

Physics

# Chapter: - 13th Nuclei



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## Chapter: - 13<sup>th</sup> Nuclei

### 1) Composition of Nucleus: -

The nucleus was first discovered in 1911 by Lord Rutherford and his associates by experiments on scattering of  $\alpha$ -particles by atoms. He found that the scattering results could be explained, if atoms consist of a small, central, massive and positive core surrounded by orbiting electrons.

The experimental results indicated that the size of the nucleus is of the order of  $10^{-14}$  m and is thus 10000 times smaller than the size of atom. The study of radioactivity revealed that nucleus is not a composite body, but is made of nucleons.

**Thus, the nucleus of an atom consists of positively charged particles and neutral-charged particles Called protons and neutrons.**

**Atomic Number(Z):** - Atomic number of an element is the number of protons present inside the nucleus of an atom of the element. It is also equal to the number of electrons revolving in various orbits around the nucleus of the neutral atom.

**Atomic number(Z) = Number of protons = Number of electrons (in neutral atom)**

**Mass Number(A):** - Mass number of an element is the total number of protons and neutrons inside the atomic nucleus of the element.

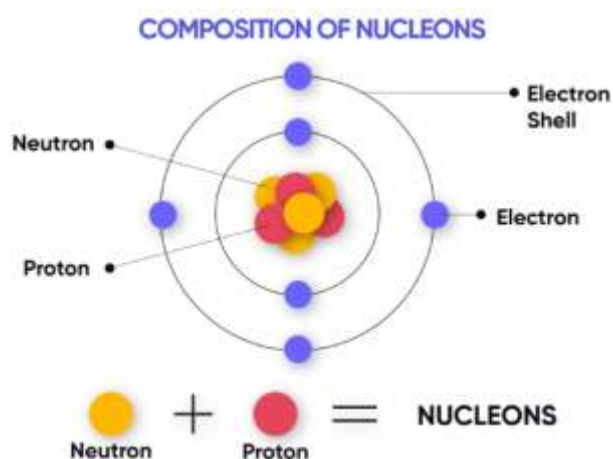
**Mass number(A) = Number of protons(Z) + Number of neutrons(N) = Number of electrons (in neutral atom) + Number of neutrons = Atomic number + Number of neutrons.**

$$A = Z + N$$

The term nucleon is also used for neutron and proton. Thus, the number of nucleons in an atom is its mass number A.

**Nucleon = Neutron + Proton**

**Size of the nucleus:** - The first experimental determination of the size of a nucleus was made from the results of Rutherford scattering of  $\alpha$ -particles. Distance of closest approach was found to be  $3 \times 10^{-14}$  m for 7.7 MeV energetic  $\alpha$ -particles.



**Note:** - This fact indicated that size of nucleus should be less than  $3 \times 10^{-14}$  m. For  $\alpha$ -particles having kinetic energy more than **7.7 MeV**, the distance of closest approach will be smaller. K.E. more than **5.5 MeV**, attractive nuclear forces start affecting the Coulomb's repulsive force between  $\alpha$ -particles and gold nucleus. Size of nucleus can be measured by using fast electron instead of  $\alpha$ -particles for the scattering experiment. The nuclear size was found to vary linearly with mass number (A).

Since nucleus is supposed to be spherical, having radius R.

$$\text{Volume (V)} = \frac{4}{3} \pi R^2 \alpha A \quad (\text{A = mass number})$$

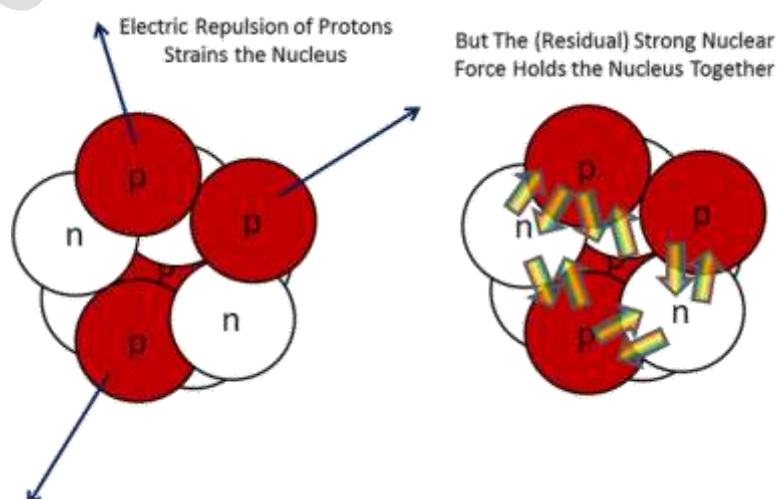
$$R \propto A^{1/3}$$

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

$R_0$  is an Empirical constant for all the nuclei i.e.,  $1.2 \times 10^{-15}$  m or 1.2 fm(fermi meter)

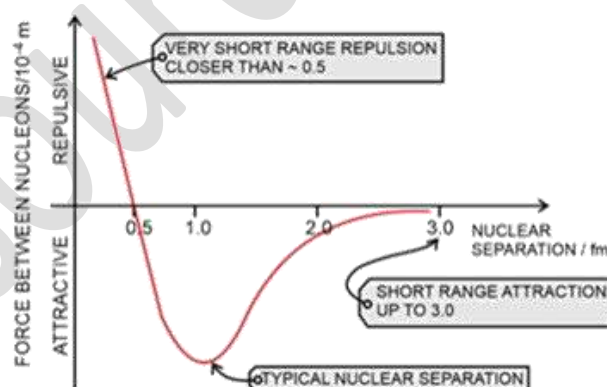
## 2) Nuclear Force:

- The nuclear force, also known as the strong nuclear force, is one of the fundamental forces in nature.
- It is responsible for binding protons and neutrons together within the atomic nucleus.
- The nuclear force is a short-range force, acting over distances on the order of a few femtometers ( $10^{-15}$  meters).
- This force is incredibly strong, overcoming the electrostatic repulsion between positively charged protons within the nucleus.
- The nuclear force is attractive and acts between nucleons (protons and neutrons) irrespective of their charge.
- It is mediated by particles called mesons, which are exchanged between nucleons, transmitting the force.
- The nuclear force plays a crucial role in determining the stability of atomic nuclei.
- Understanding the nuclear force is essential for explaining nuclear phenomena such as radioactivity, nuclear fusion, and fission.



### **Properties of Nuclear Forces: -**

- 1. Strength:** The nuclear force is one of the fundamental forces in nature and is exceptionally strong. It is about 100 times stronger than the Coulomb's electrostatic repulsive force between protons and about  $10^{36}$  times stronger than the gravitational attractive force. This strength allows it to overcome the electrostatic repulsion between protons and keep them bound in the nucleus.
- 2. Mainly attractive with a small repulsive component:** The nuclear force is primarily attractive, although it has a small repulsive component. This characteristic is evident in the variation of potential energy with distance between nucleons. At distances greater than  $r_0$ , the force is attractive, but at distances less than  $r_0$ , it becomes repulsive to prevent the collapsing of the nucleus.
- 3. Charge independence:** The interaction between nucleons is independent of their charges. This means that the nuclear force between proton-proton, proton-neutron, and neutron-neutron pairs is the same. Hence, the nuclear force is charge-independent.
- 4. Short-range:** Nuclear forces operate over very short distances, typically within the range of the size of the nucleus (approximately  $10^{-15}$  meters). Beyond this range, the forces cease to act. This short-range nature allows nucleons to interact only with their nearest neighbors within the nucleus.
- 5. Saturated force:** The nuclear force becomes zero quickly when the distance between two nucleons is around 33 femtometers (33 fm). This saturation means that a nucleon can attract only its nearest neighbors within the nucleus and has no influence on other nucleons.
- 6. Exchange force:** nuclear forces arise from the exchange of mesons (specifically, pions) between nucleons. This exchange mechanism gives rise to the attractive nature of the nuclear force.
- 7. Non-central force:** Unlike gravitational or electrostatic forces, the nuclear force does not act along the line joining the centers of the interacting particles. It is therefore termed as a non-central force.
- 8. Spin dependence:** The nuclear force is observed to be dependent on the spins of the interacting nucleons. Nucleons with parallel spins experience greater nuclear force compared to those with anti-parallel spins. This spin dependence is an important aspect of nuclear interactions.



①

Nuclear Density: Mass per unit volume of a nucleus is called nuclear density.

$$\text{Nuclear density } (\rho) = \frac{\text{Mass of nucleus}}{\text{Volume of nucleus}}$$

$$= \frac{(\text{Mass of proton or neutron}) \times (\text{Mass number})}{\text{Volume of nucleus}}$$

$$\text{Mass of proton} = 1.67 \times 10^{-27} \text{ kg}$$

$$\text{Volume of nucleus} = \left( \frac{4}{3} \pi R^3 \right) \quad [R = R_0 A^{1/3}]$$

$$V = \frac{4}{3} \pi (R_0 A^{1/3})^3$$
$$= \frac{4}{3} \pi R_0^3 A$$

$$\text{density } \rho = \frac{1.67 \times 10^{-27} \times A}{\frac{4}{3} \pi R_0^3 \times A}$$

$$\rho = \frac{1.67 \times 10^{-27}}{\frac{4}{3} \times 3.14 \times (1.2 \times 10^{-15})^3}$$

$$\rho = 2.38 \times 10^{17} \text{ kg/m}^3$$

$\rho = \text{Constant}$  (Nuclear density of all the atoms is same)  
It does not depend upon the mass number.

Note: Nuclear density  $10^{17} \text{ kg/m}^3$  is about  $10^3$  times average density of earth  $\approx 10^4 \text{ kg/m}^3$ .

## Mass - Energy Equation :-

According to Einstein equivalence Relation of mass and energy

$$E = mc^2 \quad \text{--- (i)}$$

This total mass-energy is equal to the rest mass energy  $m_0c^2$  and the kinetic energy

$$E = m_0c^2 + K.E. (T)$$

$$mc^2 = m_0c^2 + (T) \quad \text{--- (ii)}$$

This equation tells or merges two principle

- (i) law of Conservation of energy
- (ii) law of Conservation of mass.

$$T = mc^2 - m_0c^2$$

$$T = (m - m_0)c^2$$

$$\boxed{T = \Delta mc^2}$$

$$\underline{K.E} = \underline{\text{change in the mass}} \times \underline{(\text{speed of light in air})}^2$$

## Mass - Defect :-

It is defined as the difference between the mass of the constituent nucleons of the nucleus in free state and the mass of the nucleus.

Consider a nucleus of mass ( $M$ ) having  $Z$  protons and  $(A-Z)$  neutrons.

Let  $m_n$  = mass of each neutron.

$m_p$  = mass of each proton.

Mass of  $Z$  protons =  $m_p(Z)$

Mass of  $(A-Z)$  neutrons =  $m_n(A-Z)$

Sum of masses of  $Z$  protons and  $(A-Z)$  neutrons

$$m_p Z + m_n(A-Z)$$

$$\text{Mass defect } \Delta m = \{m_p Z + m_n(A-Z)\} - M.$$

Units of Mass Defect:

(1) Mass defect is measured in a.m.u. (atomic mass unit)

or in kg.

Nuclear Binding Energy:

The total energy required to disintegrate the nucleus into its constituent particles (i.e. nucleons) is known as binding energy of the nucleus or nuclear binding energy.

The Binding energy equivalent to mass defect

$$E_b = \Delta m c^2$$

$$\Delta m = \{m_p z + m_n (A-z)\} - M$$

$$E_b = \left[ \{m_p z + m_n (A-z)\} - M \right] c^2$$

This binding energy is in (joule)  
because mass defect in (kg).

If mass defect in a.m.u. Then

$$E_b = \left[ \{m_p z + m_n (A-z)\} - M \right] \text{amu}$$

$$1 \text{ a.m.u.} = 931 \text{ MeV}$$

$$\text{ie } E_b = \Delta m \times 931 \text{ MeV}$$

Q Calculate the Binding energy of a helium ( ${}^4_2\text{He}$ ).

Given mass of  ${}^4_2\text{He} = 4.0026 \text{ a.m.u}$

Mass of proton = 1.0073 a.m.u and Mass of neutron = 1.0087 a.m.u

Sol.  ${}^4_2\text{He} = 2$  protons and 2 neutrons

Mass of 2 protons =  $2 \times 1.0073 = 2.0146 \text{ a.m.u}$

Mass of 2 neutrons =  $2 \times 1.0087 = 2.0174 \text{ a.m.u}$

Total Mass of nucleons =  $2.0146 + 2.0174 = 4.0320 \text{ a.m.u}$

Mass of nucleus ( ${}^4_2\text{He}$ ) = 4.0026 amu

Mass defect =  $4.0320 - 4.0026 = 0.0294 \text{ amu}$   
 $= 0.0294 \times 931 = 27.3711 \text{ MeV}$

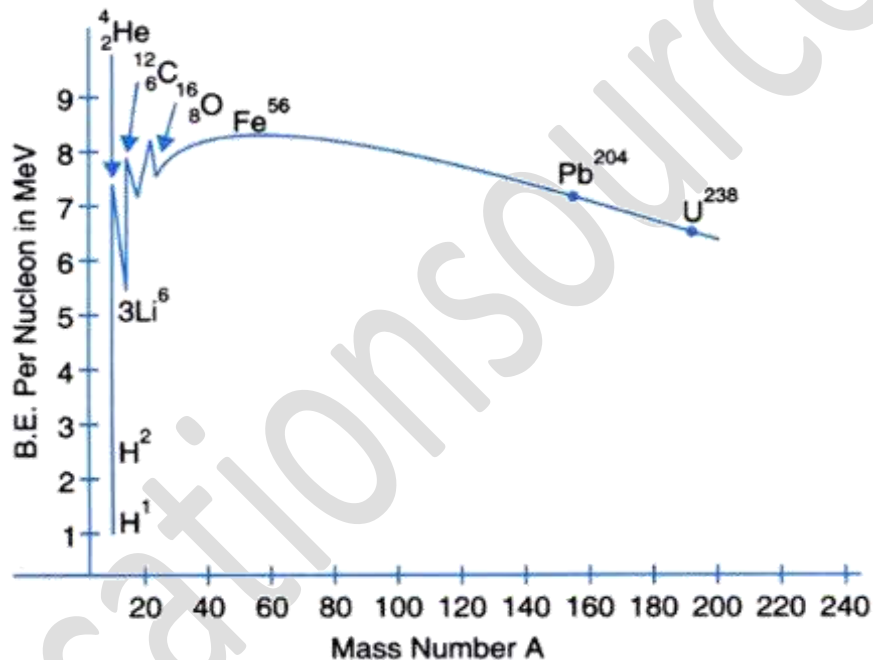
### 3) Nuclear binding energy per Nucleon and binding energy curve: -

The binding energy per nucleon is a measure of the average energy required to separate a nucleus into its individual nucleons (protons and neutrons).

The binding energy per nucleon can be calculated using the formula:

$$\text{Binding energy per nucleon} = \frac{\text{Binding energy of nucleus}}{\text{Number of nucleons}}$$

The binding energy per nucleon typically increases as you move towards iron (Fe) in the periodic table and then decreases for heavier elements. This is because the process of nuclear fusion (combining lighter elements into heavier ones) releases energy up to iron, and nuclear fission (splitting heavier elements into lighter ones) releases energy for elements heavier than iron. Therefore, elements around iron tend to have the highest binding energy per nucleon, indicating greater stability.



- (i) Average binding energy per nucleon for mass number  $< 3$  is very small: This indicates that very light nuclei have low binding energy per nucleon, making them less stable.
- (ii) Some nuclei with mass number  $3 < A < 20$  have large binding energy per nucleon than their neighboring nuclei: Nuclei such as helium-4, beryllium-8, carbon-12, oxygen-16, and neon-20 exhibit higher binding energy per nucleon compared to their neighboring nuclei. This higher binding energy per nucleon suggests greater stability for these nuclei.
- (iii) For  $30 < A < 62$ , binding energy per nucleon increases gradually till it attains a maximum value around 8.8 MeV per nucleon corresponding to nickel-62

**nucleus:** This range includes elements like iron and nickel, which are known to be stable. The high binding energy per nucleon contributes to their stability.

**(iv) For nuclei with  $A > 62$ , binding energy per nucleon gradually decreases:** As the mass number increases beyond 62, the binding energy per nucleon decreases, indicating decreasing stability. Uranium-238, one of the heaviest naturally occurring elements, demonstrates this trend with a binding energy per nucleon dropping to 7.5 MeV.

#### Conclusions:

- **Intermediate nuclei are more stable:** Nuclei with mass numbers between 3 and 62 tend to have higher binding energy per nucleon, indicating greater stability compared to lighter or heavier nuclei.
- **Light and heavy nuclei are less stable:** Both light and heavy nuclei have lower binding energy per nucleon, making them less stable.
- **Nuclear fission:** When a heavy nucleus splits into lighter nuclei, the binding energy per nucleon of the lighter nuclei is greater than that of the original heavy nucleus, releasing energy. This process is known as nuclear fission.
- **Nuclear fusion:** When two very light nuclei combine to form a relatively heavy nucleus, the binding energy per nucleon of the fused nucleus becomes greater than that of the lighter nuclei, releasing energy. This process is called nuclear fusion.

#### Nuclear Energy

**Introduction:** Nuclear energy is the energy released during nuclear reactions, either through nuclear fission or nuclear fusion processes. These reactions involve the conversion of mass into energy, as described by Einstein's famous equation,  $E=mc^2$ . Nuclear energy has significant potential as a power source due to its high energy density and relatively low environmental impact compared to fossil fuels.

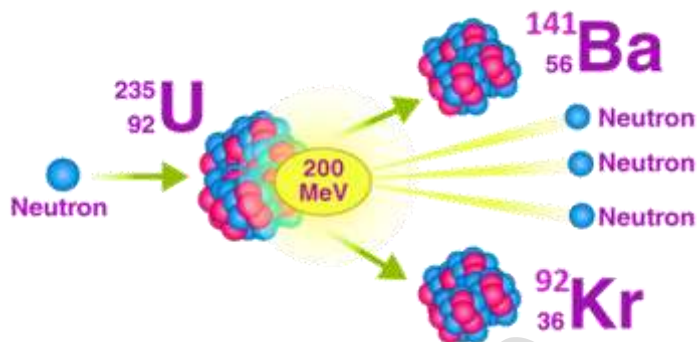
**Nuclear Fission:** *Nuclear fission is a process of splitting a heavy nucleus into two lighter nuclei along with conversion of mass defect into energy.*

Nuclear fission occurs when the nucleus of a heavy atom, such as uranium-235 or plutonium-239, is bombarded with neutrons and splits into smaller nuclei, releasing a large amount of energy along with additional neutrons. The energy released is primarily in the form of kinetic energy of the fission fragments and gamma radiation. The process of nuclear fission is utilized in nuclear reactors to generate electricity.



- **Process:**

- A heavy nucleus absorbs a neutron, becoming unstable.
- The nucleus splits into two or more smaller nuclei, known as fission fragments.
- Additional neutrons are released, which can initiate further fission reactions.
- Energy is released in the form of kinetic energy and gamma radiation.



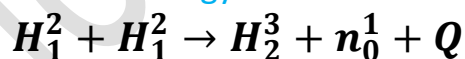
- **Energy Release:**

- The energy released per fission reaction is substantial, typically in the range of millions of electron volts (MeV).
- For example, 1 kilogram of uranium-235 undergoing fission releases approximately  $4 \times 10^{13}$  joules (or 1041 joules) of energy.

- **Utilization:**

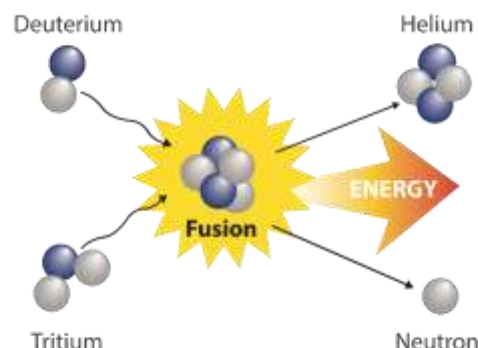
- Nuclear fission is harnessed in nuclear power plants to generate electricity by heating water to produce steam, which then drives turbines connected to generators.

**Nuclear Fusion:** Nuclear fusion involves the combining of light atomic nuclei to form a heavier nucleus, releasing a tremendous amount of energy in the process. Fusion is the process that powers stars, including our sun, and holds immense promise as a potentially limitless source of clean energy.



- **Process:**

- Two light atomic nuclei, typically isotopes of hydrogen (deuterium  $H_1^2$  and tritium), combine under high temperatures and pressure.
- The nuclei overcome their electrostatic repulsion and fuse to form a heavier nucleus.
- Energy is released due to the difference in mass between the initial and final nuclei, as well as the conversion of mass into energy.



- **Energy Release:**

- Fusion reactions release even more energy per reaction compared to fission, typically in the range of tens to hundreds of MeV.
- For example, the fusion of deuterium and tritium releases approximately 17.6 MeV of energy per reaction.

- **Challenges:**

- Achieving and maintaining the extreme conditions required for sustained nuclear fusion, including high temperature and pressure, remains a significant technological challenge.
- Research efforts are underway to develop viable fusion reactors, such as tokamaks and inertial confinement devices, to harness fusion energy for practical use.

**Comparison with Fossil Fuels:** Nuclear energy offers several advantages over traditional fossil fuels, such as coal and oil:

- **Environmental Impact:**

- Nuclear energy production does not emit greenhouse gases or pollutants such as sulfur dioxide and nitrogen oxides, which contribute to air pollution and climate change.
- However, nuclear energy does pose risks associated with radioactive waste disposal and potential accidents.

- **Energy Density:**

- Nuclear fuels, such as uranium and thorium, have much higher energy densities than fossil fuels, resulting in smaller fuel requirements for equivalent energy output.
- This can lead to reduced mining and transportation requirements, as well as decreased environmental impact.

- **Long-Term Viability:**

- Nuclear fusion, if successfully developed, could provide a virtually limitless source of clean energy, as fusion fuels are abundant in nature and do not produce long-lived radioactive waste.

#### 4) Theory of Nuclear Fission

Nuclear fission, a phenomenon first elucidated by Bohr and Wheeler, is explained through the liquid drop model of the nucleus. According to this model, the nucleus behaves akin to a drop of incompressible, electrically charged nuclear liquid. Within the nucleus, two competing forces act: the strong nuclear force and the Coulomb repulsion.

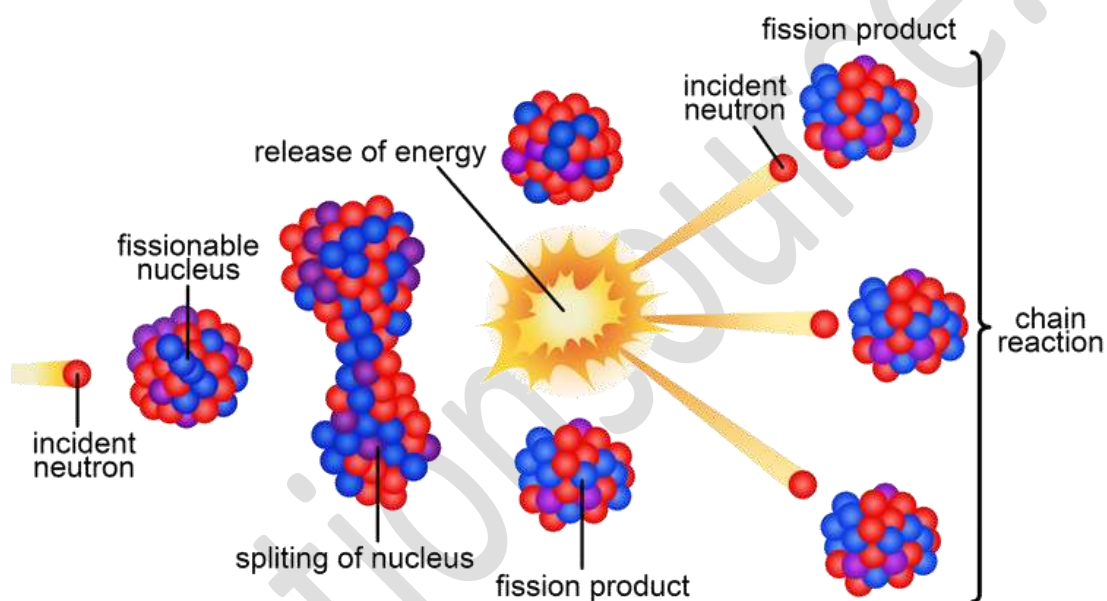
##### 1. Forces in the Nucleus:

- **Nuclear Force:** This force, operating over extremely short distances, tends to maintain the spherical shape of the nucleus by binding nucleons together.

- **Coulomb's Repulsive Force:** Arising due to the electrostatic repulsion between positively charged protons, this force works against the nuclear force, striving to disrupt the spherical shape of the nucleus.

## 2. Initiation of Fission:

- When a neutron collides with a nucleus, it may be captured, imparting excitation energy to the nucleus.
- This excitation energy temporarily strengthens the Coulomb repulsion, causing the spherical shape of the nucleus to distort.
- Oscillations begin within the nucleus, leading to deformation of its shape, eventually resembling that of a dumbbell.



## 3. Fission Process:

- If the excitation energy surpasses a certain threshold, the Coulomb repulsion becomes dominant, causing the two ends of the dumbbell-shaped nucleus to separate.
- This results in the nucleus splitting into two or more smaller nuclei, each with comparable masses.
- The release of energy during this process is substantial and primarily in the form of kinetic energy of the fission fragments and gamma radiation.

## 4. Radiative Capture:

- If the excitation energy is insufficient for fission, the nucleus may undergo a different process known as radiative capture.
- In radiative capture, the nucleus emits gamma rays, releasing the excess excitation energy, while the nucleus retains its spherical shape.

## 5. Energy Release:

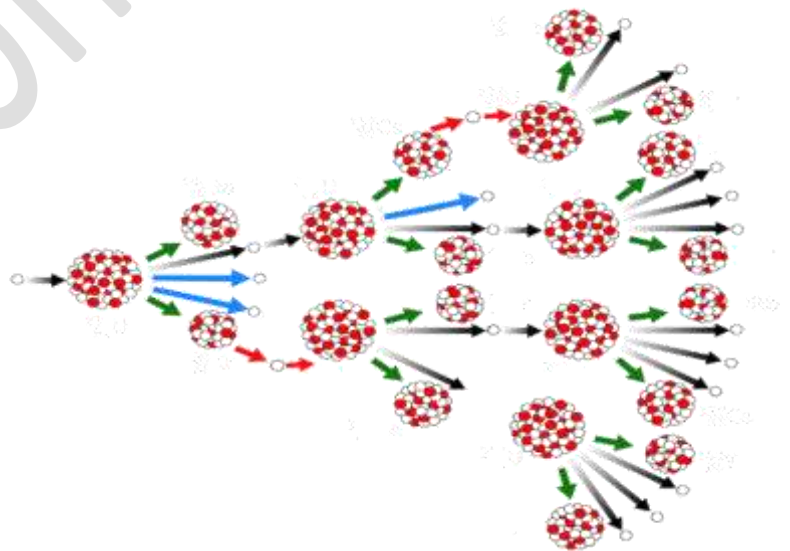
- The sum of the masses of the resultant nuclei is found to be slightly less than the mass of the original nucleus.
- This difference in mass, known as the mass defect, is converted into energy according to Einstein's famous equation,  $E=mc^2$ .
- Approximately **200 MeV** (mega-electron volts) of energy is released per fission event, making nuclear fission an incredibly efficient energy source.

## 5) Nuclear Chain Reaction

In nuclear fission reactions, additional neutrons are typically released along with a significant amount of energy. These neutrons can in turn initiate further fission reactions in neighboring fissile nuclei, leading to a self-sustaining chain reaction. The chain reaction can either be controlled or uncontrolled, depending on various factors.

### 1. Uncontrolled Chain Reaction:

- In an uncontrolled chain reaction, the released neutrons are not moderated or controlled, leading to a rapid increase in the number of fission events.
- Each fission event releases more neutrons, which go on to induce more fissions in nearby nuclei, resulting in an exponential increase in the reaction rate and energy release.
- Without intervention, this uncontrolled chain reaction can lead to a runaway process, generating a large amount of radiation and heat, potentially causing catastrophic consequences.
- Uncontrolled chain reactions are typically associated with nuclear weapons or accidents, such as the atomic bombings of Hiroshima and Nagasaki or the Chernobyl disaster.



### 2. Controlled Chain Reaction:

- In a controlled chain reaction, measures are taken to regulate the rate of neutron-induced fissions to maintain a steady and manageable energy output.
- By controlling factors such as neutron moderation, fuel composition, and reactor design, only a fraction of the neutrons released in each fission event are allowed to induce further fissions.

- This controlled approach ensures that the energy release remains steady and controllable, suitable for practical applications such as electricity generation in nuclear reactors.

### 3. Multiplication Factor (K):

- The sustainability and behavior of a nuclear chain reaction are quantified by the multiplication factor, denoted as K.
- K represents the ratio of the rate of production of neutrons to the rate of loss of neutrons in the reactor system.

$$K = \frac{\text{rate of production of neutrons}}{\text{rate of loss of neutrons}}$$

- **If  $K = 1$** , the reaction is said to be critical, meaning that the number of neutrons produced per fission event is precisely balanced by the number of neutrons lost, resulting in a steady-state reaction.
- **If  $K > 1$** , the reaction is supercritical, with the reaction rate and power increasing exponentially over time. This condition can lead to a rapid escalation of the chain reaction, potentially resulting in an explosion.
- **Conversely, if  $K < 1$** , the reaction is subcritical, and the reaction gradually diminishes over time as the number of neutrons produced is insufficient to sustain the chain reaction.

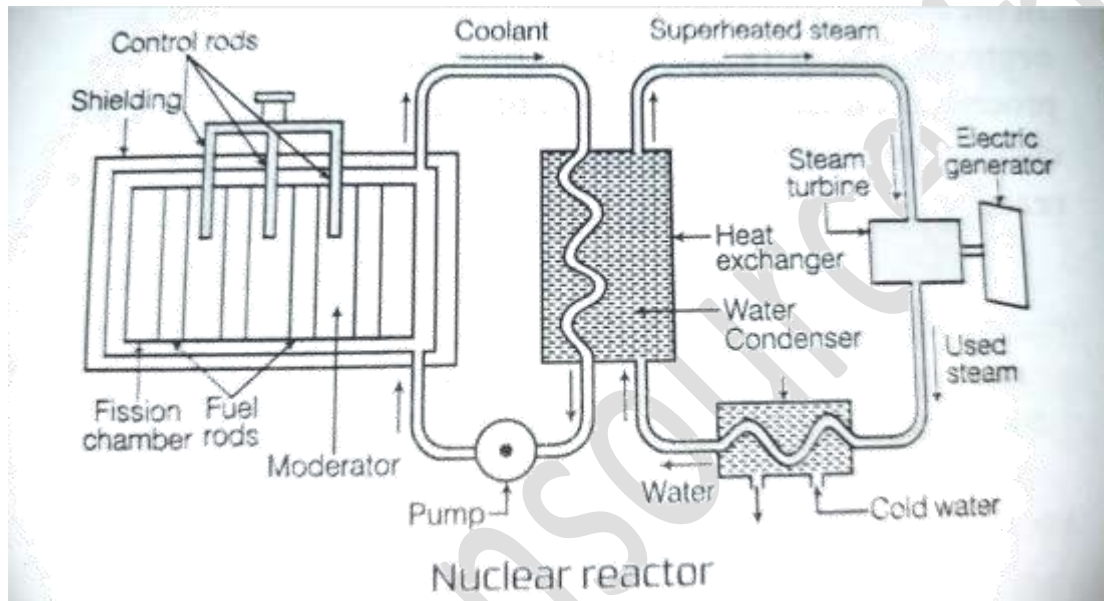
**Conclusion:** Understanding and controlling nuclear chain reactions are crucial for the safe and effective operation of nuclear reactors for power generation and other applications. By managing factors such as neutron moderation and fuel composition, engineers can harness the immense energy potential of nuclear fission while ensuring safety and stability.

**Nuclear Reactor:** - Nuclear reactors are devices designed to initiate and control a sustained chain reaction of nuclear fission, where the nuclei of certain isotopes, such as uranium-235 or plutonium-239, split into smaller nuclei, releasing a large amount of energy in the form of heat. This heat is then used to generate electricity in nuclear power plants or to propel ships in nuclear propulsion systems.

#### **Construction:**

1. **Nuclear Fuel:** This is the material that undergoes nuclear fission to produce energy. Common fuels include uranium-235 (U235) and plutonium-239 (Pu239).
2. **Nuclear Reactor Core:** The core houses the nuclear fuel components where the fission reactions take place.
3. **Moderator:** This component slows down the fast neutrons produced during fission reactions, making them more likely to cause further fission. Materials like graphite or heavy water (deuterium oxide) are commonly used as moderators.

4. **Control Rods:** These rods are inserted into the reactor core to control the rate of fission reactions by absorbing neutrons. They are typically made of materials like boron, cadmium, or hafnium.
5. **Coolant:** A coolant, usually water, is circulated through the reactor core to remove heat generated by the fission reactions. This heat is then transferred to a secondary system to produce steam, which drives turbines to generate electricity.
6. **Shielding:** Thick concrete walls surround the reactor core to contain radiation and protect workers and the environment from harmful radioactive materials.



#### Working:

1. Fission reactions occur when uranium or plutonium nuclei absorb neutrons and split into smaller nuclei, releasing energy and additional neutrons.
2. The moderator slows down the fast neutrons produced during fission, increasing the likelihood of further fission reactions.
3. Control rods are used to adjust the rate of fission reactions by absorbing excess neutrons or being withdrawn to allow more neutrons to initiate fission.
4. Heat generated by the fission reactions is transferred to the coolant, typically water, which circulates through the reactor core.
5. The hot coolant is then pumped to a heat exchanger, where it transfers its thermal energy to a secondary system, usually producing steam.
6. The steam drives turbines connected to electrical generators, producing electricity.
7. The steam is then condensed back into water and returned to the heat exchanger, completing the cycle.

Q Find the binding energy per nucleon of  ${}_{26}\text{Fe}^{56}$  (3)

Given mass of proton = 1.0078254 a.m.u

mass of neutron = 1.008665 a.m.u

Mass of  ${}_{26}\text{Fe}^{56}$  = 55.934939 a.m.u.

Sol

given

No. of protons in  ${}_{26}\text{Fe}^{56}$  = 26

No. of Neutrons in  ${}_{26}\text{Fe}^{56}$  =  $56 - 26 = 30$

Mass of 26 protons =  $26 \times 1.0078254$   
= 26.2034604 U

Mass of 30 neutrons =  $30 \times 1.008665$   
= 30.25995 U

Mass of  ${}_{26}\text{Fe}^{56}$  = 55.934939 a.m.u

Mass defect =  $(26.2034604 + 30.25995) - 55.934939$

= 0.5284714 U

=  $0.5284714 \times 931$

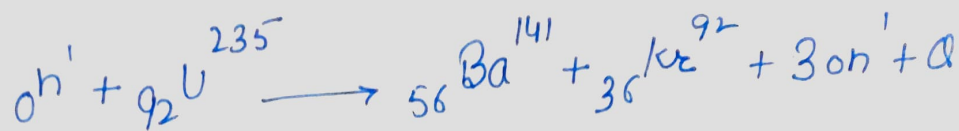
= 492 MeV

Binding energy per nucleon

=  $\frac{492}{56} = 8.79 \text{ MeV/nucleon.}$

## Nuclear Energy Released per fission of ${}_{92}\text{U}^{235}$

Nuclear fission  ${}_{92}\text{U}^{235}$



Released Energy = Mass difference of Reactants and Products.

$$\text{Mass of } {}_{92}\text{U}^{235} = 235.124 \text{ a.m.u.}$$

$$\text{Mass of } {}_0^1\text{H}^1 = 1.009 \text{ a.m.u.}$$

$$\begin{aligned} \text{Total mass of Reactant} &= 235.124 + 1.009 \\ &= 236.133 \text{ a.m.u.} \end{aligned}$$

$$\text{Mass of } {}_{56}\text{Ba}^{141} = 140.958 \text{ a.m.u.}$$

$$\text{Mass of } {}_{36}\text{Kr}^{92} = 91.926 \text{ a.m.u.}$$

$$\text{Mass of } 3{}_0^1\text{H}^1 = 3.027 \text{ a.m.u.}$$

$$\begin{aligned} \text{Total Mass of Product} &= 140.958 + 91.926 + 3.027 \\ &= 235.911 \text{ a.m.u.} \end{aligned}$$

$$\begin{aligned} \text{Mass of defect} &= \text{Mass of reactant} - \text{Mass of product.} \\ &= 236.133 - 235.911 \\ &= 0.222 \text{ a.m.u.} \end{aligned}$$

$$\begin{aligned} \therefore \text{Energy released} &= 0.222 \times 931 = 206.682 \approx \underline{200 \text{ MeV}} \\ &[\because 1 \text{ amu} = 931 \text{ MeV}] \end{aligned}$$