# 13

Rutherford established that a central core exists in every atom which contains entire positive charge and more than 99% mass of the atom, this central core was named as **Nucleus**. In this chapter, we will study the constituents of nucleus and how they are held together. Further, we will proceed with the topics, size, mass, density and stability of **Nuclei**. And finally, we will have a look at the associated nuclear phenomena such as radioactivity, nuclear fission and nuclear fusion.

# NUCLEI

Concept Physics classes, for:-11,12,NEET & JEE
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## |TOPIC 1|

## Nucleus and Its Composition

In every atom, the positive charge and mass are densely concentrated at the centre of the atom forming its nucleus. The overall dimensions of a nucleus are much smaller than those of an atom. The radius of the nucleus is smaller than the radius of an atom by a factor of $10^4$. This means the volume of a nucleus is about $10^{-12}$ times the volume of the atom.

**CHAPTER CHECKLIST**
- Nucleus and Its Composition
- Nuclear Energy

## 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 it is made of nucleons.The positive charge in the nucleus is that of the protons. A proton carries one unit of fundamental charge. A free proton is stable.

### Atomic Mass Unit

The mass of an atom is very small. Kilogram cannot be used to measure such small quantity of mass. It is measured by a unit called **atomic mass unit (amu, i.e. u)**.
It is defined as

$$1\text{u} = \frac{\text{mass of one } ^{12}\text{C atom}}{12} = \frac{1.992647 \times 10^{26}\text{ kg}}{12} = 1.660539 \times 10^{27}\text{ kg}.$$

Atomic masses are measured by an instrument called **mass spectrometer**.

## Discovery of Neutron

The study of isotopes of hydrogen led to the fact that in addition to protons, the nuclei of atoms contain neutral matter in multiples of basic unit. This hypothesis was verified in 1932 by James Chadwick. Chadwick observed that when beryllium was bombarded with $\alpha$-particles, some neutral radiations were emitted, which could knock out protons from lighter nuclei such as those of helium, carbon and nitrogen. Application of the principles of conservation of energy and momentum showed that these neutral radiations could not be photons. Chadwick satisfactorily solved this puzzle by assuming that the neutral radiation consists of a new type of neutral particles called **neutrons**.

He estimated the mass of a neutron being roughly equal to mass of a proton. However, unlike a free proton, a free neutron is unstable. The composition of a nucleus can be described by using the following terms and symbols:

## 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.

$$\boxed{\begin{aligned}\text{Atomic number, } Z &= \text{Number of protons}\\ &= \text{Number of electrons (in a neutral atom)}\end{aligned}}$$

### Mass Number $(A)$

Mass number of an element is the total number of protons and neutrons inside the atomic nucleus of the element.

$$\boxed{\begin{aligned}\text{Mass number, } A &= \text{Number of protons}\\ &\quad + \text{Number of neutrons}\end{aligned}}$$

$$\begin{aligned}&= \text{Number of electrons (in a neutral atom)}\\ &\quad + \text{ Number of neutrons}\\ &= \text{Atomic number} + \text{Number of neutrons} = Z + N\end{aligned}$$

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

Nuclear species or nuclides are shown by the notation ${}_{Z}^{A}X$, where $X$ is the chemical symbol of the species.

**EXAMPLE |1|** In a nucleus of ${}_{92}\text{U}^{238}$, find the number of protons and the number of neutrons.

**Sol.** Number of protons, $Z = 92$

$\therefore$ Number of neutrons, $N = A - Z = 238 - 92 = 146$

## Size of Nucleus

The size of the nucleus has been measured with the help of a variety of experiments involving the scattering of particles such as neutrons, protons, electrons, etc. From all these experiments, it is found that the volume of the nucleus is directly proportional to the number of nucleons (mass number) constituting nucleus.

If $R$ is the radius of the nucleus having mass number $A$, then

$$\frac{4}{3}\pi R^3 \propto A \Rightarrow R \propto A^{1/3}$$

$$\Rightarrow \quad \boxed{R = R_0\, A^{1/3}}$$

where, $R_0 = 1.2 \times 10^{-15}$ m is the range of nuclear size.

It is also known as **nuclear unit radius**.

Owing to the small size of the nucleus, fermi (fm) is found to be a convenient unit of length in nuclear physics.

It is given as,

$$1 \text{ fermi (fm)} = 10^{-15} \text{ m}$$

**EXAMPLE |2|** Obtain the approximate value of the radius of a nucleus ${}_{92}\text{U}^{238}$. Take, $R_0$ is $1.2 \times 10^{-15}$ m.

**Sol.** Given, $A = 238$, $R_0 = 1.2 \times 10^{-15}$ m

As, $\quad R = R_0 A^{1/3} = 1.2 \times 10^{-15} (238)^{1/3}$

$\therefore \quad R = 7.437 \times 10^{-15}$ m

### Nuclear Density

Density of nuclear matter is the ratio of mass of nucleus and its volume.

If $m$ is the average mass of a nucleon and $A$ is the mass number of element, then the mass of nucleus $= mA$. If $R$ is the nuclear radius, then

$$\text{volume of nucleus} = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi (R_0 A^{1/3})^3 = \frac{4}{3}\pi R_0^3 A$$

$$\text{As, density of nuclear matter} = \frac{\text{Mass of nucleus}}{\text{Volume of nucleus}}$$

$$\therefore \quad \boxed{\rho = \frac{mA}{\frac{4}{3}\pi R_0^3\, A}} \quad \text{or} \quad \boxed{\rho = \frac{3m}{4\pi R_0^3}}$$

Thus, the density of nucleus is a constant, **independent of** $A$, for all nuclei. Different nuclei are like drop of liquid of constant density. The density of nuclear matter is approximately $2.3 \times 10^{17}$ kg/m$^3$. This density is very large as compared to an ordinary matter.

**EXAMPLE |3|** Given the mass of iron nucleus as 55.85u and $A = 56$. Find the nuclear density. **NCERT**

**Sol.** Given, mass, $m = 55.85\text{ u} = 55.85 \times 1.67 \times 10^{-27}$ kg

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

$\therefore$ Nuclear density, $\rho = \frac{m}{V}$

$$= \frac{3 \times 55.85 \times 1.67 \times 10^{-27}}{4 \times \frac{22}{7} \times (1.2 \times 10^{-15})^3 \times 56}$$

$$= 2.29 \times 10^{17}\ \text{kg/m}^3$$

**EXAMPLE |4|** Supposing that protons and neutrons have equal masses. Calculate how many times nuclear matter is denser than water? Take, mass of a nucleon $= 1.67 \times 10^{-27}$ kg and $R_0 = 1.2 \times 10^{-15}$ m.

**Sol.** Density of nucleus (of water),

$$\rho = \frac{3m}{4\pi R_0^3} = \frac{3 \times 1.67 \times 10^{-27}}{4 \times \frac{22}{7} \times (1.2 \times 10^{-15})^3}$$

$$= \frac{7 \times 3 \times 1.67 \times 10^{18}}{88 \times 1.2 \times 1.2 \times 1.2}$$

$$= 2.307 \times 10^{17}\ \text{kg/m}^3$$

Density of water, $\rho' = 10^3\ \text{kg/m}^3$

$$\therefore \qquad \frac{\rho}{\rho'} = \frac{2.307 \times 10^{17}}{10^3} = 2.307 \times 10^{14}$$

# MASS-ENERGY AND NUCLEAR BINDING ENERGY

## Mass-Energy

Einstein showed that mass is another form of energy and one can convert mass-energy into other forms of energy.

Einstein's mass-energy equivalence equation is $E = mc^2$ where, $E$ is the energy, $m$ is the mass and $c$ is the velocity of light in vacuum (approximately equal to $3 \times 10^8$ m/s).

The mass of a particle measured in a frame of reference in which the particle is at rest is called its **rest mass**, usually denoted by $m_0$. The rest mass-energy of a particle would be $m_0 c^2$, which is enormously large on account of large value of $c$.

If $I$ is kinetic energy of the particle, then its total energy,

$$\boxed{E = mc^2}$$

$$= \text{rest mass-energy} + \text{KE} = m_0 c^2 + I$$

where, $m$ is called effective mass of the particle, when it is moving. Clearly, $m > m_0$.

The conservation law of energy states that the initial energy and final energy are equal, provided the energy associated with mass is also included.

## Nuclear Binding Energy

The sum of the masses of neutrons and protons forming a nucleus is more than the actual mass of the nucleus. This difference of masses is known as **mass defect**.

If a certain number of neutrons and protons are brought together to form a nucleus of a certain charge and mass, an energy $E_b$ will be released in the process. The energy $E_b$ is called the binding energy of the nucleus.

Thus, the binding energy of a nucleus may be defined as the energy equivalent to the mass defect of the nucleus.

If we separate a nucleus into its nucleons, we would have to supply a total energy equal to $E_b$, to those particles from Einstein equation,

$$E = \Delta mc^2 \qquad [\Delta m = \text{mass defect}]$$

$$E_b = [Zm_p + (A - Z)m_n - M]c^2$$

where, $M$ is mass of nucleus, $m_p$ is the mass of proton and $m_n$ is the mass of neutron.

The mass defect reappears as equivalent energy $(\Delta m)c^2$, which is liberated during the formation of nucleus. Conversely, an amount $\Delta mc^2$ of external energy is required to break the nucleus into protons and neutrons. This energy is called **binding energy**.

"The **binding energy** of a nucleus is defined as the minimum energy required to separate its nucleons and place them at rest and infinite distance apart".

## Average Binding Energy Per Nucleon of a Nucleus

It is the average energy spend to remove a nucleon from the nucleus to infinite distance. It is given by total binding energy divided by the mass number of the nucleus.

Binding energy per nucleon

$$= \frac{\text{Total binding energy}}{\text{Number of nucleons } (A)}$$

or

$$E_{\text{bn}} = \frac{E_b}{A}$$

**EXAMPLE |5|** A given coin has a mass of 3.0 g. Calculate the nuclear energy that would be required to separate all the neutrons and protons from each other. For simplicity assume that the coin is entirely made of $^{63}_{29}\text{Cu}$ atoms (of mass 62.92960 u). **NCERT**

**Sol.** Given,mass of coin = 3g

Atomic mass of Cu = 63

Mass of ${}^{63}_{29}$Cu, $m$ = 62.92960 u

Avogadro's number = $6.023 \times 10^{23}$

Mass of proton, $m_p$ = 1.007825 u

Mass of neutron, $m_n$ = 1.008665 u

Nuclear energy required to separate neutrons and protons, $E_b = ?$

Since, each atom of copper contains 29 protons and 34 neutrons. Therefore, mass defect of each atom using the relation,

$$\Delta m = [Z m_p + (A - Z) m_n] - M$$

$$\Delta m = [29 \times 1.007825 + 34 \times 1.008665] - 62.92960$$

$$= 0.591935 \text{ u}$$

$$\text{Number of atoms in 3 g coin} = \frac{6.023 \times 10^{23} \times 3}{63}$$

$$= 2.868 \times 10^{22}$$

Total mass defect of all atoms,

$$(\Delta m)_{\text{total}} = 0.591935 \times 2.868 \times 10^{22} = 1.6977 \times 10^{22}$$

The nuclear energy required ($E_b$) to separate all the neutrons and protons from each other and can be calculated by using the relation,

$$E_b = (\Delta m) \times c^2 = (\Delta m)\, c^2 \times 931 \text{MeV}/c^2$$

$$[\because 1 \text{ u} = 931 \text{MeV}]$$

$$= 1.6977 \times 10^{22} \times 931 \text{ MeV} = 1.58 \times 10^{25} \text{ MeV}$$

**EXAMPLE |6|** Find the binding energy per nucleon of ${}_{20}\text{Ca}^{40}$ nucleus. Given, $m({}_{20}\text{Ca}^{40}) = 39.962589$ u, $m_n = 1.008665$ u and $m_p = 1.007825$ u. Take, 1 amu = 931 MeV/$c^2$.

**Sol.** In a nucleus of ${}_{20}\text{Ca}^{40}$,

Number of protons = 20

Number of neutrons = 40 − 20 = 20

Total mass of 20 protons and 20 neutrons

$$= 20 m_p + 20\, m_n = 20(m_p + m_n)$$

$$= 20\,(1.007825 + 1.008665)$$

$$= 40.3298 \text{ u}$$

Mass defect, $\Delta m = 40.3298 - 39.962589 = 0.367211$ u

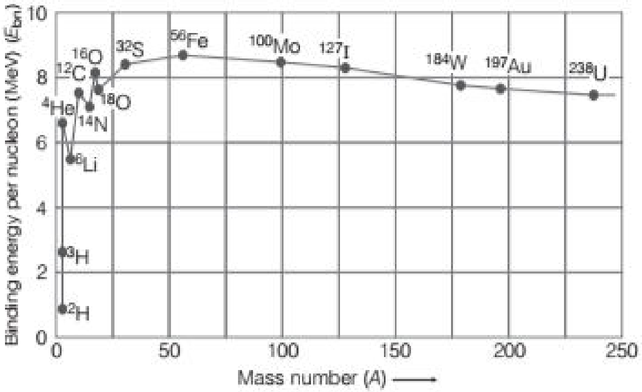
Total binding energy = $0.367211 \times 931 = 341.873441$ MeV

$$E_b \text{ per nucleon, } E_{\text{bn}} = \frac{341.873441}{40}$$

$$= 8.547 \text{ MeV/nucleon}$$

## Binding Energy Curve

It is a plot of the binding energy per nucleon $E_{\text{bn}}$ *versus* the mass number $A$ for a large number of nuclei.



Binding energy per nucleon as a function of mass number

The following are the features of the plot

(i) Average BE/nucleon for lighter nuclei; like ${}_1\text{H}^1$, ${}_1\text{H}^2$, ${}_1\text{H}^3$ is small.

(ii) For mass numbers ranging from 2 to 20, there are sharply defined peaks corresponding to ${}_2\text{He}^4$, ${}_6\text{C}^{12}$, ${}_8\text{O}^{16}$, etc. The peaks indicate that these nuclei are relatively more stable than the other nuclei in their neighbourhood.

(iii) The BE curve has a broad maximum peak in the range $A = 30$ to $A = 120$, which is practically constant corresponding to average binding energy per nucleon is 8.8 MeV per nucleon for ${}_{26}\text{Fe}^{56}$.

(iv) As, the mass number increases, the BE/nucleon decreases gradually falling to about 7.6 MeV per nucleon for ${}_{92}\text{U}^{238}$. The decrease may be due to Coulomb repulsion between the protons. The heavy nuclei are therefore, relatively less stable.

### Conclusions

Following conclusions are obtained from the graph

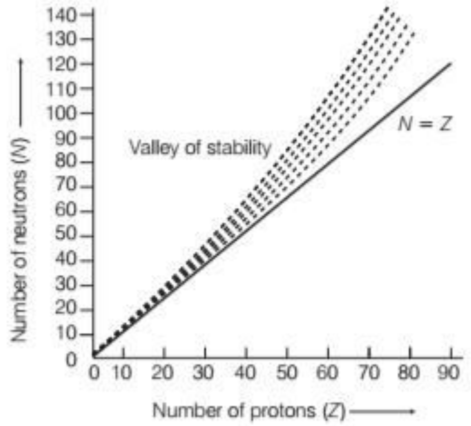
(i) A very heavy nucleus $A = 240$ has lower $E_{\text{bn}}$ compared to that of a nucleus with $A = 120$. Thus, if a nucleus $A = 240$ breaks into two $A = 120$ nuclei, nucleons get more tightly bound. Energy would be released in this process (nuclear fission).

(ii) When two light nuclei ($A \leq 10$) join to form a heavier nucleus, $E_{\text{bn}}$ of fused heavier nuclei is more than the $E_{\text{bn}}$ of lighter nuclei. Energy would be released in this process (nuclear fusion).

**Note** This topic has been frequently asked in previous years 2014, 2013,2012, 2011, 2010.

# NUCLEAR STABILITY

The stability of a nucleus is determined by the value of its binding energy per nucleon. Higher the binding energy of nucleon, more stable is the nucleus. The stability of nucleus is also determined by its neutron to proton ratio. A plot of number of neutrons and number of protons is shown in the figure below. The solid line shows the nuclei with equal number of protons and neutrons. Only light nuclei are on this line, i.e. they are stable, if they contain approximately same number of protons and neutrons.



Graphical representation of number of neutrons *versus* number of protons

Heavy nuclei are stable only when they have more neutrons than protons.

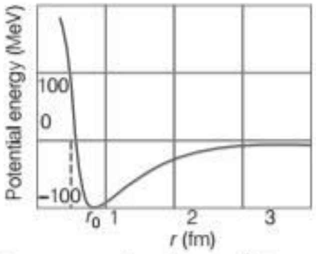
The long narrow region shown in the figure, which contains the cluster of short lines representing stable nuclei is referred to as the valley of stability.

Experimental study shows that the more stable nuclei contain even number of protons or neutrons or both.

# NUCLEAR FORCE

From binding energy curve, we have seen that for average mass nuclei, the binding energy per nucleon is approximately 8 MeV, which is much larger than the binding energy in atoms. Thus, for binding a nucleus together, there must be a strong attractive force of a totally different kind. The force must be strong enough to overcome the repulsion between protons and to bind both protons and neutrons into tiny nuclear volume. The constancy of binding energy per nucleon is a consequence of the fact that nuclear force is short-ranged.

From the plot, it is concluded that potential energy is minimum at a distance $r_0$ ($\approx 0.8$ fm) which means, the force is attractive for distances larger than 0.8 fm and repulsive for the distances less than 0.8 fm between nucleons.



Graphical representation of potential energy *versus* distance for a pair of nucleon. For a distance greater than $r_0$, the force is attractive and for distances less than $r_0$, the force is strongly repulsive

Some of the important characteristics of these forces are as given below:

(i) Nuclear forces among a pair of neutrons, a pair of protons and also between a neutron-proton pair, is approximately the same. This shows that nuclear forces are independent of charge.

(ii) The nuclear forces are very short range forces. They are operative upto distances of the order of a few fermi.

(iii) The nuclear force is much stronger than the coulomb force acting between charges or gravitational forces between masses.

(iv) Nuclear force between two nucleons falls rapidly to zero as their distance is more than a few femtometres (fm). This leads to saturation of forces in a medium or large sized nucleus, i.e. each nucleon interacts with its immediate neighbours only, rather than with all the other nucleons in the nucleus.

(v) The nuclear forces are dependent on spin or angular momentum of nuclei.

**Note** Nuclear forces are the strongest attractive forces between nucleons. It is non-conservative force and does not obey inverse square law. It is non-central force also.

# TOPIC PRACTICE 1

## OBJECTIVE Type Questions

**1.** Atomic mass unit (1 u) is

(a) 1/12 of mass of ${}^{12}C$ atom

(b) 1/14 of mass of ${}^{14}C$ atom

(c) 1/12 of mass of ${}^{14}C$ atom

(d) 1/6 of mass of ${}^{12}C$ atom

**2.** Ratio of radius of an atom to the radius of its nucleus is around

(a) $10^{-2}$ (b) $10^{4}$
(c) $10^{12}$ (d) $10^{15}$

**3.** The number of neutrons in a ${}_{84}Po^{218}$ nucleus is

(a) 84 (b) 218 (c) 222 (d) 134

**4.** As compared to ${}^{12}C$ atom, ${}^{14}C$ atom has

(a) two extra protons and two extra electrons

(b) two extra protons but no extra electrons

(c) two extra neutrons and no extra electrons

(d) two extra neutrons and two extra electrons

**5.** Density of a nucleus is

(a) more for lighter elements and less for heavier elements

(b) more for heavier elements and less for lighter elements

(c) very less compared to ordinary matter

(d) a constant

**6.** Energy equivalent of 2 g of a substance is

(a) $18\times10^{13}$ mJ (b) $18\times10^{13}$ J
(c) $9\times10^{13}$ mJ (d) $9\times10^{13}$ J

**7.** Given, $m\,({}^{56}_{26}Fe) = 55.934939$ u and $m\,({}^{209}_{83}Bi)$
$= 208.980388$ u
$m_{proton} = 1.007825$ u, $m_{neutron} = 1.008665$ u.
Then, BE per nucleon of Fe

(a) 8.790 MeV (b) 7.75 MeV
(c) 7.5 MeV (d) Data insufficient

**8.** Nature of nuclear force is

(a) electrical

(b) magnetic

(c) gravitational

(d) None of the above

**9.** The gravitational force between a H-atom and another particle of mass $m$ will be given by Newton's law $F = G\,\dfrac{M.m}{r^2}$, where $r$ is in km.
**NCERT Exemplar**

(a) Gravitational mass of H-atom

(b) Effective mass of H-atom

(c) Nuclear mass of H-atom

(d) Mass of electrons in H-atom

**10.** Heavy stable nuclei have more neutrons than protons. This is because of the fact that
**NCERT Exemplar**

(a) neutrons are heavier than protons

(b) electrostatic force between protons are repulsive

(c) neutrons decay into protons through beta decay

(d) nuclear forces between neutrons are weaker than that between protons

## VERY SHORT ANSWER Type Questions

**11.** Select the pairs of isotopes and isotones from the following nuclei.

${}^{22}_{11}Na$, ${}^{24}_{12}Mg$, ${}^{24}_{11}Na$, ${}^{23}_{10}Na$.

**12.** Two nuclei have different number of protons and different number of neutrons. Can they have the same radii and same nuclear density?

**13.** The isotope ${}^{16}_{8}O$ has 8 protons, 8 neutrons and 8 electrons, while ${}^{8}_{4}Be$ has 4 protons, 4 neutrons and 4 electrons. Yet the ratio of their atomic masses is not exactly 2. Why?

**14.** ${}^{3}_{2}He$ and ${}^{3}_{1}He$ nuclei have the same mass number. Do they have same binding energy?
**NCERT Exemplar**

**15.** Why do stable nuclei never have more protons than neutrons? **NCERT Exemplar**

**16.** Which property of nuclear forces is responsible for constancy of $E_b$ per nucleon? Comment.

## SHORT ANSWER Type Questions

**17.** From the relation $R = R_0A^{1/3}$, where $R_0$ is a constant and $A$ is the mass number of a nucleus, show that the nuclear matter density is nearly constant (i.e. independent of $A$). **NCERT**

**18.** Check whether the given statement is correct or incorrect, if incorrect then correct it with proper explaination.

The order of magnitude of density of nuclear matter is $10^4\,kg/m^3$.

**19.** The mass of a nucleus is less than the sum of the masses of constituent neutrons and protons. Comment.

**20.** If both the numbers of protons and neutrons are conserved in a nuclear reaction like

$${}_6C^{12} + {}_6C^{12} \longrightarrow {}_{10}Ne^{20} + {}_2He^4$$

In what way is the mass converted into energy? Explain. **Delhi 2010**

**21.** Draw a plot of potential energy between a pair of nucleons as a function of their separation. Mark the regions where potential energy is
(i) positive and (ii) negative. **Delhi 2013**

**22.** Explain the processes of nuclear fission and nuclear fusion by using the plot of binding energy per nucleon (BE/$A$) *versus* the mass number $A$. **CBSE 2018**

**23.** Proton and neutron exist together in an extremely small space within the nucleus. How is this possible, when protons repel each other?

**24.** Why heavy stable nucleus must contain more neutrons than protons?

## LONG ANSWER Type I Questions

**25.** (i) Write three characteristic properties of nuclear force.

(ii) Draw a plot of potential energy of a pair of nucleons as a function of their separation. Write two important conclusions that can be drawn from the graph. **Delhi 2015**

**26.** Answer the following.

(i) Why is the binding energy per nucleon found to be constant for nuclei in the range of mass number ($A$) lying between 30 and 170?

(ii) When a heavy nucleus with mass number $A = 240$ breaks into two nuclei, $A = 120$, energy is released in the process. **Foreign 2012**

**27.** In the study of Geiger-Marsdon experiment on scattering of $\alpha$-particles by a thin foil of gold, draw the trajectory of $\alpha$-particles in the Coulomb field of target nucleus. Explain briefly how one gets the information on the size of the nucleus from this study. From the relation $R = R_0 A^{1/3}$, where $R_0$ is constant and $A$ is the mass number of the nucleus, show that nuclear matter density is independent of $A$. **All India 2015**

**28.** Nuclei with magic number of protons $Z = 2, 8, 20, 28, 50, 52$ and magic number of neutrons $N = 2, 8, 20, 28, 50, 82$ and 126 are found to be very stable.

(i) Verify this by calculating the proton separation energy $S_p$ for ${}^{120}Sn$ ($Z = 50$) and ${}^{121}Sb$ ($Z = 51$). The proton separation energy for a nuclide is the minimum energy required to separate the least tightly bound proton from a nucleus of that nuclide. It is given by

$$S_p = (M_{Z-1,N} + M_H - M_{Z,N})\,c^2$$

Given, ${}^{119}In = 118.9058$ u, ${}^{120}Sn = 119.902199$ u

${}^{121}Sb = 120.903824$ u,

${}^{1}H = 1.0078252$ u

(ii) What does the existence of magic number indicate? **NCERT Exemplar**

**29.** Deuteron is a bound state of a neutron and a proton with a binding energy $B = 2.2$ MeV. A $\gamma$-ray of energy $E$ is aimed at a deuteron nucleus to try to break it into a (neutron + proton) such that the $n$ and $p$ move in the direction of the incident $\gamma$-ray. If $E = B$, show that this cannot happen. Hence, calculate how much bigger than $B$ must be $E$ be for such a process to happen? **NCERT Exemplar**

## NUMERICAL PROBLEMS

**30.** Obtain approximately the ratio of the nuclear radii of the gold isotope ${}^{197}_{79}Au$ and the silver isotope ${}^{107}_{47}Ag$. **NCERT**

**31.** Calculate the energy equivalent of 2 g of substance.

**32.** Calculate the energy in fusion reaction ${}^2_1H + {}^2_1H \longrightarrow {}^3_2He + n$, where BE of ${}^2_1H = 2.23$ MeV and of ${}^3_2He = 7.73$ MeV. **Delhi 2016**

**33.** Determine the nuclear radii of

(i) ${}^{60}_{27}Co$

(ii) ${}^{197}_{79}Au$.

**34.** A heavy nucleus $X$ of mass number 240 and binding energy per nucleon 7.6 MeV is splitted, into two fragments $Y$ and $Z$ of mass numbers 110 and 130 . The binding energy of nucleons in $Y$ and $Z$ is 8.5 MeV per nucleon. Calculate the energy released per fission in MeV. **Delhi 2010**

**35.** Obtain the binding energy (in MeV) of a nitrogen nucleus (${}^{14}_{7}N$), given

$m({}^{14}_{7}N) = 14.00307$u. **NCERT**

**36.** The neutron separation energy is defined as the energy required to remove a neutron from the nucleus. Obtain the neutron separation energies of the nuclei ${}^{41}_{20}\text{Ca}$ and ${}^{27}_{13}\text{Al}$ from the following data :

$m({}^{40}_{20}\text{Ca}) = 39.962591$ u

$m({}^{41}_{20}\text{Ca}) = 40.962278$ u

$m({}^{26}_{13}\text{Al}) = 25.986895$ u

$m({}^{27}_{13}\text{Al}) = 26.981541$ u **NCERT**

**37.** A nuclide 1 is said to be the mirror isobar of nuclide 2, if $Z_1 = N_2$ and $Z_2 = N_1$.

(i) What nuclide is a mirror isobar of ${}^{23}_{11}\text{Na}$?

(ii) Which nuclide out of the two mirror isobars have greater binding energy and why? **NCERT**

**38.** (i) Two stable isotopes of lithium ${}^{6}_{3}\text{Li}$ and ${}^{7}_{3}\text{Li}$ have respective abundances of 7.5% and 92.5%. These isotopes have masses 6.01512 u and 7.01600 u respectively. Find the atomic mass of lithium.

(ii) Boron has two stable isotopes ${}^{10}_{5}\text{B}$ and ${}^{11}_{5}\text{B}$. Their respective masses are 10.01294 u and 11.00931 u, and the atomic mass of boron is 10.811 u. Find the abundances of ${}^{10}_{5}\text{B}$ and ${}^{11}_{5}\text{B}$. **NCERT**

**39.** In a periodic table, the average atomic mass of magnesium is given as 24.312 u. The average value is based on their relative natural abundance on the earth.

The three isotopes and their masses are ${}^{24}_{12}\text{Mg}$ (23.98504 u), ${}^{25}_{12}\text{Mg}$ (24.98584 u) and ${}^{26}_{12}\text{Mg}$(25.98259 u). The natural abundance of ${}^{24}_{12}\text{Mg}$ is 78.99% by mass. Calculate the abundances of other two isotopes. **NCERT**

**40.** The three stable isotopes of neon ${}^{20}_{10}\text{Ne}$, ${}^{21}_{10}\text{Ne}$ and ${}^{22}_{10}\text{Ne}$ have respective abundances of 90.51%, 0.27% and 9.22%. The atomic masses of three isotopes are 19.99 u, 20.99 u and 21.99 u, respectively. Obtain the average atomic mass of neon. **NCERT**

**41.** (i) What is the nuclear density of ${}^{228}_{90}\text{Th}$ ?

(ii) Is the nuclear density of an $\alpha$-particle (${}^{4}_{2}\text{He}$) to be greater than, less than or equal to ${}^{228}_{90}\text{Th}$ ? Explain.

(iii) Determine the nuclear density of an $\alpha$-particle. **NCERT**

**42.** Obtain the binding energy of the nuclei ${}^{56}_{26}\text{Fe}$ and ${}^{209}_{83}\text{Bi}$ in units of MeV from the following data:

$m({}^{56}_{26}\text{Fe}) = 55.934939$ u

$m({}^{209}_{83}\text{Bi}) = 208.980388$ u **NCERT**

# HINTS AND SOLUTIONS

**1.** (a) Atomic mass unit (1 u) is defined as

$$1\text{ u} = \frac{\text{mass of } {}^{12}\text{C atom}}{12}$$

**2.** (b) Radius of atom $\simeq 10^{-10}$

Radius of nucleus $\simeq 10^{-14}$

$$\therefore \quad \frac{\text{Radius of atom}}{\text{Radius of nucleus}} = \frac{10^{-10}}{10^{-14}} \simeq 10^{4}$$

**3.** (d) Given, ${}_{84}\text{Po}^{218}$

Here, $Z = 84$, $A = 218$, $A = Z + N$

$N = A - Z = 218 - 84 = 134$

**4.** (c) For ${}^{12}_{6}\text{C}$, $A = 12 = N + Z$, $Z = 6 \Rightarrow N = 6$

For ${}^{14}_{6}\text{C}$; $A = 14 = N + Z$, $Z = 6 \Rightarrow N = 8$

Also, number of electrons in both atoms

= number of protons $= Z = 6$

**5.** (d) Density $= \dfrac{\text{Mass}}{\text{Volume}} = \dfrac{mA}{\frac{4}{3}\pi R_0^3 A}$

$$= \frac{3m}{4\pi R_0^3}, \; m = m_p = M_N$$

$= 23 \times 10^{17}\ \text{kgm}^{-3}$, which is a constant.

**6.** (b) Energy, $E = 2 \times 10^{-3} \times (3 \times 10^{8})^2$ J

$$E = 2 \times 10^{-3} \times 9 \times 10^{16}$$

$$= 18 \times 10^{13}\ \text{J}$$

Thus, if one gram of matter is converted to energy, there is a release of enormous amount of energy.

**7.** (a) ${}^{56}_{26}\text{Fe}$ nucleus has 26 protons and 30 neutrons.

$\therefore$ Mass defect $= (26 m_p + 30\, m_n) - m({}^{56}_{26}\text{Fe})$

$= 56.46340 - 55.934939 = 0.528461$ amu

Total BE $= 0.528461 \times 931.5 = 492.26$ MeV

$\therefore$ Binding energy per nucleon

$$= \frac{492.26}{56} = 8.790 \text{ MeV}$$

**8.** (d) Nuclear force is an exchange force, it does not come under electrical, gravitational or magnetic force category.

**9.** (b) Given, $F = \frac{GMm}{r^2}$

$M$ = effective mass of hydrogen atom

$G$ = gravitational constant

and $r$ = distance between H-atom and particle of mass $m$

**10.** (b) Stable heavy nuclei have more neutrons than protons. This is because electrostatic force between protons is repulsive , which may reduce stability.

**11.** Isotopes = ${}_{11}^{22}\text{Na}$, ${}_{11}^{24}\text{Na}$

(both have same atomic number, i.e. 11)

Isotones = ${}_{11}^{24}\text{Na}$, ${}_{10}^{23}\text{Na}$

(both have same number of neutrons, i.e. 13)

**12.** Since, radius of nucleus (i.e. $R = R_0 A^{1/3}$) is proportional to the cube root of its mass number, hence nuclei will have same radii, if their mass numbers are same. But nuclear density is independent on mass number. It remains constant for all nuclei, i.e. $2.3 \times 10^{17}$ kg/m$^3$.

**13.** It is because of the fact that the mass of a nucleus is slightly less than the mass of it's constituent nucleons. This decrease in mass is called mass defect. Since, the mass defect in case of ${}_{8}^{16}\text{O}$ is not exactly twice the mass defect in case of ${}_{4}^{8}\text{Be}$, so the ratio of the atomic masses is not exactly.

**14.** Since, the repulsive force between protons is missing in ${}_{1}^{3}\text{He}$, so the binding energy of ${}_{1}^{3}\text{He}$ is greater than that of ${}_{2}^{3}\text{He}$ .

**15.** Because the protons are positively charged, so they repel each other. Since, this repulsion force is more, so that an excess of neutrons are required to reduce this repulsion.

**16.** Nuclear forces are saturated in character. This property makes $E_b$ per nucleon constant for most of the nuclei.

**17.** Refer to text on page 502.

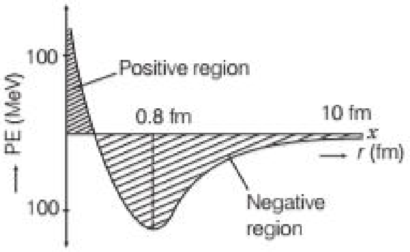
**18.** Given statement is incorrect because the order of magnitude of density of nuclear matter is the order of $10^{17}$ kg/m$^3$.

**19.** When nucleons approach each other to form a nucleus, they strongly attract each other. Their potential energy decreases and becomes negative. It is the potential energy which holds the nucleons together in the nucleus. The decrease in PE results in the mass of nucleons inside the nucleons.

**20.** The sum of masses of nuclei of product element is less than sum of masses of reactants and hence, loss of mass takes place during the reaction. This difference of mass of product element and reactant converts into energy and liberated in the form of heat.

Here, sum of masses of ${}_{10}\text{Ne}^{20}$ and ${}_{2}\text{He}^{4}$ is less than the sum of two ${}_{6}\text{C}^{12}$ and conversion of this mass defect is used to produce energy.

**21.** The graph between the potential energy of a pair of nucleons as a function of their separation is given below

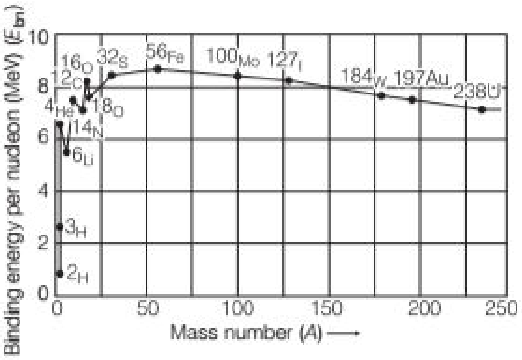


(i) For distance less than 0.8 fm, negative PE decreases to zero and then becomes positive.

(ii) For distances larger than 0.8 fm, negative PE goes on decreasing.

**22.** From the given plot, we can conclude that,

a very heavy nucleus $A = 240$ has lower $E_{bn}$ compared to that of a nucleus with $A = 120$. Thus, if a nucleus $A = 240$ breaks into two $A = 120$ nuclei, nucleons get more tightly bound. Energy would be released in this process which is known as nuclear fission.



Binding energy per nucleon as a function of mass number

Also, when two light nuclei ($A \leq 10$) join to form a heavier nucleus, $E_{bn}$ of fused heavier nuclei is more than the $E_{bn}$ of lighter nuclei. Energy would be released in this process, which is known as nuclear fusion.

**23.** Refer to the text on page 505.

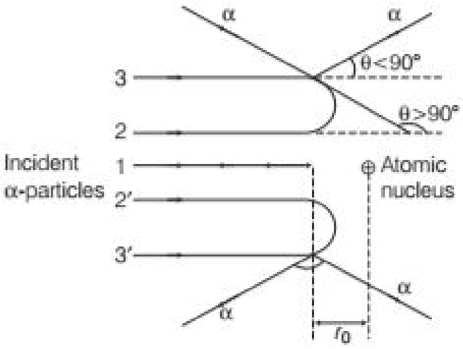
**24.** Refer to the text on page 505.

**25.** Refer to text on page 505.

**26.** (i) The binding energy per nucleon for nucleus of range, $30 < A < 170$ is close to its maximum value. So, the nucleus belongs to this region is highly stable and does not show radioactivity.

(ii) Binding energy per nucleon is smaller for heavier nuclei than the middle ones, i.e. heavier nuclei are less stable. When a heavier nucleus such as nucleus of mass number 240 splits into lighter nuclei (mass number 120), the BE/nucleon changes from about 7.6 MeV to 8.4 MeV. Greater BE of the product nuclei result in the liberation of energy.

**27.** Trajectory of α-particles in the coulomb field of target nucleus is shown below:



From this experiment, the following points are observed.

(i) Most of the α-particles pass straight through the gold foil. It means that they do not suffer any collision with gold atoms.

(ii) About one α-particle in every 8000 α-particles deflects by more than 90°. As most of the α-particles go undeflected and only a few get deflected, this shows that most of the space in an atom is empty and at the centre of the atom, there exists a nucleus. By the number of α-particles get deflected, the information regarding size of the nucleus can be known.

Refer to text on page 502.

**28.** (i) The proton separation energy is given by

$$S_{p\,(\text{Sn})} = (M_{119,\,70} + M_H - M_{120,\,70})c^2$$

$$= (118.9058 + 1.0078252 - 119.902199)\ c^2$$

$$= 0.0114262\,c^2$$

Similarly, $S_{p\,(\text{Sb})} = (M_{120,\,70} + M_H - M_{121,\,70})\,c^2$

$$= (119.902199 + 1.0078252 - 120.903822)\,c^2$$

$$= 0.006202\ c^2$$

Since, $S_{p\,(\text{Sn})} > S_{p\,(\text{Sb})}$, Sn nucleus is more stable than Sb nucleus.

(ii) The existence of magic numbers indicates that the shell structure of nucleus is similar to the shell structure of an atom. This also explains the peaks in binding energy/nucleon curve.

**29.** Apply conservation of energy as well as conservation of momentum.

Given, binding energy, $B = 2.2$ MeV

From the energy conservation law,

$$E - B = K_n + K_p = \frac{p_n^2}{2m} + \frac{p_p^2}{2m} \qquad \text{...(i)}$$

From conservation of momentum,

$$p_n + p_p = \frac{E}{c} \qquad \text{...(ii)}$$

As, $E = B$

Eq. (i) becomes, $p_n^2 + p_p^2 = 0$

It only happen, if $p_n = p_p = 0$

So, the Eq.(ii) cannot be satisfied and the process cannot take place.

Let $E = B + X$, where $X << B$ for the process to take place.

Put the value of $p_n$ from Eq. (ii) in Eq. (i), we get

$$\Rightarrow \quad X = \frac{\left(\frac{E}{c} - p_p\right)^2}{2m} + \frac{p_p^2}{2m}$$

$$\Rightarrow \quad 2p_p^2 - \frac{2Ep_p}{c} + \frac{E^2}{c^2} - 2mX = 0$$

Using the formula of quadratic equation, we get

$$p_p = \frac{\frac{2E}{c} \pm \sqrt{\frac{4E^2}{c^2} - 8\left(\frac{E^2}{c^2} - 2mX\right)}}{4}$$

For the real value $p_p$, the determinant is positive

$$\frac{4E^2}{c^2} = 8\left(\frac{E^2}{c^2} - 2mX\right) \Rightarrow 16mX = \frac{4E^2}{c^2}$$

$$\therefore \quad X = \frac{E^2}{4mc^2} = \frac{B^2}{4mc^2} \qquad [\because X << B \Rightarrow E \equiv B]$$

**30.** Radius of nuclei, $R = R_0 A^{1/3}$

where, $A$ is the mass number of nucleus and $R_0$ is an empirical constant.

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

$$\Rightarrow \quad \frac{R_{\text{gold}}}{R_{\text{silver}}} = \left(\frac{A_{\text{gold}}}{A_{\text{silver}}}\right)^{1/3} = \left(\frac{197}{107}\right)^{1/3} = 1.225 = 1.23$$

**31.** Given, $m = 2\text{ g} = 2 \times 10^{-3}$ kg

According to mass-energy equivalence equation,

$$E = mc^2 = 2 \times 10^{-3} \times (3 \times 10^8)^2$$

$$= 18 \times 10^{13} = 1.8 \times 10^{14}\ \text{J}$$

**32.** According to question,

$${}_1^2\text{H} + {}_1^2\text{H} \rightarrow {}_2^3\text{He} + {}_0n^1$$

$\therefore$ Energy of fusion = Binding energy of ${}_3^2$He

$- 2 \times$ Binding energy of ${}_1^2$H

$$= 7.73 - 2 \times 2.23 = 3.27\ \text{MeV}$$

**33.** Refer to the Example 2 on page 502.

**34.** In these type of questions, we have to keep in mind about the difference of mass involved between output and input. Energy will be involved accordingly.

Energy released per fission

$$= (110 + 130) \times 8.5\ \text{MeV} - 240 \times 7.6\ \text{MeV}$$

$$= 240 \times (8.5 - 7.6)\ \text{MeV}$$

$$= 240 \times 0.9 = 216\ \text{MeV}$$

**35.** Mass of proton, $m_p = 1.00783$ u

Mass of neutron, $m_n = 1.00867$ u

In $^{14}_{7}$N, there are 7 protons and 7 neutrons.

$\therefore$ Mass defect, $\Delta m = (7m_p + 7m_n) - m$

$= 7 \times 1.00783 + 7 \times 1.00867 - 14.00307 = 0.11243$ u

Binding energy of nitrogen nucleus $= \Delta m \times 931$MeV

$= 0.11243 \times 931$MeV $= 104.67$ MeV

**36.** (i) When a neutron is separated from $^{41}_{20}$Ca, we are left with $^{40}_{20}$Ca and the reaction becomes

$$^{41}_{20}\text{Ca} \longrightarrow {}^{40}_{20}\text{Ca} + {}_0n^1$$

Mass defect,

$$\Delta m = m\,(^{40}_{20}\text{Ca}) + m(_0n^1) - m(^{41}_{20}\text{Ca})$$

$$= 39.962591 + 1.008665 - 40.962278$$

$$= 0.008978 \text{ u}$$

Energy for separation of neutron $= \Delta m \times 931$

$$= 0.008978 \times 931$$

$$= 8.358 \text{ MeV}$$

(ii) When a neutron is separated from $^{27}_{13}$Al, we are left with $^{26}_{13}$Al. Thus, the reaction becomes

$$^{27}_{13}\text{Al} \longrightarrow {}^{26}_{13}\text{Al} + {}^1_0n$$

Mass defect, $\Delta m = m\,(^{26}_{13}\text{Al}) + m(_0n^1) - m(^{27}_{13}\text{Al})$

$$= 25.986895 + 1.008665 - 26.981541$$

$$= 0.014019$$

$\therefore$ Energy for separation of neutron

$$= \Delta m \times 931 = 0.014019 \times 931$$

$$= 13.06 \text{ MeV}$$

**37.** (i) According to the question, a nuclide 1 is said to be mirror isobar of nuclide 2, if $Z_1 = N_2$ and $Z_2 = N_1$. Now, in $^{23}_{11}$Na, $Z_1 = 11$, $N_1 = 23 - 11 = 12$

$\therefore$ Mirror isobar of $^{23}_{11}$Na is $^{23}_{12}$Mg, for which

$Z_2 = 12 = N_1$ and $N_2 = 23 - 12 = 11 = Z_1$

(ii) As, $^{23}_{12}$Mg contains even number of protons (12) against $^{23}_{11}$Na which has odd number of protons (11), therefore $^{23}_{11}$Mg has greater binding energy than $^{23}_{11}$Na.

**38.** (i) Atomic mass of Li = Weighted average of the isotopes

$$= \frac{7.5 \times 6.01512 + 92.5 \times 7.01600}{7.5 + 92.5}$$

$$= \frac{45.1134 + 648.98}{100} = 6.94 \text{ u}$$

(ii) Suppose $x$ and $y$ are the abundances of $^{10}_{5}$B and $^{11}_{5}$B, respectively.

Atomic mass of boron

= Weighted average of the isotopes

$$= \frac{x \times 10.01294 + y \times 11.00931}{100}$$

$$\Rightarrow \quad 10.811 = \frac{x \times 10.01294 + (100 - x) \times 11.00931}{100}$$

$[\because y = (100 - x)]$

$$\Rightarrow \quad 1081.1 = 10.01294x + 1100.931 - 11.00931x$$

$$\Rightarrow 0.99637x = 19.831 \Rightarrow x = 19.90$$

$$y = (100 - x) = 80.1$$

So, abundance percent $^{10}_{5}$B $= 19.90\%$

Abundance percent of $^{11}_{5}$B $= 80.1\%$

**39.** Given, atomic mass of Mg = 24.312 u

Mass of $^{24}_{12}$Mg = 23.98504 u

Mass of $^{25}_{12}$Mg = 24.98584 u

Mass of $^{26}_{12}$Mg = 25.98259 u

Abundance of $^{24}_{12}$Mg = 78.99%

Let the abundance of $^{25}_{12}$Mg be $x$ %.

The abundance of $^{26}_{12}$Mg $= 100 - 78.99 - x = (21.01 - x)\%$

Atomic mass = Weight average of masses

$$= \frac{\text{Abundance of the isotopes}}{\text{Total abundance}}$$

$$\Rightarrow \quad 24.312 = \frac{78.99 \times 23.98504 + x \times 24.98548 + (21.01 - x) \times 25.98259}{100}$$

$$\Rightarrow \quad x = 9.303\%$$

So, the abundance of $_{12}\text{Mg}^{25}$ is 9.303% and the abundance of $_{12}\text{Mg}^{26}$ is 11.71%.

**40.** Given, abundance per cent of $\text{Ne}^{20} = 90.51\%$

Abundance per cent of $\text{Ne}^{21} = 0.27\%$

Abundance per cent of $\text{Ne}^{22} = 9.22\%$

Mass of $\text{Ne}^{20} = 19.99$ u

Mass of $\text{Ne}^{21} = 20.99$ u

Mass of $\text{Ne}^{22} = 21.99$ u

Average atomic mass, $m$ = Weighted average of all isotopes

$$= \frac{90.51 \times 19.99 + 0.27 \times 20.99 + 9.22 \times 21.99}{90.51 + 0.27 + 9.22}$$

$$= \frac{1809.29 + 5.67 + 202.75}{100} = \frac{2017.71}{100} = 20.18$$

**41.** (i) We know that,

$$\rho = \frac{3m}{4\pi R_0^3} = \frac{3 \times 1.6 \times 10^{-17}\,\text{kg}}{4 \times 3.14 \times (1.2 \times 10^{-15})^3}$$

$$= 2.3 \times 10^{17} \text{ kg/m}^3$$

(ii) Nuclear density ($\rho$) is independent on mass number, hence nuclear density of $\alpha$-particle ($^4_2$He) and thorium ($^{228}_{90}$Th) is equal to each other.

(iii) For $\alpha$-particle, also nuclear density is equal to $2.3 \times 10^{17}$ kg/m$^3$, as explained earlier.

**42.** Given, $m_p = 1.00783$ u, $m_n = 1.00867$ u

(i) For $^{56}_{26}\text{Fe}$, there are 26 protons and $(56 - 26) = 30$ neutrons.

$\Delta m$ = mass of nucleons − mass of nucleus

$= 26m_p + 30m_n - m$

$= 26 \times 1.00783 + 30 \times 1.00867 - 55.934939$

$= 0.528741$ u

Total binding energy $= \Delta m \times 931$ MeV

$= 0.528741 \times 931 = 492.26$ MeV

Binding energy per nucleon

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

$$= \frac{492.26}{56} = 8.790 \text{ MeV}$$

(ii) For $^{209}_{83}$ Bi ,there are 83 protons and $(209 - 83) = 126$ neutrons.

$\Delta m$ = mass of nucleons − mass of nucleus

$= 83\, m_p + 126\, m_n - m$

$\Delta m = 83 \times 1.00783 + 126 \times 1.00867 - 208.980388$

$= 1.761922$ u

Binding energy $= \Delta m \times 931$ MeV

$= 1.761922 \times 931$

$= 1640.35$ MeV

Binding energy per nucleon

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

$$= \frac{1640.35}{209} = 7.848 \text{ MeV}$$

Thus, binding energy per nucleon of Fe is more than Bi.

# |TOPIC 2|

# Nuclear Energy

## NUCLEAR ENERGY

Nuclear energy is the energy released during the transformation of nuclei with less total binding energy to nuclei with greater binding energy.

Two distinct ways of obtaining energy from nucleus are as follows:

1. Nuclear fission
2. Nuclear fusion

### Nuclear Fission

Nuclear fission is the phenomenon of splitting of a heavy nucleus (usually $A > 230$) into two or more lighter nuclei by the bombardment of proton, neutron, $\alpha$-particle, etc. Energies associated with nuclear processes are about a million times larger than chemical process.

In fission, a heavy nucleus like $^{235}_{92}\text{U}$ breaks into two smaller fragments by the bombardment of thermal neutron (low energy or slow moving).

e.g. $$^{235}_{92}\text{U} + {}^{1}_{0}n \longrightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}_{0}n^{1} + Q$$

(Energy released)

$Q$-value here refer to the energy released in the nuclear process, which can be determined using Einstein's mass - energy relation, $E = mc^2$. The $Q$-value is equal to the difference of mass of products and reactants multiplied by square of velocity of light. Energy released per fission of $^{235}_{92}\text{U}$ is 200.4 MeV.

The fragment nuclei produced in fission are highly unstable. They are highly radioactive and emit $\beta$-particles in succession until each reaches to a stable end product.

### Nuclear Chain Reaction

In the nuclear fission reaction, there is a release of extra neutrons. The extra neutrons in turn initiate fission process, producing still more neutrons and so on. Thus, a chain of nuclear fission is set up called **nuclear chain reaction**. The chain reactions may be of two types:

**Uncontrolled Chain Reaction** During fission reaction, neutrons released are again absorbed by the fissile isotopes, the cycle repeats to give a chain reaction, i.e. self-sustaining and gives off energy at a rate that increases rapidly with time leading to large amount of radiation. This is called **uncontrolled chain reaction**.

**Controlled Chain Reaction** If by some means, the reaction is controlled in such a way that only one of the neutrons emitted in a fission causes another fission, then the fission rate remains constant and the energy is released steadily. Such a chain reaction is called a controlled chain reaction. It is used in a nuclear reactor.

The sustained fissibility of nuclear chain reaction depends on the multiplication factor or reproduction factor $K$.

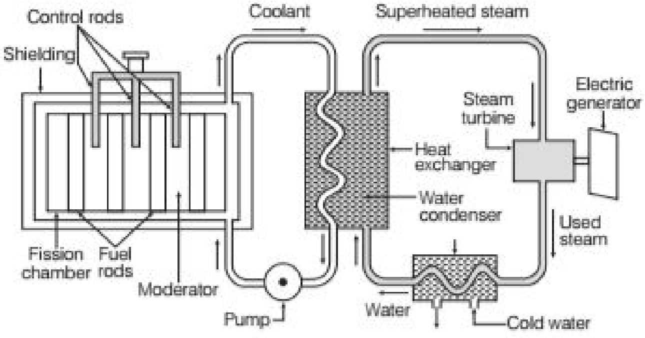
$$K = \frac{\text{Rate of production of neutrons}}{\text{Rate of loss of neutrons}}$$

If $K = 1$, the operation of reactor is said to be **critical**. It is what we wish to be for steady power operation.

If $K > 1$, the reaction rate and reactor power increases exponentially. In this case, reaction is **super-critical** and can even explode. If $K < 1$, the reaction gradually stops. And the condition is called **sub-critical**.

## Nuclear Reactor

It is a device that can initiate a self-sustaining controlled chain reaction of a fissionable material. They are used at nuclear power plants for generating electricity and in propulsion of ships.



Nuclear reactor

### Construction

The key components of nuclear reactor are as follows:

(i) **Nuclear fuel** It is a material that can be **burned** by **nuclear fission** or **fusion** to derive nuclear energy. The common fuels used in nuclear reactor are $^{233}U$, $^{235}U$, $^{239}Pu$, etc.

(ii) **Nuclear reactor core** It is the portion of a nuclear reactor containing the nuclear fuel components where the nuclear reaction takes place.

(iii) **Moderator** It is a medium to slow down the fast moving secondary neutrons produced during the fission. Heavy water, graphite, deuterium, paraffins, etc., acts as moderator.

(iv) **Control rods** It is used in nuclear reactors to control the rate of fission of uranium and plutonium. These are made of chemical elements capable of absorbing many neutrons without fissioning themselves such as silver, indium, boron and cadmium.

(v) **Coolant** It is a liquid used to remove heat from nuclear reactor core and transfer it to electrical generator and environment. Ordinary water under high pressure is used as coolant.

(vi) **Shielding** It is the protective covering made of concrete wall to protect from harmful radiations.

## India's Atomic Energy Programme

The Atomic Energy Programme of our country was launched around 1950 under the leadership of Homi J Bhabha (1909-1966). The major milestones achieved so far are as below:

(i) First nuclear reactor named Apsara went critical on 4 August, 1956. It used enriched uranium as fuel and water as moderator.

(ii) Another reactor named Canada India Research US (CIRUS) became operative in 1960. It used natural uranium as fuel and heavy water as moderator.

(iii) Indigenous design and construction of plutonium plant at Trombay. It ushered in the technology of fuel reprocessing.

(iv) Research reactors like Zerlina, Purnima, Dhruva and Kamini were commissioned. The last one uses U-233 as fuel.

(v) The fast breeder reactors which use plutonium-239 as fuel do not need moderators. They can be used to produce fissile uranium-233 from thorium-232 and to build power reactors based on them. Considerable work has been done by our scientists in this direction at Kalpakkam nuclear plant.

(vi) We have mastered the complex technologies of mineral exploration, mining, fuel fabrication, heavy water production, fuel reprocessing, etc.

## Nuclear Fusion

Nuclear fusion is the phenomenon of fusing two or more lighter nuclei forming a single heavy nucleus.For fusion to take place, the two nuclei must come close enough so that, attractive short range nuclear force is able to affect them. Since both the nuclei are positively charged particles, so they experience Coulomb's repulsion. Therefore, they must have enough energy to overcome this Coulomb barrier.

e.g.
$$ {}_1H^1 + {}_1H^1 \longrightarrow {}_1H^2 + {}_1e^+ + \nu + 0.42\ \text{MeV} $$
$$ {}_1H^2 + {}_1H^2 \longrightarrow {}_2He^3 + {}_0n^1 + 3.27\ \text{MeV} $$
$$ {}_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_1H^1 + 4.03\ \text{MeV} $$

Fusion of hydrogen nuclei into helium nuclei is the source of energy of most of the stars including the sun.

### Energy Generation in Stars

Thermonuclear fusion is the source of energy output in the interior of stars. The interior of the sun has a temperature of $1.5 \times 10^7$ K, which is considerably less than the estimated temperature required for fusion of particles of average energy. Fusion in the sun involves protons whose energies are much above the average energy, i.e. protons which are in the high velocity fall of Maxwell-Boltzmann distribution.

The fusion reaction in the sun is a multi-step process in which the hydrogen is fused into helium. The **proton-proton** $(p, p)$ **cycle** by which this occurs is represented by the following sets of reactions:

$$ {}_1^1\mathrm{H} + {}_1^1\mathrm{H} \rightarrow {}_1^2\mathrm{H} + e^+ + \nu + 0.42\ \mathrm{MeV} \qquad \text{...(i)} $$

$$ e^+ + e^- \rightarrow \gamma + \gamma + 1.02\ \mathrm{MeV} \qquad \text{...(ii)} $$

$$ {}_1^2\mathrm{H} + {}_1^1\mathrm{H} \rightarrow {}_2^3\mathrm{He} + \gamma + 5.49\ \mathrm{MeV} \qquad \text{...(iii)} $$

$$ {}_2^3\mathrm{He} + {}_2^3\mathrm{He} \rightarrow {}_2^4\mathrm{He} + {}_1^1\mathrm{H} + {}_1^1\mathrm{H} + 12.86\ \mathrm{MeV} \qquad \text{...(iv)} $$

For the fourth reaction to occur, the first three reactions must occur twice, in case two light helium nuclei unite to form ordinary helium nucleus. If we consider the combination $2(\mathrm{i}) + 2(\mathrm{ii}) + 2(\mathrm{iii}) + (\mathrm{iv})$, the net effect is

$$ 4\,{}_1^1\mathrm{H} + 2e^- \rightarrow {}_2^4\mathrm{He} + 2\nu + 6\gamma + 26.7\ \mathrm{MeV} $$

or $(4\,{}_1^1\mathrm{H} + 4e^-) \rightarrow ({}_2^4\mathrm{He} + 2e^-) + 2\nu + 6\gamma + 26.7\ \mathrm{MeV}$

Thus, four hydrogen atoms combine to form ${}_2^4\mathrm{He}$ atom with a release of 26.7 MeV of energy.

As the hydrogen in the core gets depleted and becomes helium, the core starts to cool. The star begins to collapse under its own gravity, which increases the temperature of the core.

The age of the sun is about $5 \times 10^9$ yr and it is estimated that there is enough hydrogen in the sun to keep it going for another 5 billion years.

### Nuclear Holocaust

It is the name given to large scale destruction and devastation that would be caused by the use of nuclear weapons.

During fission of a single nucleus of ${}_{92}\mathrm{U}^{235}$, about $0.9 \times 235$ MeV ($\approx 200$ MeV) energy is released in $10^{-9}$ s. If each nucleus of about 50 kg of ${}^{235}\mathrm{U}$ undergoes fission, then the total energy released is $4 \times 10^{15}$ J. This energy is equivalent to about 20000 tonnes of TNT.

The first explosion occured on 6th August, 1945, when USA dropped an atom bomb on Hiroshima in Japan. This resulted in killing of 66000 persons, injured 69000 persons and 67% of the city structures smashed.

The radioactive waste will hang like a cloud in the earth's atmosphere. It will absorb the sun's radiation and there may be a long nuclear winter.

### Controlled Thermonuclear Fusion

The essential condition for carrying out nuclear fusion is to raise the temperature of the material so that particles have enough energy due to their thermal motions alone and they can overcome the Coulomb barrier. This process is called **thermonuclear fusion.**

The natural thermonuclear fusion in a star is replicated in a thermonuclear fusion device. The aim of controlled thermonuclear fusion is to generate the steady power by heating the nuclear fuel to a temperature in the range of $10^8$ K. At these temperature, the fuel is a mixture of positive ions and electrons (plasma).

The challenge is to confine this plasma, since no container can stand such a high temperature. Several countries around the world including india are developing techniques in this connection. If successful, fusion reactors will hopefully supply almost unlimited power to humanity.

## Distinction between Nuclear Fission and Nuclear Fusion

(i) Fission is the splitting of large nucleus into two or more smaller ones, on the other hand, fusion is the combining of two or more lighter nuclei to form larger one.

(ii) Fission does not normally occur in nature but fusion occurs in stars such as the sun.

(iii) Fission requires critical mass of the substance and high speed neutrons but in fusion, high density and high temperature environment are required.

(iv) In fission, energy released is million times greater than in chemical reactions, but lower than energy released by nuclear fusion.

(v) Uranium is the primary fuel for fission reaction and hydrogen isotopes are the primary fuel in nuclear fusion reaction.

# | TOPIC PRACTICE 2 |

## OBJECTIVE Type Questions

**1.** In a nuclear reaction ${}^{238}_{92}\mathrm{U} \rightarrow {}^{A}_{Z}\mathrm{Th} + {}^4_2\mathrm{He}$, the value of $A$ and $Z$ are

(a) $A = 234, Z = 94$
(b) $A = 238, Z = 94$
(c) $A = 234, Z = 90$
(d) $A = 238, Z = 90$

**2.** For sustaining the chain reaction in a sample (of small size) of ${}^{235}_{92}U$, it is desirable to slow down fast neutrons by

(a) friction
(b) elastic damping/scattering
(c) absorption
(d) None of the above

**3.** In a nuclear reactor , moderators slow down the neutrons which come out in a fission process. The moderator used have light nuclei. Heavy nuclei will not serve the purpose, because

(a) they will break up **NCERT Exemplar**
(b) elastic collision of neutrons with heavy nuclei will not slow them down
(c) the net weight of the reactor would be unbearably high
(d) substances with heavy nuclei do not occur in liquid or gaseous state at room temperature

## VERY SHORT ANSWER Type Questions

**4.** What is nuclear holocaust?

**5.** Four nuclei of an element undergo fusion to form a heavier nucleus, with release of energy. Which of the two–the parent or the daughter nucleus–would have higher binding energy per nucleon? **CBSE 2018**

## SHORT ANSWER Type Question

**6.** An atomic power nuclear reactor can deliver 300 MW. The energy released due to fission of each nucleus of uranium atoms $U^{238}$ is 170 MeV. What will be the number of uranium atoms fissioned per hour?

## LONG ANSWER Type II Question

**7.** Suppose India had a target of producing by 2020 AD, 200000 MW of electric power, 10% of which was to be obtained from nuclear power plants. Suppose we are given that, on an average, the efficiency of utilisation (i.e. conversion to electric energy) of thermal energy produced in a reactor was 25%. How much amount of fissionable uranium would our country need per year by 2020? Take the heat energy per fission of ${}^{235}U$ to be about 200 MeV. **NCERT**

## NUMERICAL PROBLEMS

**8.** Complete the following fission reaction and calculate the amount of energy it releases.

$${}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{88}_{38}Sr + {}^{136}_{54}Xe + (?)$$

**9.** Determine the energy released in the following fusion reaction.

$${}^{1}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + \gamma$$

**10.** Suppose we think of fission of a ${}^{56}_{26}Fe$ nucleus into two equal fragments, ${}^{28}_{13}Al$. Is the fission energetically possible? Argue by working out $Q$ of the process. Given, $m({}^{56}_{26}Fe) = 55.93494$ u and $m({}^{28}_{13}Al) = 27.98191$ u. **NCERT**

**11.** The sun is believed to be getting its energy from the fusion of four protons to form a helium nucleus and a pair of positrons. Calculate the release of energy per fusion in MeV.
Mass of proton = 1.007825 amu, mass of positron = 0.000549 amu, mass of helium nucleus = 4.002603 amu.
Take, 1 amu = 931.5 MeV.

**12.** The fission properties of ${}^{239}_{94}Pu$ are very similar to those of ${}^{235}_{92}U$. The average energy released per fission is 180 MeV. How much energy in MeV is released, if all the atoms in 1 kg of pure ${}^{239}_{94}Pu$ undergo fission? **NCERT**

**13.** The $Q$-value of a nuclear reaction $A + b \longrightarrow C + d$ is defined by $Q = [m_A + m_b - m_C - m_d]c^2$, where the masses refer to the respective nuclei. Determine from the given data, the $Q$-value of the following reactions and state whether the reactions are exothermic or endothermic.

(i) ${}^{1}_{1}H + {}^{3}_{1}H \longrightarrow {}^{2}_{1}H + {}^{2}_{1}H$
(ii) ${}^{12}_{6}C + {}^{12}_{6}C \longrightarrow {}^{20}_{10}Ne + {}^{4}_{2}He$

Atomic masses are given to be

$m({}_1H^1) = 1.007825$ u, $m({}^{2}_{1}H) = 2.014102$ u,
$m({}^{3}_{1}H) = 3.016049$ u , $m({}^{12}_{6}C) = 12.000000$ u
$m({}^{20}_{10}Ne) = 19.992439$ u **NCERT**

**14.** Find the $Q$-value and the kinetic energy of the emitted $\alpha$-particle in the $\alpha$-decay of

(i) ${}^{226}_{88}Ra$ and (ii) ${}^{220}_{86}Rn$.

Given, $m({}^{226}_{88}Ra) = 226.02540$ u ,
$m({}^{222}_{86}Rn) = 222.01750$ u , $m_a = 4.00260$ u
$m({}^{220}_{86}Rn) = 220.01137$u ,
$m({}^{216}_{84}Po) = 216.00189$ u **NCERT**

**15.** How long can an electric lamp of 100 W be kept glowing by fusion of 2 kg of deuterium? Take the fusion reaction as **CBSE SQP (Term-II)**

$$^{2}_{1}\mathrm{H}+^{2}_{1}\mathrm{H}\longrightarrow ^{3}_{2}\mathrm{He}+n+3.27\ \mathrm{MeV}$$

**16.** Calculate and compare the energy released by

(i) fusion of 1 kg of hydrogen deep within sun and

(ii) the fission of 1 kg of $^{235}\mathrm{U}$ in a fission reactor.

**NCERT**

**17.** Distinguish between nuclear fission and fusion. Show how in both these processes energy is released?

Calculate the energy release in MeV in the deuterium-tritium fusion reaction.

$$^{2}_{1}\mathrm{H}+^{3}_{1}\mathrm{H}\longrightarrow ^{4}_{2}\mathrm{He}+n$$

Using the data,

$$m(^{2}_{1}\mathrm{H})=2.014102\ \mathrm{u},\quad m\,(^{3}_{1}\mathrm{H})=3.016049\ \mathrm{u}$$

$$m(^{4}_{2}\mathrm{He})=4.002603\ \mathrm{u},\qquad m_n=1.008665\ \mathrm{u}$$

$$1\ \mathrm{u}=931.5\ \frac{\mathrm{MeV}}{c^2}$$

**All India 2015**

**18.** A 1000 MW fission reactor consumes half of its fuel in 5 yr. How much $^{235}_{92}\mathrm{U}$ did it contain initially? Assume that the reactor operates 80% of the time that all the energy generated arises from the fission of $^{235}_{92}\mathrm{U}$ and that this nuclide is consumed only by the fission process.

**NCERT**

## HINTS AND SOLUTIONS

**1.** (c) $^{238}_{92}\mathrm{U}\rightarrow ^{234}_{90}\mathrm{Th}+^{4}_{2}\mathrm{He}$

When a $\alpha$-particle is emittted mass number decreases by 4 and atomic number by 2.

**2.** (b) Fast neutrons are slowed down by elastic scattering with light nuclei. Each collision takes away nearly 50% of energy.

**3.** (b) According to the question, the moderator used have light nuclei (like proton). When protons undergo perfectly elastic collision with the neutron emitted, their velocities are exchanged, i.e., neutrons come to rest and protons move with the velocity of neutrons.

Heavy nuclei will not serve the purpose because elastic collisions of neutrons with heavy nuclei will not slow them down.

**4.** It is the name given to large scale destruction and devastation that would be caused by the uncontrolled release of large energy from the nuclear weapons.

**5.** According to question,

$$\underset{\text{(Parent nuclei)}}{4\ _{Z}X^{A}}\quad\longrightarrow\quad\underset{\text{(Daughter nucleus)}}{_{Z'}Y^{A'}}+Q$$

As the daughter nucleus is a heavier nucleus as compared to parent nuclei, which are more stable than lighter nuclei, hence daughter nucleus has more binding energy per nucleon than parent nuclei.

**6.** As, we know that,

$$\text{power}=\frac{\text{energy}}{\text{time}}=300\times10^{6}\,\mathrm{W}=3\times10^{8}\ \mathrm{J/s}$$

$$170\ \mathrm{MeV}=170\times10^{6}\times1.6\times10^{-19}=27.2\times10^{-12}\ \mathrm{J}$$

Number of atoms fissioned per second

$$=\frac{3\times10^{8}}{27.2\times10^{-12}}=\frac{3\times10^{20}}{27.2}$$

$\therefore$ Number of atoms fissioned per hour

$$=\frac{3\times10^{20}\times3600}{27.2}$$

$$=\frac{3\times36}{27.2}\times10^{22}=4\times10^{22}\mathrm{m}$$

**7.** Total target power $=200000=2\times10^{5}$ MW

Total nuclear power $=10\%$ of total target power

$$=\frac{10}{100}\times2\times10^{5}=2\times10^{4}\ \mathrm{MW}$$

Energy produced/fission = 200 MeV

Efficiency of power plant = 25%

Energy converted into electrical energy per fission

$$=\frac{25}{100}\times200=50\ \mathrm{MeV}$$

$$=50\times1.6\times10^{-13}\ \mathrm{J}$$

Total electrical energy to be produced per year

$$=2\times10^{4}\ \mathrm{MW}$$

$$=2\times10^{4}\times10^{6}=2\times10^{10}\ \mathrm{W}$$

$$=2\times10^{10}\mathrm{J/s}$$

$$=2\times10^{10}\times60\times60\times24\times365\ \mathrm{J/yr}$$

Number of fission in one year,

$$n=\frac{2\times10^{10}\times60\times60\times24\times365}{50\times1.6\times10^{-13}}$$

$$n=\frac{2\times36\times24\times365}{8}\times10^{24}$$

Mass of $6.023\times10^{23}$ atoms of $^{235}\mathrm{U}=235$ g

$$=235\times10^{-3}\mathrm{kg}$$

Mass of $^{235}_{92}\mathrm{U}$ required to produce

$$=\frac{2\times36\times24\times365}{8}\times10^{24}\ \text{atoms}$$

$$=\frac{235\times10^{-3}\times2\times36\times24\times365\times10^{24}}{6.023\times10^{23}\times8}$$

$$=3.08\times10^{4}\mathrm{kg}$$

Thus, the mass of uranium needed per year is $3.08\times10^{4}$ kg.

**8.** By conservation of charge and mass, given equation can be written as

$${}^{1}_{0}n + {}^{235}_{92}\text{U} \longrightarrow {}^{88}_{38}\text{Sr} + {}^{136}_{54}\text{Xe} + 12\,{}^{1}_{0}n + Q\ (\text{Energy})$$

For amount of energy released, use

$$Q = \Delta m \times 931\ \text{MeV}$$

**9.** Use $Q = \Delta m \times 931$ MeV

**Ans.** 5.94 MeV

**10.** The given reaction for decay process,

$${}^{56}_{26}\text{Fe} \longrightarrow 2\,{}^{28}_{13}\text{Al}$$

Mass defect, $\Delta m = m({}^{56}_{26}\text{Fe}) - 2m({}^{28}_{13}\text{Al})$

$$= 55.93494 - 2(27.98191)$$

$$= -0.02888\ \text{u}$$

$$\Rightarrow \quad Q = \Delta m \times 931 = -0.02888 \times 931$$

$$= -26.88728\ \text{MeV}$$

Because the energy is negative, so the fission is not possible energetically.

**11.** ${}^{1}_{1}\text{H} + {}^{1}_{1}\text{H} + {}^{1}_{1}\text{H} + {}^{1}_{1}\text{H} + \longrightarrow {}^{4}_{2}\text{He} + 2\,{}^{0}_{1}e + \text{Q}$

Initial mass = Mass of 4 hydrogen atoms

$$= 4 \times 1.007825\ \text{amu} = 4.031300\ \text{amu}$$

Final mass $= m({}^{4}_{2}\text{He}) + 2m({}^{0}_{1}e)$

$$= 4.002604 + 2 \times 0.000549$$

$$= 4.002604 + 0.001098 = 4.003702\ \text{amu}$$

Mass defect,

$$\Delta m = 4.031300 - 4.003702 = 0.027598\ \text{amu}$$

∴ Energy released,

$$Q = 0.027598 \times 931\ \text{MeV} = 25.7\ \text{MeV}$$

**12.** According to the concept of Avogadro number, The number of atoms in 239 g of ${}^{239}_{94}\text{Pu} = 6.023 \times 10^{23}$

Number of atoms in 1 kg of ${}^{239}_{94}\text{Pu}$

$$= \frac{6.023 \times 10^{23} \times 1000}{239} = 2.52 \times 10^{24}$$

The average energy released in one fission

$$= 180\ \text{MeV}$$

So, total energy released in fission of 1 kg of

$${}^{239}_{94}\text{Pu} = 180 \times 2.52 \times 10^{24}$$

$$= 4.53 \times 10^{26}\ \text{MeV}$$

**13.** (i) The given reaction, ${}^{1}_{1}\text{H} + {}^{3}_{1}\text{H} \longrightarrow {}^{2}_{1}\text{H} + {}^{2}_{1}\text{H}$

Mass defect, $\Delta m = m\,({}^{1}_{1}\text{H}) + m\,({}^{3}_{1}\text{H}) - 2m\,({}^{2}_{1}\text{H})$

$$= 1.007825 + 3.016049 - 2(2.014102)$$

$$= -\ 0.00433\ \text{u}$$

$Q$-value of the reaction,

$$Q = \Delta m \times 931 = -\ 0.00433 \times 931$$

$$Q = -\ 4.031\ \text{MeV}$$

As, the energy is negative, so the reaction is

endothermic.

(ii) The given reaction,

$${}^{12}_{6}\text{C} + {}^{12}_{6}\text{C} \longrightarrow {}^{20}_{10}\text{Ne} + {}^{4}_{2}\text{He}$$

Mass defect, $\Delta m = 2\,m({}^{12}_{6}\text{C}) - m({}^{20}_{10}\text{Ne}) - m({}^{4}_{2}\text{He})$

$$= 2 \times 12 - 19.992439 - 4.002603$$

$$\Delta m = 0.00495\ \text{u}$$

$Q$-value of the reaction,

$$Q = \Delta m \times 931 = 0.00495 \times 931$$

$$= 4.62\ \text{MeV}$$

Since, the energy is positive, thus the reaction is exothermic.

**14.** (i) The process of α-decay of ${}^{226}_{88}\text{Ra}$ can be expressed as,

$${}^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He} + Q$$

$Q$-value of the reaction is given by

$$= [m({}^{226}_{88}\text{Ra}) - m({}^{222}_{86}\text{Rn}) - m_a] \times 931\ \text{MeV}$$

$$= (226.02540 - 222.01750 - 4.00260) \times 931$$

$$= 0.0053 \times 931 = 4.93\ \text{MeV}$$

Kinetic energy of emitted α-particle computed using conservation of momentum

$$= \left(\frac{A-4}{A}\right) \cdot Q = \left(\frac{226-4}{226}\right) \times 4.93$$

$$= 4.84\ \text{MeV}$$

(ii) The process of α-decay of ${}^{220}_{86}\text{Rn}$ can be expressed as,

$${}^{220}_{86}\text{Rn} \longrightarrow {}^{216}_{84}\text{Po} + {}^{4}_{2}\text{He}$$

$Q$-value of the reaction,

$$Q = [m({}^{220}_{86}\text{Rn} - m({}^{216}_{84}\text{Po}) - m_{\alpha}] \times 931\ \text{MeV}$$

$$= [220.01137 - 216.00189 - 4.00260] \times 931$$

$$Q = 6.41\ \text{MeV}$$

∴ Kinetic energy of emitted α-particle

$$= \frac{(A-4)Q}{A} = \left(\frac{220-4}{220}\right) \times 6.41$$

$$= 6.29\ \text{MeV}$$

**15.** Let $t$ be the time.

According to the Avogadro number concept,

Number of atoms in 2 g of deuterium $= 6.023 \times 10^{23}$

Number of atoms in 2 kg of deuterium

$$= \frac{6.023 \times 10^{23} \times 2 \times 10^{3}}{2}$$

$$= 6.023 \times 10^{+26}\ \text{nuclei}$$

Energy released during fusion of two deuterium

$$= 3.27\ \text{MeV}$$

∴ Energy released per deuterium = 1.635 MeV

Energy released in $6.023 \times 10^{26}$ deuterium atoms

$$= 1.635 \times 6.023 \times 10^{26}$$

$$= 9.848 \times 10^{26}\ \text{MeV}$$

$$= 9.848 \times 10^{26} \times 1.6 \times 10^{-13}$$

$$= 15.75 \times 10^{13}\ \text{J}$$

Energy used by bulb in 1s = 100 J

100 J energy used in time = 1 s

$15.75\times10^{13}$ J energy used in time $=\dfrac{1\times15.75\times10^{13}}{100}$

$$= 15.75\times10^{11}\,\text{s}\quad [\because 1\text{ yr} = 60\times24\times60\times365\text{ s}]$$

$$=\frac{15.75\times10^{11}}{60\times24\times60\times365}\text{ yr} \;= 4.99\times10^{4}\text{yr}$$

Thus, the bulb glows for $4.99\times10^{4}$ yr.

**16.** (i) In sun, four hydrogen nuclei fuse to form a helium nucleus with release of 26 MeV energy.

$\because$ 1 g of hydrogen contains $= 6.023\times10^{23}$ nuclei

$\therefore$ Energy released by fusion of 1 kg (= 1000 g) of hydrogen, $E_1 = \dfrac{6.023\times10^{23}\times26\times10^{3}}{4}$

$$= 39\times10^{26}\text{ MeV}$$

(ii) Energy released in one fission of $^{235}_{92}$U nucleus

$$= 200\text{ MeV}$$

Mass of uranium = 1 kg = 1000 g

We know that, 235 g of $^{235}$U has $6.023\times10^{23}$ atoms or nuclei.

$\therefore$ Energy released in fission of 1 kg of $U^{235}$,

$$E_2 = \frac{6.023\times10^{23}\times1000\times200}{235} = 5.1\times10^{26}\text{ MeV}$$

$$\therefore\quad \frac{E_1}{E_2} = \frac{39\times10^{26}}{5.1\times10^{26}} = 7.65 = 8$$

Thus, the energy released in fusion is 8 times the energy released in fission.

**17.** Nuclear fission is the phenomenon of splitting of a heavy nucleus (usually $A > 230$) into two or more lighter nuclei.

$$U^{235}_{92} + n^1_0 \longrightarrow \text{Ba}^{141}_{56} + \text{Kr}^{92}_{36} + 3n^1_0 + Q$$

In this case, the energy released per fission of $U^{235}_{92}$ is 200.4 MeV.

Nuclear fusion is the phenomenon of fusion of two or more lighter nuclei to form a single heavy nucleus.

The mass of the product nucleus is slightly less than the sum of the masses of the lighter nuclei fusing together. This difference in the masses results the release of tremendous amount of energy.

e.g. $^1_1\text{H} + {}^1_1\text{H} \longrightarrow {}^2_1\text{He} + e^+ + \nu + 0.42\text{ MeV}$

$$^2_1\text{H} + {}^2_1\text{H} \longrightarrow {}^3_1\text{He} + {}_0n^1 + 3.27\text{ MeV}$$

$$^2_1\text{H} + {}^2_1\text{H} \longrightarrow {}_1\text{H}^3 + {}^1_1\text{H} + 4.03\text{ MeV}$$

$$^2_1\text{H} + {}^3_1\text{H} \longrightarrow {}^4_2\text{He} + n\text{ MeV}$$

$$\Delta m = (2.014102 + 3.016049) - (4.002603 + 1.008665)$$
$$= 0.018883\text{ u}$$

Energy released, $Q = 0.018883\times931.5\dfrac{\text{MeV}}{c^2}$

$$= 17.589\text{ MeV}$$

**18.** Given, power of reactor, $P = 1000$ MW

We will use concept that the energy generated in one fission of $^{235}_{92}$U is 200 MeV.

Number of $^{235}_{92}$U atoms in 1 g $= \dfrac{1}{235}\times6.023\times10^{23}$

$\therefore$ Energy generated per gram of $^{235}_{92}$U

$$= \left(\frac{1}{235}\times6.023\times10^{23}\times200\times1.6\times10^{-13}\right)$$

Total energy generated in 5 yr with 80% of the time

$$= 1000\times10^{6}\;\times5\times365\times24\times60\times60\times\frac{80}{100}$$

[as $E = Pt$]

$\therefore$ Mass of $^{235}_{92}$U consumed in 5 yr,

$$m = \frac{\text{Total energy}}{\text{Energy consumed per gram}}$$

$$= \frac{1000\times10^{6}\times5\times365\times24\times60\times60\times0.8}{\left(\dfrac{1}{235}\right)\times6.023\times10^{23}\times200\times1.6\times10^{-13}}$$

$$= 1.538\times10^{6}\text{ g}$$

$$= 1538\text{ kg}$$

$\therefore$ Initial amount of $^{235}_{92}\text{U} = (1544\times2) = 3076\,\text{kg}$

# SUMMARY

- Volume of a nucleus is about $10^{-12}$ times the volume of the atom. But the nucleus contains more than 99% of the mass of an atom.
- The unit used to express atomic masses is **atomic mass unit** (u).

$$1\text{u} = 1.660539 \times 10^{-27}\ \text{kg}$$

- **Isotopes** The atomic species of the same element differing in mass but having the same chemical properties are called isotopes.
- **Nucleus** It consists of protons and neutrons. The positive charge in the nucleus is that of **protons**. A proton is stable.
- **Neutron** was discovered by **James Chadwick.** A free neutron is unstable.
- **Atomic Number** It is the number of protons present inside the nucleus.
- **Mass Number** It is the total number of protons and neutrons inside the nucleus.
- **Nuclear Density** The ratio of the mass of nucleus and its volume. So, it can be given by $\rho = \frac{3m}{4\pi R_0^3}$.
- **Size of Nucleus** The radius $R$ of the nucleus having mass number $A$ can be given by

$$R \propto A^{1/3} \Rightarrow R = R_0 A^{1/3}$$

where, $R_0 = 1.2 \times 10^{-15}\text{m}$

- **Mass Energy** Einstein showed that mass is another form of energy. Einstein's mass-energy equivalence equation is $\boldsymbol{E = mc^2}$.
- **Binding Energy** Minimum energy required to separate the nucleons (present inside the nucleus) and place them at rest and infinite distance apart.
- **Average Binding Energy per Nucleon of Nucleus**

$$= \frac{\text{Total binding energy}}{\text{Number of nucleons } (A)}$$

- **Nuclear Stability** The stability of nucleus is determined by the value of its binding energy per nucleon and its neutron to the proton ratio.
- **Nuclear Force** is the strong attractive forces between nucleons. It is a non-conservative force and does not obey inverse-square law.
- **Nuclear Energy** It is the energy released during the transformation of a nuclei.
- **Nuclear Fission** It is phenomenon of splitting of a heavy nucleus into two or more lighter nuclei by the bombardment of proton, neutron, $\alpha$-particles, etc.
- **Nuclear Fusion** It is phenomenon of fusing of two or more lighter nuclei forming a single heavy nucleus.

# CHAPTER PRACTICE

## OBJECTIVE Type Questions

**1.** If the nuclear radius of $^{27}$Al is 3.6 Fermi, the approximate nuclear radius of $^{64}$Cu in Fermi is

(a) 2.4 (b) 1.2
(c) 4.8 (d) 3.6

**2.** How much mass has to converted into energy to produce electric power of 200 MW for one hour?

(a) $2 \times 10^{-6}$ kg (b) $8 \times 10^{-6}$ kg
(c) $1 \times 10^{-6}$ kg (d) $3 \times 10^{-6}$ kg

**3.** The mass defect of helium nucleus is 0.0303 amu. The binding energy per nucleon for helium nucleus will be

(a) 28 MeV (b) 7 MeV (c) 14 MeV (d) 1 MeV

**4.** Binding energy of hydrogen nucleus is

(a) – 13.6 eV (b) 0
(c) 13.6 eV (d) 6.8 eV

**5.** Two protons are attracting each other, then separation between them is

(a) $10^{-10}$ m (b) $10^{-2}$ m
(c) $10^{-8}$ m (d) $10^{-15}$ m

**6.** In fusion reaction occurring in the sun,

**NCERT Exemplar**

(a) hydrogen is converted into carbon
(b) hydrogen and helium are converted into carbon and other heavier metals/elements
(c) helium is converted into hydrogen
(d) hydrogen is converted into helium

## ASSERTION AND REASON

**Directions** (Q. Nos. 7-8) *In the following questions, two statements are given- one labeled Assertion (A) and the other labelled Reason (R). Select the correct answer to these questions from the codes (a), (b), (c) and (d) as given below*

(a) Both Assertion and Reason are true and Reason is the correct explanation of Assertion.
(b) Both Assertion and Reason are true but Reason is not the correct explanation of Assertion.
(c) Assertion is true but Reason is false.
(d) Assertion is false but Reason is true.

**7.** **Assertion** Nuclear force between neutron-neutron, proton-neutron and proton-proton is approximately the same.

**Reason** The nuclear force does not depend on the electric charge.

**8.** **Assertion** Naturally, thermonuclear fusion reaction is not possible on earth.

**Reason** For thermonuclear fusion to take place, extreme condition of temperature and pressure are required.

## CASE BASED QUESTIONS

**Directions** (Q.Nos. 9-10) *These questions are case study based questions. Attempt any 4 sub-parts from each question. Each question carries 1 mark.*

**9.** **Discovery 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.

(i) Ratio of mass of nucleus with mass of atom is approximately

(a) 1 (b) 10
(c) $10^{3}$ (d) $10^{10}$

(ii) Masses of nuclei of hydrogen, deuterium and tritium are in ratio

(a) 1 : 2 : 3 (b) 1 : 1 : 1
(c) 1 : 1 : 2 (d) 1 : 2 : 4

(iii) Density of a nucleus is
  (a) more for lighter elements and less for heavier elements
  (b) more for heavier elements and less for lighter elements
  (c) very less compared to ordinary matter
  (d) a constant

(iv) If $R$ is the radius and $A$ is the mass number, then log $R$ *versus* log $A$ graph will be
  (a) a straight line
  (b) a parabola
  (c) an ellipse
  (d) None of the above

(v) The ratio of the nuclear radii of the gold isotope $^{197}_{79}$ Au and silver isotope $^{107}_{47}$ Au is
  (a) 1.23　　(b) 0.216
  (c) 2.13　　(d) 3.46

**10.** **Disappeared Mass**

In the year 1939, German scientist Otto Hahn and Strassmann discovered that when an uranium isotope was bombarded with a neutron, it breaks into two intermediate mass fragment. It was observed that, the sum of the masses of new fragments formed were less than the mass of the original nuclei. This difference in the mass appeared as the energy released in the process.

Thus, the phenomenon of splitting of a heavy nucleus (usually $A > 230$) into two or more lighter nuclei by the bombardment of proton, neutron, α-particle, etc with liberation of energy is called nuclear fission.

Fission reaction resulting from the absorption of neutron is known as induced fission.

$$ {}_{92}U^{235} + {}_{0}n^{1} \rightarrow \underset{\text{Unstable nucleus}}{{}_{92}U^{236}} \rightarrow {}_{56}Ba^{144} + {}_{36}Kr^{89} + 3\,{}_{0}n^{1} + Q $$

(i) Fission of nuclei is possible because the binding energy per nucleon in them
  (a) increases with mass number at high mass numbers
  (b) decreases with mass number at high mass numbers
  (c) increases with mass number at low mass number
  (d) decreases with mass number at low mass number

(ii) For sustaining the nuclear fission chain reaction in a sample (of small size) of $^{235}_{92}$U, it is desirable to slow down fast neutrons by
  (a) friction
  (b) elastic damping/scattering
  (c) absorption
  (d) None of the above

(iii) Which of the following is/are fission reaction(s)?
  I. $^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U \rightarrow ^{133}_{51}Sb + ^{99}_{41}Nb + 4\,^{1}_{0}n$
  II. $^{1}_{0}n + ^{235}_{92}U \rightarrow ^{1.40}_{54}Xe + ^{94}_{38}Sr + 2\,^{1}_{0}n$
  III. $^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$
  (a) Both II and III　　(b) Both I and III
  (c) Only II　　(d) Both I and II

(iv) If a nucleus with mass number $A = 240$ with $E_{bn} = 7.6$ MeV breaks into two fragments of $A = 120$ and $E_{bn} = 8.5$ MeV, then released energy is around
  (a) 216 MeV
  (b) 200 MeV
  (c) 100 MeV
  (d) Cannot be estimated from given data

(v) In any fission process, ratio of mass of daughter nucleus to mass of parent nucleus is
  (a) less than 1
  (b) greater than 1
  (c) equal to 1
  (d) depends on the mass of parent nucleus

**11.** The neutron is bombarded on a $^{10}_{5}$B nucleus and an α-particle is emitted. The nuclear reaction involved is **CBSE 2020**

$^{1}_{0}n + ^{10}_{5}B \longrightarrow ^{4}_{2}He + ....$

**12.** Name the particle emitted spontaneously in the following nuclear reaction: **CBSE 2020**

$^{32}_{15}P \longrightarrow ^{32}_{16}S + \overline{\nu} + .......$

## VERY SHORT ANSWER Type Questions

**13.** Two nuclei have mass numbers in the ratio of 27 : 512. What is the ratio of their nuclear radii?

**14.** In the following nuclear reaction, identify unknown labelled $X$. **CBSE SQP (Term-I)**

$^{22}_{11}Na + X \rightarrow ^{22}_{10}Ne + \nu_e$

**15.** Why is it necessary to slow down the neutrons, produced through the fission of $^{235}_{92}$U nuclei (by neutrons) to sustain a chain reaction? What type of nuclei are (preferably) needed for slowing down fast neutrons?

**16.** Name the materials used as moderators in nuclear reactors and write the reasons for their use as moderator.

## SHORT ANSWER Type Questions

**17.** (i) Write two characteristic features of nuclear force.

(ii) Draw a plot of potential energy of a pair of nucleons as a function of their separation.

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**18.** (a) State two distinguishing features of nuclear force. **CBSE 2019**

(b) Draw a plot showing the variation of potential energy of a pair of nucleons as a function of their separation. Mark the regions on the graph where the force is (i) attractive and (ii) repulsive.

**19.** If both the numbers of protons and neutrons are conserved in a nuclear reaction like

$$_6C^{12} + {}_6C^{12} \longrightarrow {}_{10}N^{20} + {}_2He^4$$

In what way is the mass converted into the energy? Explain.

**20.** Calculate for how many years will the fusion of 2.0 kg deuterium keep 800 W electric lamp glowing. Take the fusion reaction as **CBSE 2020**

$${}_1^2H + {}_1^2H \longrightarrow {}_2^3He + {}_0^1n + 3.27 \text{ MeV}$$

## LONG ANSWER Type I Questions

**21.** (a) Give one point of difference between nuclear fission and nuclear fusion.

(b) Suppose we consider fission of a ${}_{26}^{56}Fe$ into two equal fragments of ${}_{13}^{28}Al$ nucleus. Is the fission energetically possible? Justify your answer by working out $Q$-value of the process.

Given $(m)\,{}_{26}^{56}Fe = 55.93494$ u

and $(m)\,{}_{13}^{28}Al = 27.98191$. **CBSE SQP (Term-I)**

**22.** Draw the curve showing the variation of binding energy per nucleon with the mass number of nuclei. Using it explain the fusion of nuclei lying on ascending part and fission of nuclei lying on descending part of this curve.

**CBSE 2020**

**23.** A heavy nucleus $P$ of mass number 240 and binding energy 7.6 MeV per nucleon splits in to two nuclei $Q$ and $R$ of mass numbers 110, 130 and binding energy per nucleon 8.5 MeV and 8.4 MeV, respectively. Calculate the energy released in the fission. **CBSE 2020**

## LONG ANSWER Type II Questions

**24.** Define $Q$-value of a nuclear process. When can a nuclear process not proceed simultaneously?

If both the number of protons and the number of neutrons are conserved in a nuclear reaction, in what way is mass converted into energy

(or *vice-versa*) in nuclear reaction?

**25.** (i) In a typical nuclear reaction, e.g.

$${}_1^2H + {}_1^2H \longrightarrow {}_2^3He + 3.27\,\text{MeV}$$

Although number of nucleons is conserved, yet energy is released. How? Explain.

(ii) Show that nuclear density in a given nucleus is independent of mass number $A$.

# ANSWERS

**1.** (*c*) **2.** (*b*) **3.** (*b*) **4.** (*c*) **5.** (*d*)

**6.** (*d*) **7.** (*a*) **8.** (*a*)

**9.**(i) (*a*) As nearly 99.9% mass of atom is in nucleus.

$$\therefore \quad \frac{\text{Mass of nucleus}}{\text{Mass of atom}} = \frac{99.9}{100} = 0.99 = 1$$

(ii) (*a*) Since, the nuclei of deuterium and tritium are isotopes of hydrogen, they must contain only one proton each. But the masses of the nuclei of hydrogen, deuterium and tritium are in the ratio of 1 : 2 : 3, because of presence of neutral matter in deuterium and tritium nuclei.

(iii) (*d*) Density $= \dfrac{\text{Mass}}{\text{Volume}}$

$$= \frac{mA}{\frac{4}{3}\pi R_0^3 A} = \frac{3m}{4\pi R_0^3}$$

As, $\quad m = m_P = m_N$

$$= 2.3 \times 10^{17} \text{ kgm}^{-3}, \text{ which is a constant.}$$

(iv) (*a*) $R = R_0 A^{1/3}$

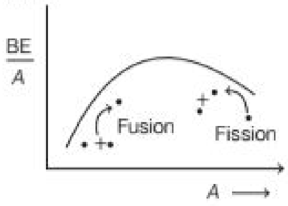
$$\log R = \log R_0 + \frac{1}{3}\log A$$

On comparing the above equation of straight line; $y = mx + c$, so the graph between log $A$ and log $R$ is a straight line also.

(v) (*a*) Here $A_1 = 197$ and $A = 107$

$$\therefore \quad \frac{R_1}{R_2} = \left(\frac{A_1}{A_2}\right)^{1/3} = \left(\frac{197}{107}\right)^{1/3} = 1.225 \doteq 1.23$$

**10.** (i) (*b*)



So, from graph, it is clear that binding energy per nucleon decreases with mass number at high mass numbers.

(ii) (*b*) Fast neutrons are slowed down by elastic scattering with light nuclei as each collision takes away nearly 50% of energy.

(iii) (*d*) Reactions I and II represent fission of uranium isotope $^{235}_{92}U$, when bombarded with neutrons that breaks it into two intermediate mass nuclear fragments. However, reaction III represents two deuterons fuses together to form the light isotope of helium.

(iv) (*a*) The energy released (i.e. *Q*-value) in the fission reaction of nuclei like uranium is of the order of 200 MeV per fissioning nucleus. This is estimated as follows

Let us take a nucleus with $A = 240$ breaking into two fragments each of $A = 120$, then

$E_{bn}$ for $A = 240$ nucleus is about 7.6 MeV.

$E_{bn}$ for the two $A = 120$ fragment nuclei is about 8.5 MeV.

So, gain in binding energy for nucleon is about 0.9 MeV.

Hence, the total gain in binding energy is $240 \times 0.9$ or 216 MeV.

(v) (*a*) In fission process, when a parent nucleus breaks into daughter products, then some mass is lost in the form of energy. Thus, mass of fission products < mass of parent nucleus.

$$\Rightarrow \frac{\text{Mass of fission products}}{\text{Mass of parent nucleus}} < 1$$

**11.** $^1_0n + ^{10}_5B \longrightarrow ^4_2He + ^7_3Li$

**12.** $^{32}_{15}P \longrightarrow ^{32}_{16}S + \overline{\nu} + e^-$

**13.** We know that, radius of nucleus in terms of mass number (*A*), given as

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

$$\therefore \quad \frac{R_1}{R_2} = \frac{R_0(27)^{1/3}}{R_0(512)^{1/3}} \Rightarrow \frac{3}{8} \Rightarrow 3:8$$

**14.** In the given nuclear reaction, the atomic number of product side is one less than that of reactant side. So, the *X* must be an electron and the reaction can be written as

$$^{22}_{11}Na + ^0_{-1}e \longrightarrow ^{22}_{10}Ne + \nu_e$$

**15.** In fission each nucleus of $^{235}U$, emits on the average more than two neutrons. If one of these neutrons is absorbed by another $^{235}U$ nucleus, causing it to fission, we can have a sustainable chain reaction. However, only a slow neutron, rather than a fast neutron has a high cross-section (chance) of absorption. i.e. Why neutrons are slowed down by use of moderator. Heavy nuclei are (preferably) needed for slowing down fast neutrons.

**16.** Heavy water and graphite are used as moderator in nuclear reactors. The main reason why heavy water and graphite used as moderator because they capture less neutrons than other substance.

**17.** Refer to text on page 505.

**18.** Refer to text on page 505. (Nuclear force)

**19.** Here, sum of masses of constituents of product is less than the sum of masses of constituents of reactants, which causes some mass defect. This mass defect gets converted into energy, as per mass-energy equivalence.

**20.** Let *t* be the time.

According to the Avogadro number concept,

number of atoms in 2 g of deuterium

$$= 6.023 \times 10^{23}$$

and number of atoms in 2 kg of deuterium

$$= \frac{6.023 \times 10^{23} \times 2 \times 10^3}{2}$$

$$= 6.023 \times 10^{+26} \text{ nuclei}$$

Energy released during fusion of two deuteriums

$$= 3.27 \text{ MeV}$$

$\therefore$ Energy released per deuterium = 1.635 MeV

Energy released in fusion of $6.023 \times 10^{26}$ deuterium atoms

$$= 1.635 \times 6.023 \times 10^{26}$$

$$= 9.848 \times 10^{26} \text{ MeV}$$

$$= 9.848 \times 10^{26} \times 1.6 \times 10^{-13}$$

$$= 15.75 \times 10^{13} \text{ J}$$

Energy used by bulb in 1s = 800 J $\quad (\because W = J/s)$

As, 800 J of energy used in time = 1 s.

So, $15.75 \times 10^{13}$ J of energy used in time

$$= \frac{1 \times 15.75 \times 10^{13}}{800}$$

$$= 1.969 \times 10^{11} \text{s}$$

$$[\because 1 \text{ yr} = 60 \times 24 \times 60 \times 365 \text{ s}]$$

$$= \frac{1.969 \times 10^{11}}{60 \times 24 \times 60 \times 365} \text{ yr}$$

$$= 6.243 \times 10^3 \text{yr}$$

Thus, the bulb glows for $6.243 \times 10^3$ yr.

**21.** (a) **Distinction between Nuclear Fission and Nuclear Fusion** Fission is the splitting of large nucleus into two or more smaller ones, on the other hand, fusion is the combining of two or more lighter nuclei to form larger one.

(b) The given reaction for decay process,

$$^{56}_{26}\text{Fe} \longrightarrow 2\,^{28}_{13}\text{Al}$$

Mass defect, $\Delta m = m(^{56}_{26}\text{ Fe}) - 2m(^{28}_{13}\text{Al})$

$$= 55.93494 - 2(27.98191)$$

$$= -\ 0.02888 \text{ u}$$

$$\Rightarrow \quad Q = \Delta m \times 931$$

$$= -0.02888 \times 931$$

$$= -26.88728 \text{ MeV}$$

Because the energy is negative, so the fission is not possible energetically.

**22.** Refer to text on page 504.

**23.** Energy released $(\Delta E) = \Delta m \times c^2$

where, $\Delta m$ is the mass defect.

$$\Rightarrow \quad \Delta E = \mu c^2 = [110 + 130] \times 8.5 - 240 \times 7.6 \text{ MeV}$$

$$(\because c^2 = 931.5 \text{ MeV})$$

$$= 240 \times (8.5 - 7.6) = 240 \times 0.9$$

$$= 216 \text{ MeV}$$

**24.** $Q$-value; refer to the text on pages 512 and 513.
In fact the number of protons and number of neutrons are same before and after nuclear reaction, but the binding energies of nuclei present before and after a nuclear reaction are different. This difference is called mass defect. This mass defect appears as energy of reaction. In this sense, a nuclear reaction is an example of mass-energy inter conversion.

**25.** (i) Refer to Q. 20 on page 507.

(ii) Refer to text on page 502.