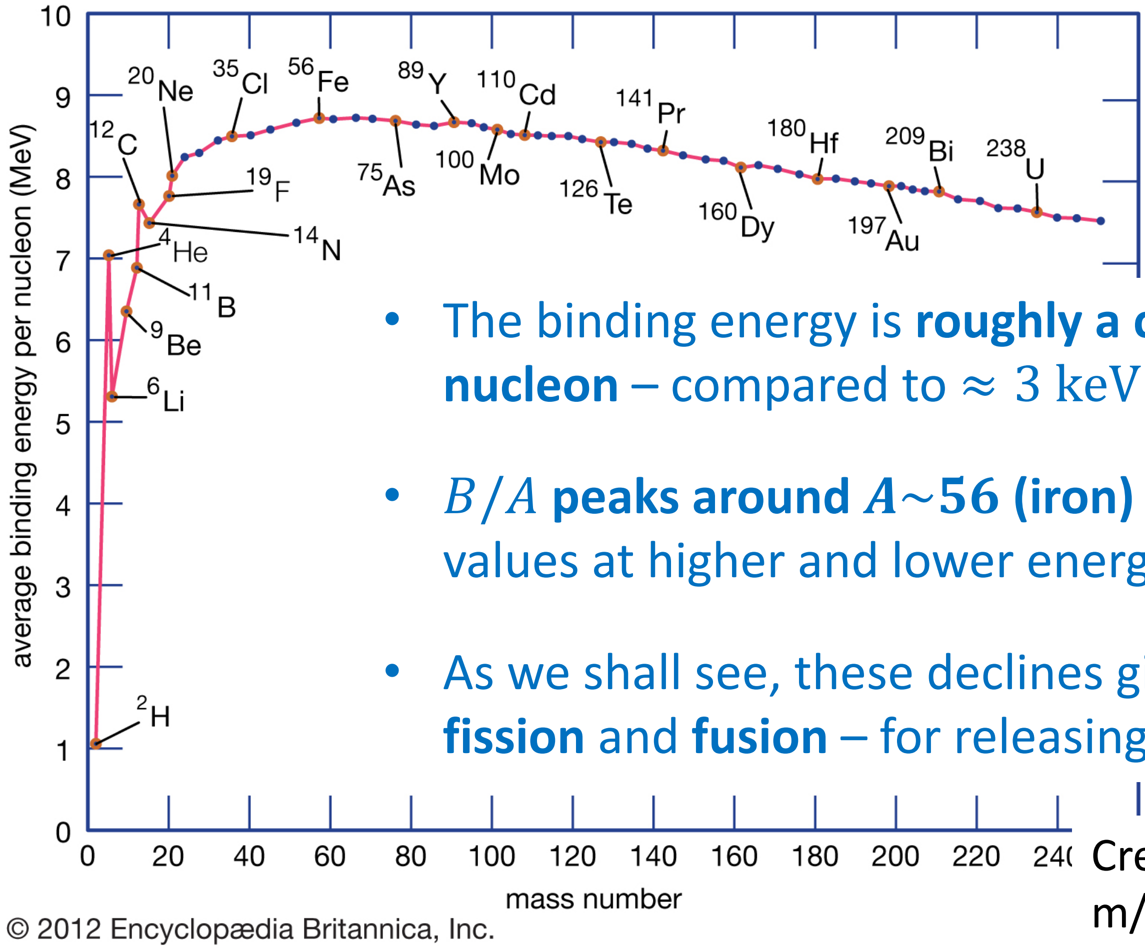
- Usually **atomic masses** of nuclides are given – which include both the nucleus **and** the electrons

- Therefore, it is useful to write the above formula in terms of atomic masses and m_H, the mass of the hydrogen atom including the electron:

$$\boxed{M_{atom} = Zm_H + Nm_N - \Delta M}$$

Nuclear binding energy

- Let's consider the **average binding energy per nucleon**, B/A, for all the nuclides:



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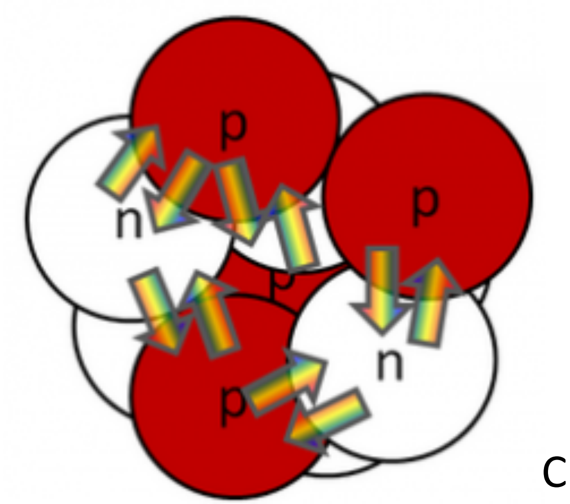
- The binding energy is **roughly a constant** $\approx$ **8 MeV per nucleon** – compared to $\approx 3\ \mathrm{keV}$ per electron!
- B/A **peaks around** $A \sim 56$ **(iron)** and declines to lower values at higher and lower energies
- As we shall see, these declines give us two methods – **fission** and **fusion** – for releasing nuclear energy!

Credit:https://www.britannica.com/science/nuclear-binding-energy

Nuclear binding energy



Credit: https://www.proprofs.com

- The fact that B/A is approximately constant implies that the **nuclear force is short range**: nucleons only interact with their neighbours, *not* with all other nucleons

- If nucleons interacted with all other nucleons, we would expect the binding energy to grow as $B \propto A(A-1) \sim A^2$, hence B/A would be approximately proportional to A

Key take-aways

- Nuclides are represented by the **symbol** ${}^{A}_{Z}X$
- Nuclei are bound together by the **strong nuclear force**
- Nuclei have **radii** $R \approx R_0\, A^{1/3}$ with $R_0 = 1.2\ \mathrm{fm}$
- Nuclei have a **binding energy** $B = \Delta m\, c^2$ which is released when they break apart, given in terms of the **mass defect** $\Delta m = Zm_H + Nm_N - m_{atom}$
- The binding energy per nucleon B/A is approximately constant, although decreases at low and high A
- Atomic and nuclear masses are expressed in terms of **atomic mass units** $\mathrm{u} = 1.66054 \times 10^{-27}\ \mathrm{kg}$