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**

$$E = mc^2$$

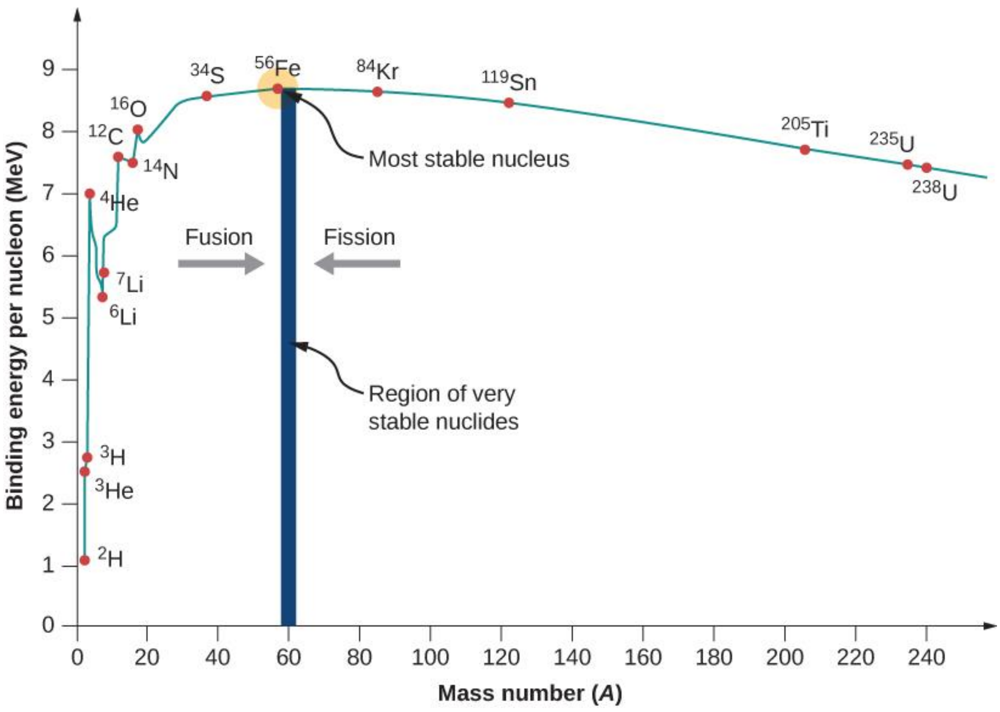
- Nuclear reactions can be represented by balanced equations of nuclei in AZX form

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

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

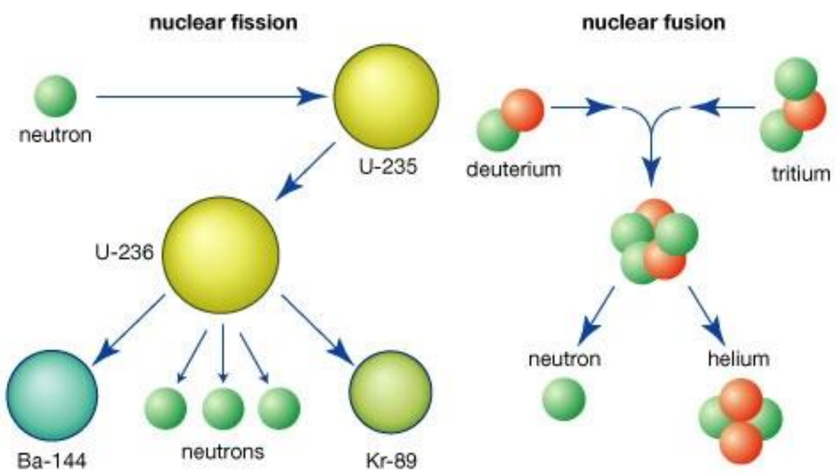
Where m_p is the mass of a proton (kg), m_n is the mass of a neutron (kg) and M_n is the mass of the nucleus (kg).

- 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



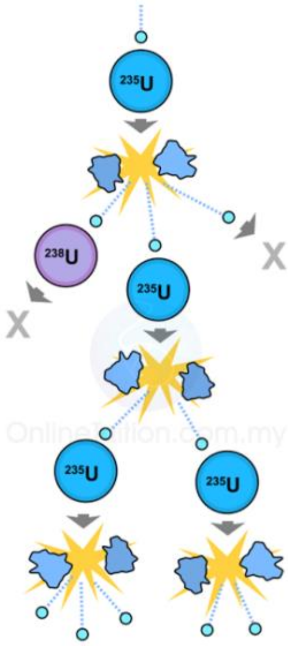
- From the graph above it can be seen that the lower A is, the lower binding energy per nucleon.
- Attractive forces between nucleons dominate over repulsive electrostatic forces between protons.
- This implies that they are generally less stable and can undergo fusion.
- With exception of Helium.

- 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 Δm is the mass defect (kg)

23.2 Radioactive decay

Candidates should be able to:

1 understand that fluctuations in count rate provide evidence for the random nature of radioactive decay

2 understand that radioactive decay is both spontaneous and random

3 define activity and decay constant, and recall and use $A = \lambda N$

4 define half-life

5 use $\lambda = 0.693 / t_{\frac{1}{2}}$

6 understand the exponential nature of radioactive decay, and sketch and use the relationship $x = x_0 e^{-\lambda t}$, where x could represent activity, number of undecayed nuclei or received count rate

- **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

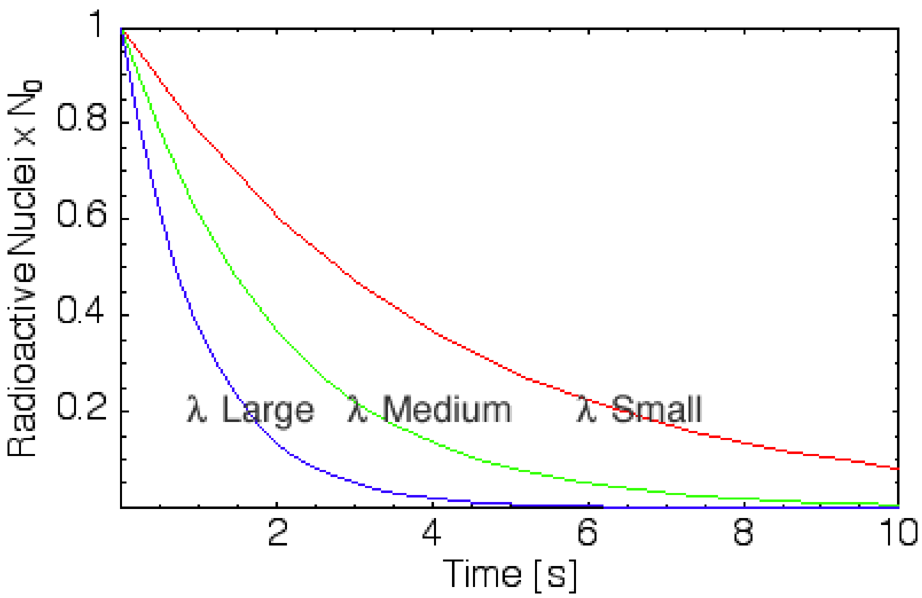
$$A = \frac{\Delta N}{\Delta t} = -\lambda N$$

Here ΔN is the number of decayed nuclei, Δt is the rate (s), λ 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.