13

NUCLEI

- **Atomic mass unit**

  It is a unit used to express the mass of atoms and particles inside it.
  One atomic mass unit is $\frac{1}{12}$ the mass of C^{12} atom.
  1u = 1.660539× $10^{-27}kg$.

- Chadwick discovered neutron.
- The sum of number of protons neutrons constitutes mass number.
- **Isotopes**

  Isotopes are atoms of same element having same atomic number but different mass numbers.

  eg: The isotopes of hydrogen are protium, deuterium and tritium $\left[\,{}_{1}H^{1},\ {}_{1}H^{2},\ {}_{1}H^{3}\right]$.

  The isotopes of carbon are $C_6^{12}$and C_6^{14} .

- **Isobars**

  Isobars are atoms with same mass numbers but different atomic numbers.

  eg: N_{11}^{22} and Ne_{10}^{22}

  C_6^{14} and N_7^{14}

- **Isotones**

  Isotones are atoms containing equal number of neutrons.

  eg:Hg_{80}^{198} and Au_{79}^{197}

- **Radius of nucleus**

  R = $R_0\ A^{\frac{1}{3}}$ where A is the mass number and R_0 is 1.2 × 10^{-15}m.

- **Prove that density of all nuclei equal.**

  We know that the radius of a nucleus R = $R_0\ A^{\frac{1}{3}}$(Assuming nucleus as a sphere)

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

  Volume ∝ A

  Density = $\frac{mass}{volume}$ = $\frac{mA}{\frac{4\pi}{3}R_0^3\ \text{A}}$

  where m is the average mass of a nucleon.

∴ Density = $\frac{3\,m}{4\pi R_0^3}$ which is a constant.

ie, The density is the same for all nuclei.

- **Einstein's mass –energy equivalence relation**

  E =mc^2 where E- energy, m= mass, c – velocity of light.

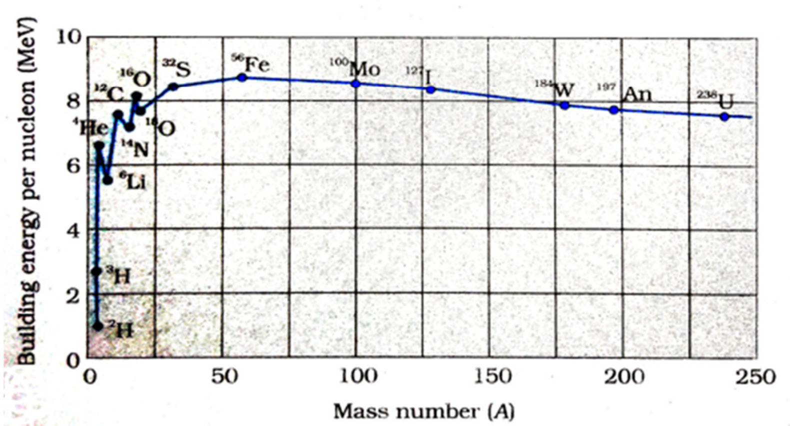
- **Mass defect and binding energy**

  Mass defect is difference between rest mass of nucleus and the sum of masses of protons and neutrons. The energy equivalent to mass defect is called binding energy. This energy holds the nucleons together inside the nucleus.

  If Δm is mass defect, then

  Binding energy = $\Delta\, mc^2$

- **Graph showing binding energy per nucleon versus mass number**



❖ <u>**Observation from the graph**</u>**:**

Binding energy per nucleon is independent of mass number in the range 30<A <170. The maximum binding energy is for Fe^{56} [8.75 MeV].

Binding energy is lower for both light nuclei [A<30] and heavy nuclei (A> 170).

❖ <u>**Conclusions**</u>

The force between nucleons is attractive and is very strong [certain Me V].

In the range of mass numbers from 30 to 170 the binding energy is constant. It shows that nuclear force is short ranged.

Very heavy nuclei have lower binding energy per nucleon compared to lighter nuclei .Thus if a heavier nucleus splits into lighter nuclei, nucleons get tightly bound. Thus energy is released. This is the reason for the energy released in nuclear fission.

When two lighter nuclei combine to form a heavier nucleus, binding energy per nucleon of heavier nucleus is more than binding energy per nucleon of lighter nuclei. The final system is more tightly bound than the initial system. Energy is released which is observed in nuclear fusion.

- **Properties of nuclear force**

It is a special type of force holding the nucleons together inside the nucleus.
It is charge independent.
It is short ranged .If the distance between nucleons is more than 0.8fm, the force is attractive. If the distance is less than 0.8 fm the force is repulsive.

- **Isomers**

Nuclei with same atomic number and mass number but existing in different energy states.

e.g. A nucleus in its ground state and the identical nucleus in meta stable excited state are isomers.

- **Transmutation**

The conversion of one element to another is called transmutation.

- Gravitational force: Electrostatic force: Nuclear force = $1: 10^{36}: 10^{38}$
- Nuclear force exists up to short distances of 2 to 3 fm.
- **Saturation effect of nuclear force:**

A nucleon interacts only with its neighboring nucleon. This property is supported by the result of the same binding energy per nucleon over a large of mass numbers.

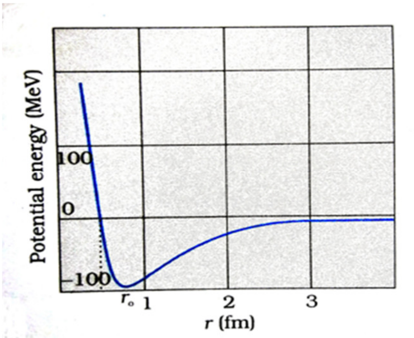
- **Spin dependent character of nuclear force:**

Nuclear force between two nucleons having parallel spins is stronger than that between nucleons of anti parallel spins.

- Nuclear force between two nucleons is due to the exchange of particles called mesons (found by Yukawa, a Japanese physicist in 1935)
- Nuclear force between two nucleons is non – central force.
- **Packing fraction of a nucleus** = $\frac{Mass\ Defect}{Mass\ Number}$

If packing fraction (PF) is positive, (as in the case of nuclei with mass number less than 20 or above 200), the nucleus is unstable. If PF is negative (Nuclei of mass number between 20 and 200), the nucleus is stable.

- **Graph showing the potential energy of a pair of nucleons versus distance between them**



- Natural radio activity was discovered by Henry Becquerel.
- **Radiations emitted from a radioactive substance**

  The three types of radio active radiations emitted from a radio active substance are the following.

  1. alpha (∝): During alpha decay, a helium nucleus (He_2^4)is emitted.
  2. Beta (β) : During beta decay, electron or positron is emitted.
  3. Gamma (γ) : During gamma decay, high energy photons are emitted.

- **Law of radioactive decay**

  The number of atoms disintegrated in unit time (rate of disintegration) is directly proportional to the number of atoms present.

$\frac{dN}{dt} \propto N$

$\frac{dN}{dt} = -\lambda N$ where λ is called decay constant or disintegration constant.

-ve sign indicates that the number of atoms decreases with time.

$\frac{dN}{N} = -\lambda\, dt$

Integrating, $\int_{N_o}^{N} \frac{dN}{N} = \int_0^t -\lambda\, dt$

$[log_e N]_{N_o}^{N} = -\lambda\ [t]_0^t$

$[log_e N - log_e N_o] = -\lambda\,[t - 0]$

$[\,log_e \frac{N}{N_o}\,] = -\lambda t$ OR $\frac{N}{N_o} = e^{-\lambda t}$

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

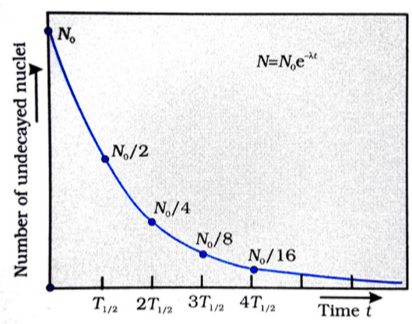
- **Radio activity**

  The phenomenon of spontaneous disintegration of nucleus with the release of radiations is known as radio activity.

- **<u>Soddy – Fajan's displacement law for radioactive transformations</u>:**

  No nucleus can simultaneously emit α and β. The emission of β is usually accompanied by the emission of γ ray.

- **Number of undecayed nuclei verses time**



- The SI unit of activity is becquerel (Bq).

- 1 curie = 3.7 × $10^{10} Bq$.

- **<u>Half life period of radioisotope</u>**

  It is the time taken by the radioactive isotope to disintegrate to half the initial number of atoms.

  We know that N = $N_o e^{-\lambda t}$

  where N_o is the number of atoms initially present.

  In this case t = $T_{1/2}$, N = $\frac{N_o}{2}$

$$\frac{N_o}{2} = N_o e^{-\lambda T_{1/2}}$$

$$\frac{1}{2} = e^{-\lambda T_{1/2}}$$

OR $$2 = e^{\lambda T_{1/2}}$$

$$log_e 2 = \lambda T_{1/2}$$

OR $$2.303 \times log2 = \lambda T_{1/2}$$

$$2.303 \times 0.3010 = \lambda T_{1/2}$$

OR $$T_{1/2} = \frac{0.6930}{\lambda}$$

- **Mean life** $\tau = \frac{1}{\lambda}$

  But $\lambda = \frac{0.6930}{T_{1/2}}$

  Mean life $\tau = \frac{1}{\lambda}$

  $\tau = \frac{T_{1/2}}{0.6930}$

  or $T_{1/2} = \tau \times 0.6930$ or $T_{1/2} = \tau \, log_e 2$

- **Change during alpha emission**

  Atomic number decreases two units and mass number decreases four units.

  $X_a^b \rightarrow Y_{a-2}^{b-4}$

- **Two types of beta emission**

  Beta emission takes place in two ways.

  ***β*(-) Emission**: During β(-) emission, the nucleus emits electron.

  One neutron in the nucleus splits into a proton, electron and an anti-neutrino. This electron is emitted as β(-).

  $n_0^1 \rightarrow H_1^1 + e_{-1}^0 + \bar{v}$

  $X_a^b \xrightarrow{\beta(-)} Y_{a+1}^b$

  During β(-) emission, the atomic number increases one unit, but the mass number remains the same.

  ***β*(+) emission :** During β(+) emission , the nucleus emits a positron.

  One proton in the nucleus splits into a neutron, positron and neutrino. This positron is emitted as β(+).

  $H_1^1 \rightarrow n_0^1 + e_1^0 + v$

  $X_a^b \xrightarrow{\beta(+)} Y_{a-1}^b$

  During β(+) emission, the atomic number decreases one unit, but the mass number remains the same.

- **Change when gamma is emitted**

  No change for atomic number or mass number.

- **Q value (or disintegration energy) of a nuclear reaction**

  It is the difference between the initial mass energy and total mass energy of decay products.

- $P_{15}^{32} \rightarrow S_{16}^{32} + e_{-1}^{0} + \bar{\nu}$

  $Na_{11}^{22} \rightarrow Ne_{10}^{22} + e_{1}^{0} + \nu$

- **Difference between nuclear fission and nuclear fusion**

  The splitting of a heavier nucleus into lighter nuclei with the release of energy is called nuclear fission. The process of combing two or more lighter nuclei to from a heavier nucleus with the release of energy is called nuclear fusion

- **Chain reaction**

  When U^{235} is bombarded with neutron, it splits in to two with the release of three neutrons. These neutrons strike against other U^{235} nuclei. They also split. In each case three neutrons are emitted . If the reaction is allowed to proceed, it spreads very fast in the sample . Such a continuous and fast spreading nuclear fission is called chain reaction.

- **Working principle of atom bomb**

  Uncontrolled change reaction (fission) leads to a violent explosion.

- The device which helps to get nuclear energy by controlled chain reaction called **Nuclear Reactor.**

- **Reason why neutrons are most suitable for fission**

  Neutrons are electrically neutral. Hence they are neither attracted nor repelled by any charged particle in the atom.

- **<u>Fission of Uranium – 235 with a neutron</u>**

When $92^{U^{235}}$ is bombarded with a neutron, it breaks into fragments of intermediate masses.

$o^{n^1} + 92^{U^{235}} \rightarrow 92^{U^{236}} \rightarrow 56^{Ba^{144}} + 36^{Kr^{89}} + 3\ o^{n^1}$.

The same reaction can produce other pairs of intermediate mass fragments.

$o^{n^1} + 92^{U^{235}} \rightarrow 92^{U^{236}} \rightarrow 51^{Sb^{133}} + 41^{Nb^{99}} + 4\ o^{n^1}$.

The reaction may take place in the following way also.

$o^{n^1} + 92^{U^{235}} \rightarrow 54^{Xe^{140}} + 38^{Sr^{94}} + 2\ o^{n^1}$.

The products are radioactive. They emit β particles in succession and attain stable products.

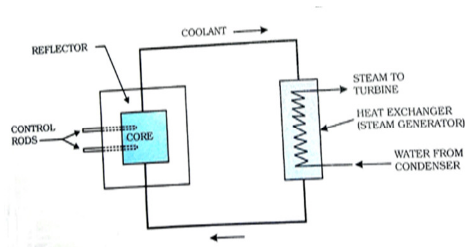
- **Nuclear reactor**

Core: It is the part where the nuclear fuel is kept. It is the site of nuclear fission. The fuel used is enriched Uranium (Uranium that has greater abundance of U^{235}).

Moderator: It is used to slow down neutrons. The moderators used are water, heavy water (D_2O) and graphite.

Neutron source: A powdered mixture of beryllium and polonium acts as neutron source.

The core is surrounded by a **reflector** to reduce leakage. The energy (heat) released in fission is continuously removed by a suitable **coolant**. Air, water, CO_2, liquid sodium etc. are used as coolants.



Radiation shield: The reactor is surrounded by a **radiation shield** made of thick concrete and lead to prevent the escape of radiations to the surrounding area.

Control rods are used to shut down the reactor. Rods made of cadmium are used as control rods. They can absorb neutrons.

In addition to control rods, reactors are provided with **safety rods** which can be inserted into the reactor to keep the multiplication factor less than one. The coolant transfers heat to a liquid which produces steam. Steam drives turbine of generator and generates electricity.

- **Multiplication factor**:
  It is the ratio of the number of neutrons generated in fission to the number of neutrons produced in the preceding step.
  If K = 1 the operation of the reactor is said to be critical (helps in getting steady operation).
  If K > 1 the reaction rate increases. It becomes super critical and may explode.
- The more abundant isotope $92^{U^{238}}$ in naturally occurring Uranium is non – fissionable. When it captures a neutron, it produces highly radioactive plutonium through the following reactions.

$$92^{U^{238}} + o^{n^1} \rightarrow 92^{U^{239}} \rightarrow 93^{Np^{239}} + -1^{e^0} + \bar{\vartheta}$$

$$93^{Np^{239}} \rightarrow 94^{Pu^{239}} + -1^{e^0} + \bar{\vartheta}$$

Plutonium undergoes fission with slow neutrons.

- **Nuclear fusion is called thermonuclear reaction**

  The combining nuclei in nuclear fusion repel each other as they have the same charge. Large energy has to be supplied to overcome this electrostatic repulsion. This energy is provided in the form of heat. Hence the reaction is called thermo nuclear reaction.

- **Essential conditions for nuclear fusion**

  High temperature, high pressure, high density.

- It is practically very difficult to control nuclear fusion. It is very difficult to create and sustain the high temperature needed for this reaction. We have not yet devised any method to control this reaction.
- Monozite sand in the coastal area of Kerala is rich in **Thorium.**
- Hydrogen bomb is the most powerful explosive material man has ever made. The summary of the reaction in it is, four hydrogen nuclei combine to form a helium nucleus. The high temperature needed for this reaction is produced by the explosion of an atom bomb. Thus atom bomb is the trigger of hydrogen bomb.
- The first chairman of atomic energy commission in India was **Dr. H.J. Bhabha**.
- **Apsara** is the first nuclear reactor in India.
- The main objectives of Indian atomic energy commission are to provide safe and reliable power for the country and to be self dependent in the matter of nuclear technology.
- **Fast breeder reactors**: They are nuclear reactors which produce nuclear fuel simultaneously with nuclear energy. They use fast neutrons. Hence they require no moderator. They breed fuels like plutonium.
- **Kalpakkam** is a fast breeder reactor.
- The fuel used in Kalpakkam reactor is **plutonium uranium carbide**. We are the first country in the world, using a carbide fuel.
- **Breeder reactors** produce more fissionable products than they consume.
- The neutron produced in the fission of U^{235} has energy about 2 Me V. They are called **fast neutrons**. U^{235} will not absorb fast neutrons. If the fast neutrons are slowed down to thermal energies about 0.0235 e V, they are called **thermal neutrons.**
- Controlled chain reaction was invented by **Enrico Fermi**.

- The size of fissionable material for which the multiplication factor is equal to one is called critical size and its mass is called **critical mass**. Critical mass is essential for sustaining the fission reaction.
- **Energy production in stars**

The sun and the stars are at a high temperature. Protons fuse to form helium nuclei and liberate large amount of energy. This fusion reaction takes place through two cycles (explained by Hans Bethe).

1. Proton – proton cycle 2. Carbon – nitrogen cycle.

1. **Proton – proton cycle**

$1^{H^1} + 1^{H^1} \rightarrow 1^{H^2} + e^+ + \vartheta$ + 0.42 Me V

$e^+ + e^- \rightarrow \gamma + \gamma$ + 1.02 Me V

$1^{H^2} + 1^{H^1} \rightarrow 2^{He^3} + \gamma$ + 5.49 Me V

$2^{He^3} + 2^{He^3} \rightarrow 2^{He^4} + 1^{H^1} + 1^{H^1}$ + 12.86 Me V.

For the fourth reaction to take place, the first three reactions must take place twice.
The net reaction can be written as

$4\ 1^{H^1} + 2e^- \rightarrow 2^{He^4} + 2\,\vartheta + 6\,\gamma$ +26.7 Me V

2. Carbon – Nitrogen cycle

$6^{C^{12}} + 1^{H^1} \rightarrow 7^{N^{13}} + \gamma$ + 1.93 Me V

$7^{N^{13}} \rightarrow 7^{C^{13}} + e^+ + \vartheta$ + 1.20 Me V

$6^{C^{13}} + 1^{H^1} \rightarrow 7^{N^{14}} + \gamma$ + 7.6 Me V

$7^{N^{14}} + 1^{H^1} \rightarrow 8^{O^{15}} + \gamma$ + 7.39 Me V

$8^{O^{15}} \rightarrow 7^{N^{15}} + e^+ + \vartheta$ + 1.71 Me V

$7^{N^{15}} + 1^{H^1} \rightarrow 6^{C^{12}} + 2^{He^4}$ + 4.99 Me V

The net reaction can be written as

$1^{H^1} + 6^{C^{12}} \rightarrow 2^{He^4} + 6^{C^{12}} + 2e^+ + 2\,\vartheta + 3\,\gamma$ + 24.8 Me V

Stars hotter than the sun get energy through carbon – nitrogen cycle, while cooler than the sun get energy through proton – proton cycle.