# 23 Nuclear physics

## 23.1 Mass defect and nuclear binding energy

Candidates should be able to:

1. understand the equivalence between energy and mass as represented by $E = mc^2$ and recall and use this equation
2. represent simple nuclear reactions by nuclear equations of the form $^{14}_{7}\text{N} + ^{4}_{2}\text{He} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{H}$
3. define and use the terms mass defect and binding energy
4. sketch the variation of binding energy per nucleon with nucleon number
5. explain what is meant by nuclear fusion and nuclear fission
6. explain the relevance of binding energy per nucleon to nuclear reactions, including nuclear fusion and nuclear fission
7. calculate the energy released in nuclear reactions using $E = c^2 \Delta m$

- Based on Einstein's theory of relativity, matter can be considered a form of energy.
- What this means is that mass can be converted to energy and vice versa.
- This is known as **mass-energy equivalence**

$$E = mc^2$$

- Nuclear reactions can be represented by balanced equations of nuclei in AZX form

- **Mass defect** is **the difference between the mass of the separated nucleons and the combined mass of the nucleus.**
- To calculate mass defect ($\Delta m$) for a nucleus that has **A** protons and **B** neutrons:

$$\Delta m = A m_p + B m_n - M_n$$

Where $m_p$ is the mass of a proton (kg), $m_n$ is the mass of a neutron (kg) and $M_n$ is the mass of the nucleus (kg).

- Due to the equivalence of mass and energy, this decrease in mass implies that energy is released in the process.
- Since nuclei are made up of protons and neutrons, there are forces of repulsion between the positive protons.
- It takes energy (binding energy) to hold nucleons together as a nucleus.
- **Binding energy** is defined as **the energy required to break a nucleus into its constituent protons and neutrons**.
- **Binding energy per nucleon** is defined as **the binding energy of a nucleus divided by the number of nucleons in the nucleus**.
- The higher the binding energy per nucleon the more stable the nucleus is and the more energy is required to split the nucleus.
- The graph below shows the graph of binding energy per nucleon with nucleon number
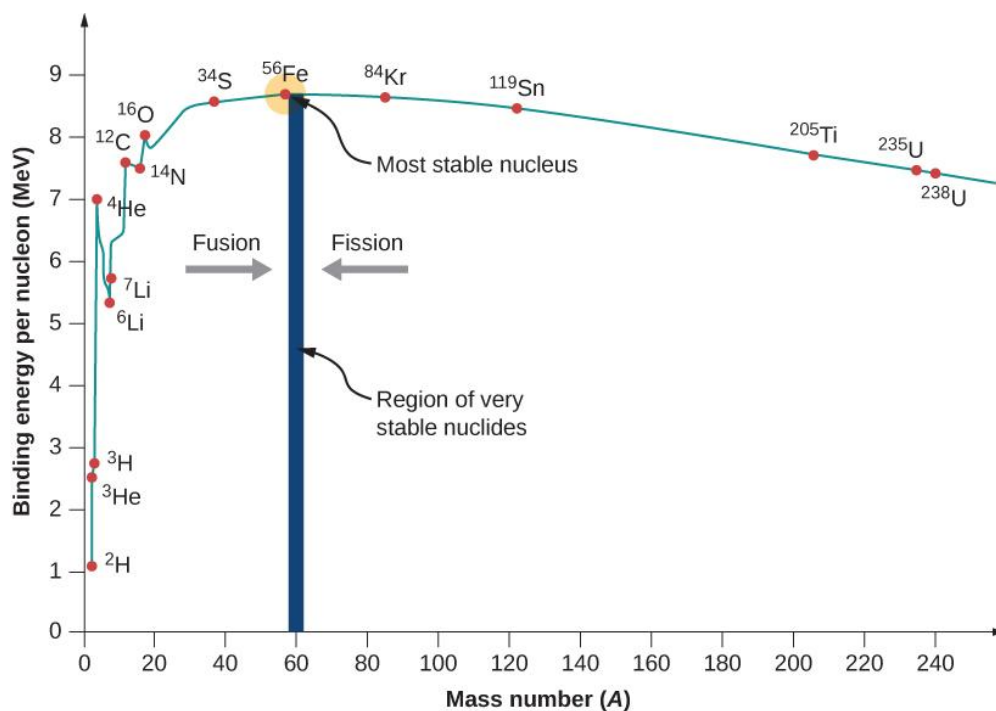


- From the graph above it can be seen that the lower A is, the lower binding energy per nucleon.
- Attractive forces between nucleons dominate over repulsive electrostatic forces between protons.
- This implies that they are generally less stable and can undergo fusion.
- With exception of Helium.

- Carbon and Oxygen (which are multiples of Helium) have high binding energy as well.
- The binding energy increases as A increases.
- This trend continues until Fe and after that increasing A decreases binding energy.
- At very high A binding energy is lower and the heaviest elements are unstable and likely to undergo fission.
- This is because repulsive electrostatic forces begin to dominate and there forces tend to break apart the nucleus rather than hold it together.
- **Fusion** is defined as **the fusing together of two small nuclei to produce a larger nucleus**.
- For fusion to occur, two small light nuclei (usually hydrogen and deuterium) join together to make one heavy nuclei (typically helium).
- There are a number of different nuclear fusion reactions happening in the Sun.
- The simplest is when four hydrogen nuclei become one helium nuclei.
- The combined mass of the four hydrogen nuclei is higher than the helium nuclei.
- The **mass defect** here is converted to **energy**.
- The process of fusion involves fusing of nuclei which are positive particles.
- As both nuclei approach, they will repel.
- In order to overcome the **electrostatic force,** both nuclei must have high KE energy.
- It takes a lot of energy to overcome the electrostatic force hence it can only be achieved in a very high pressure and temperature environment (think the core of a star)
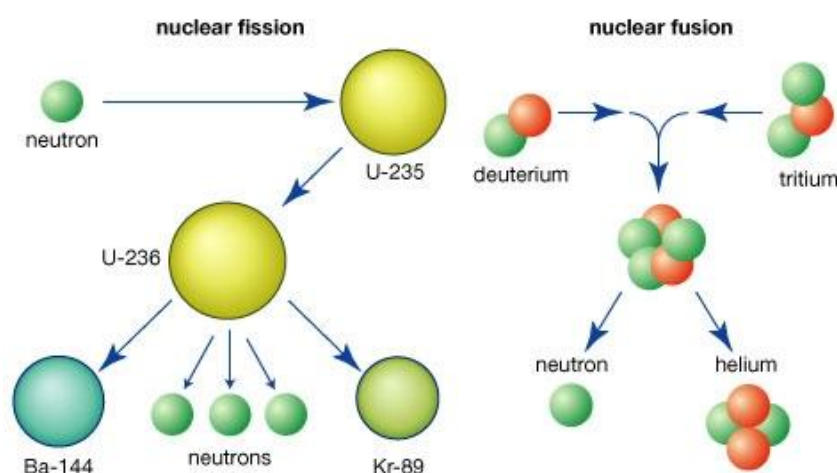


- **Fission** is defined as **the splitting of a large atomic nucleus into smaller nuclei.**

- Nuclear fission starts when a heavy nucleus is bombarded by a neutron.
- For e.g. when the nucleus of U-235 is bombarded by a neutron, the nucleus of U-236 is produced.
- The nucleus of U-236 is unstable and disintegrates quickly.
- When the unstable U-236 nucleus disintegrates, it fragments into two smaller nuclei such as barium-141 and krypton-92.
- During the process new neutrons are also produced thus continuing the process.
- This self-sustaining process is called **chain reaction**.
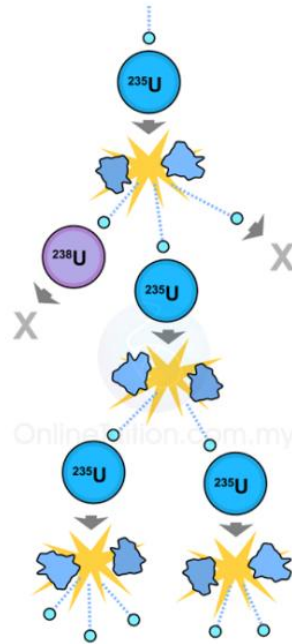


- To calculate energy in nuclear reactions (both fission and fusion) just use

$$E = \Delta mc^2$$

Here $\Delta m$ is the mass defect (kg)

## 23.2 Radioactive decay

- **Radioactive decay** is **the spontaneous disintegration of a nucleus to form a more stable nucleus, resulting in the emission of an alpha, beta or gamma particles**.
- Evidence for the random nature of radioactive decay can be seen from the fluctuations in the count rate of a Geiger-Muller counter.
- This proves that radioactive decay is both **spontaneous** and **random**.
- The **average decay rate** (A) is **the average number of nuclei which are expected to decay per unit overtime**.
- A is measured in **Becquerels (Bq)** and can be found from

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

Here $\Delta N$ is the number of decayed nuclei, $\Delta t$ is the rate (s), $\lambda$ is the decay constant ($s^{-1}$) and N is the number of nuclei remaining in a sample.

- The decay constant is the probability that the nucleus will decay per unit time.
- **Half-life** is **the time taken for the initial number of nuclei in radioactive substance to reduce by half**.
- It can be calculated from the equation

$$t_{0.5} = \frac{0 \cdot 693}{\lambda}$$

- The number of nuclei in a radioactive decay is said to fall at an exponential rate.
- This model is known as **exponential decay**.
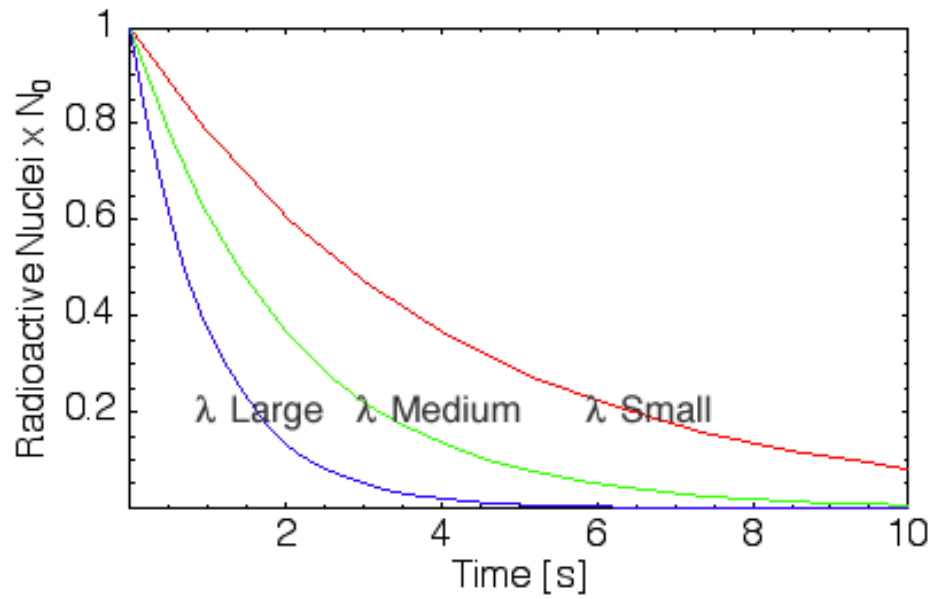
- The number of undecayed nuclei can be represented by

$$N = N_0 e^{-\lambda t}$$

- From the plot above it can be seen that the higher the decay constant (λ), the faster the decay.