

Nuclear radius

Estimates of nuclear radius can be determined by two experiments: the **closest approach of alpha particles** and **electron diffraction**.

The nucleus has a radius of around $\sim 10^{-15}$ m

Closest approach of alpha particles

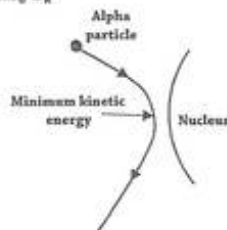
Alpha particles are directed towards the atom and are deflected due to **electrostatic repulsion**.

The **kinetic energy**, E_k , of the alpha particle will reduce and the **potential energy**, E_p , will increase.

$$E_k \text{ lost} = E_p \text{ gained}$$

$$E_k = E_p = \frac{1}{4\pi\epsilon_0} \frac{Qq}{R}$$

$$R = \frac{1}{4\pi\epsilon_0} \frac{Qq}{E_k}$$

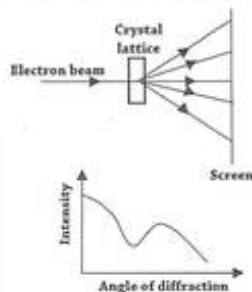


Electron diffraction

A **beam of electrons** is directed at a sample of metal. The electrons **diffract around the nuclei** in the sample.

Intensity of electrons is plotted against angle of diffraction.

The angle of the first diffraction minimum ($\theta_{\min}$) is used to determine the diameter of the nucleus and, therefore, the radius.



Exam Tip!

The plot of R against $A^{1/3}$ is a straight line

Nuclei and nuclear energy

Dependence of nuclear radius on nucleon number

- Use experimental data of samples of different elements to plot graph of R against $A^{1/3}$
- The plot will give a straight line through the origin with gradient equal to R_0
- Therefore, it can be said that the nuclear radius of an atom is dependent on the nucleon number of the element:

$$R = R_0 A^{1/3}$$

R = nuclear radius
 R_0 = nuclear radius constant ≈ 1.25 fm
 A = nucleon number

Constant density of nuclear material

You may be asked to prove that nuclear density is constant. First find an equation for the **volume of the nucleus**, V :

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi R_0^3 A$$

then the **density**, ρ

$$\rho = \frac{m}{V} = \frac{Au}{\frac{4}{3}\pi R_0^3 A}$$

$$\rho = \frac{u}{\frac{4}{3}\pi R_0^3}$$

All of these are constants! So

$$\rho = \frac{u}{\frac{4}{3}\pi R_0^3} = \text{constant}$$

u = atomic mass unit
 $1 u = 1.661 \times 10^{-27}$ kg

Mass and energy

Binding energy: The work required to separate the nucleus into its constituent parts (i.e. protons and neutrons). The greater the binding energy, the more stable the nucleus.

Mass defect: the difference between the mass of the nucleus and the total mass of its individual constituent parts:

$$\Delta m = Zm_p + (A - Z)m_n - m_{\text{nucleus}}$$

m = nuclear mass
 Z = proton number
 A = nucleon number

Einstein's theory of relativity states that **mass and energy are related**, and mass can be converted to energy and back. This is what happens in nuclear decay, when the products of a decay have lower mass than the original nuclei – the **missing mass is converted to energy**.

Einstein's energy equation:

$$E = mc^2$$

E = energy
 c = speed of light
 $= 3 \times 10^8 \text{ m s}^{-1}$

Energy changes:

$$\Delta E = \Delta mc^2$$

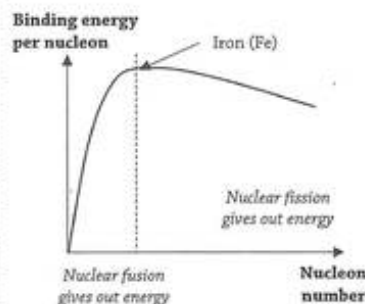
Energy change processes

- Nuclear fusion:** two low-mass nuclei fuse together to create a larger nucleus. In this process the larger nucleus will, therefore, have a greater binding energy per nucleon than the low mass nuclei.
- Nuclear fission:** a large unstable nucleus breaks apart into two smaller, more stable nuclei. The binding energy per nucleon will also increase in this process.

Knowledge of the process of nuclear fission and fusion has allowed scientists to make informed decisions about its place in our future energy use as an alternative energy source to fossil fuels.



The **binding energy per nucleon** is an indication of the nuclear stability of a nucleus.



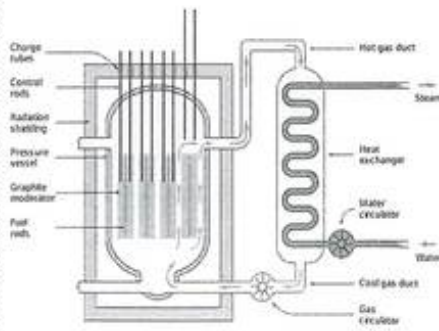
Induced fission

- Fission can be induced by bombarding the **uranium isotope** $^{235}_{92}\text{U}$ with neutrons.
- The uranium isotope is split into **two smaller nuclei** with roughly equal mass and two or three **fission (thermal) neutrons** are released.
- Fission (thermal) neutrons can be harnessed and used to cause more fission events and a **chain reaction** is induced.
- Chain reactions only occur if the material used during fission of the uranium isotope is larger than the **critical mass**.
- With each fission event huge amounts of energy are released.
- Fission chain reactions are used in **nuclear reactors** in nuclear power plants to create energy that can be harnessed into electricity.



The thermal nuclear reactor

- The **moderator** controls the speed of the neutrons as the speed needs to be a specific value in order to induce fission. Graphite or water can be used and are chosen for their **low probability of absorbing neutrons and low mass**.
- The **control rods** absorb neutrons to ensure that there is only one thermal neutron per each fission event. They have the ability to absorb even more neutrons if the rate of release of energy needs to be reduced. The material of the control rods is chosen on their ability to **absorb neutrons effectively**.
- The **coolant** extracts the heat and allows it to be transferred to be used to produce electricity. Coolant is usually water or carbon dioxide gas and is used due to the **high specific heat capacity** of the materials.



An uncontrolled nuclear reactor can be extremely dangerous and cause huge harm to the surrounding environment and population.

Safety aspects

Safety aspects of a nuclear reactor:

- Shielding:**
 - The building housing the reactor is made of concrete walls in order to absorb neutrons and gamma radiation leaving the reactor.
 - The reactor core is also constructed from steel in order to absorb beta gamma radiation as well as some of the gamma radiation and neutrons.
- Emergency shutdown:** Reactors are constructed so that the control rods drop directly into the core to entirely cease fission events if the reactor gets too hot.
- Remote handling:** Fuel rods are operated by remote handling devices.
- Storage:** Strict protocols are in place regarding how to store and transport radioactive waste.

There are risks involved with dealing with nuclear power, seen in events such as Chernobyl and Fukushima. However, if safety features and protocols are followed, the benefits of nuclear power are large; huge amounts of power can be generated and less fuel is required than fuels such as fossil fuels for the same amount of energy production.

