Unit-7

Nuclear Physics

Syllabus:
Nuclear composition, mass defect, binding energy, nuclear force, liquid drop model, elementary idea about nuclear fission and fusion

Nuclear constituents:

By β particle scattering, Rutherford conclude that the atom of any element consist of central core called nucleus and electrons moving around it. The entire mass of the atom and positive charge is concentrated inside the nucleus. The nucleus is supposed to consists of two particles the protons and neutrons. The protons are positively charged particles while the neutrons are neutral particles. The mass of the protons and neutrons are almost same and the charge on the proton is equal and opposite to that of electron.

S.N.	Name of the particle	Mass of the particle	Charge on the particle
1	electron	$9.108 \times 10^{-31} kg$	$-1.6 \times 10^{-19} C$
2	proton	$1.67261 \times 10^{-27} kg$	$1.6 \times 10^{-19} C$
3	neutron	$1.6492 \times 10^{-27} kg$	NIL

Both the neutrons and protons inside the nucleus together are called the nucleons. The number of protons $(i.e.\ equal\ to\ the\ number\ of\ electrons)$ is called the $atomic\ number$ and the sum of the number of protons and neutrons is called the $mass\ number$. The stability of the nucleus is depends on the relative number of neutrons and protons.

The conventional symbol of the nuclear species follows the following pattern-

$$_{Z}X^{A}$$

Where

A = mass number

Z = atomic number (i.e. the number of the protons/electrons)

X = chemical symbol

General Properties of the nucleus:

(a) The nuclear mass:

Mass of the nucleus is the sum of the mass of the protons and neutrons combined in a nucleus. This is usually expressed in terms of $atomic\ mass\ unit\ (amu)$

$1\ amu = 1.66 \times 10^{-27}\ kg$. It is $\left(\frac{1}{12}\right)^{th}$ part of the $_{6}C^{12}$ nucleus.

it is assume that the total mass of the nucleus should be the sum of the mass of the neutrons and protons i.e.

$$mass\ of\ the\ neucleous = Z(m_p) + N(m_n)$$

$$mass\ of\ the\ neucleous = Z(m_p) + (A - Z)(m_n)$$

Where

$$m_p = mass\ of\ one\ proton$$
$$m_n = mass\ of\ the\ neutron$$
$$A = atomic\ mass\ number$$
$$Z = atomic\ number$$

(b) Nucleus charge:

The charge on the nucleus is due to the protons contained in it. This can be given as

$$Nuclear\ charge = Z(1.6 \times 10^{-19})C$$

(c) Nucleus radius:

It has been observed that volume of the nucleus of directly proportional to the number of the nucleons A,

$$volume \propto A$$
$$\frac{4}{3}\pi r^3 \propto A$$
$$r^3 \propto \left(\frac{3}{4\pi}\right) A$$
$$r \propto \left(\frac{3}{4\pi}\right)^{1/3} A^{1/3}$$
$$r = c\left(\frac{3}{4\pi}\right)^{1/3} A^{1/3}$$

where c is the proportionality constant

$$r = r_0 A^{1/3}$$

where

$$r_0 = c\left(\frac{3}{4\pi}\right)^{1/3}$$
$$r_0 = 1.5 \times 10^{-15}$$

(d) Nuclear density-

The density of the nucleus can be calculated as follows.

$$density\ of\ nucleus = \frac{mass}{volume} \quad .....(1)$$

but
$$volume\ of\ the\ nucleus = \frac{4}{3}\pi r^3$$
$$volume\ of\ the\ nucleus = \frac{4}{3}\pi(1.5 \times 10^{-15})^3\left(A^{\frac{1}{3}}\right)^3$$
$$volume\ of\ the\ nucleus = 14.15 \times 10^{-45} A$$
$$mass\ of\ the\ nucleus = A \times mass\ of\ the\ proton$$

$$mass\ of\ the\ nucleus = A \times 1.673 \times 10^{-27}\ kg$$

now putting these values in the equation number (1)

$$Desity = \frac{A \times 1.673 \times 10^{-27}}{A \times 14.15 \times 10^{-45}}$$

$$Desity = 1.18 \times 10^{17}\ kg/m^3$$

Spin and magnetic moment:

Like electron neutrons, protons are also fermions with spin quantum number $s = \frac{1}{2}$ therefore spin angular momentum $\vec{s}$ of magnitude of-

$$s = \frac{h}{2\pi}\sqrt{s(s+1)}$$

$$s = \frac{h}{2\pi}\sqrt{\frac{1}{2}\left(\frac{1}{2}+1\right)}$$

$$s = \frac{h}{2\pi}\frac{\sqrt{3}}{2}$$

In nuclear physics magnetic moments are expressed in nuclear magnetron(μ_H)

$$(\mu_H) = \frac{h}{2\pi}.\frac{e}{2m_p}$$

Where m_p is the mass of the proton

Classification of the nuclei:

The atoms of different elements are classified as follows.

(i) **Isotopes:** Isotopes are the nucleus with same number of atomic number Z, but different mass numbers A. The nuclei ${}_8O^{15}$, ${}_8O^{16}$, ${}_8O^{17}$, ${}_8O^{18}$ are all isotopes of oxygen. The isotopes of the element have identical chemical properties but different physical properties.

(ii) **Isobars:** nuclei with the same mass number A but different atomic number Z the nuclei ${}_8O^{16}$, ${}_7N^{16}$ are the examples of the isobars. These elements have the different chemical and physical properties.

(iii) **Isotones:** Isotones are the nuclei with equal number of neutron $i.\ e.\ N(= A - Z)$. Examples are ${}_6C^{14}$, ${}_7N^{15}$& ${}_8O^{16}$ $(N = .8)$

(iv) **Mirror nuclei:** Mirror nuclei have the same number of A but the number of protons and neutrons are interchanged.

(v) **Examples are:** ${}_4B^7(Z = 4 \text{ and } N = 3), {}_3Li^7(Z = 3 \text{ and } N = 4)$

Nuclear Liquid Drop Model:

This model was proposed by Neil-Bohr in 1937. This model shows the analogy of the nucleus with the liquid drop that's why this model is known as liquid drop model. According to this model followings are the analogies between the liquid drop and the nucleus.

1. Both are spherical in shape.
2. Both liquid drop and nuclei filled with an incompressible substance.
3. Short range nuclear forces are analogous to the intermolecular forces in liquid.
4. The density of nuclear matter is very large which do not depends on the number of nuclei just as the density of the liquid drop not depends on the number of molecules.
5. Both nuclear and intermolecular forces are saturated forces.
6. Inside the nucleus the nucleons moves as an atom moves in a liquid drop.
7. Nucleons are bound with the nuclear forces just as the atom in a liquid bound together by the inter-molecular forces.

This is why the nucleus is considered as a small drop of liquid and this model is called the liquid drop model.

some other similarities in liquid drop and nucleus:

S.N.	Basic	Liquid drop	Nucleus
1.	Shape	Due to surface tension	Due to nuclear force.
2.	Density depends on volume	Do not depends on the radius	Do not depend on number of the nucleon.
3.	Emission of particle	Due to the mutual collision the kinetic energy of some molecules increases and leaves the liquid surface.	α Particles emission takes place due to the collision of nucleons and extent the kinetic energy.
4.	Analogy in the energy	Latent heat of vaporisation.	Binding energy per nucleons.
5.	Absorption of the particle	Condensation of the drop.	Absorption of the particle striking the nucleus.

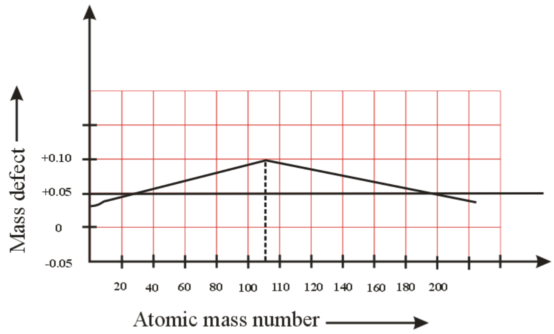
On the basis of the liquid drop model, the nuclear fission can be explained. This model can also explain radioactive decay $(\alpha, \beta, \gamma\ emission)$ successfully. Moreover this model can also explain the nuclear quadruple moment.

Un-success of the liquid drop model:

This model could not explain the reason for most stability of the lighter nuclei such as He^4, C^{12}, O^{16} etc. which have equal number of protons and neutrons. Similarly this model could not be successful to explain the magic numbers.

Mass Defect:

The actual mass of the nucleus is less than the total mass of protons and nucleons present inside it, because some mass is lost in the form the binding energy. This defect is called the mass defect and denoted by ΔM.



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

Where

A = Mass number of nuclei.

Z = Number of protons.

$(A - Z)$ = Number of neutrons

m_p = Mass of protons.

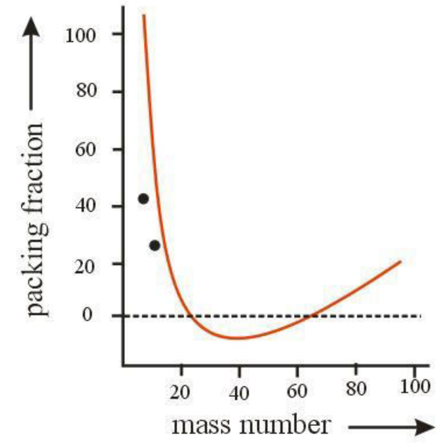
m_n = Mass of neutrons.

M = Measured mass.

Curve between the mass defect and nuclear number:

Figure shows the variation of mass defect per nucleons with atomic numbers.

The mass defect per mass number in the nuclear is known as packing fraction and denoted by $p = \frac{\Delta M}{A}$



Figure(2): Graph between packing fraction and atomic number

From the graph, we can say

1. Mass defect is positive for elements having mass number less than 20.3
2. Mass defect/ packing fraction is negative for elements having mass number between $20\ to\ 160$.
3. The mass defect is again positive for elements having mass number above 200.

The significance of packing fraction is that it is directly related to the availability and its stability of nuclear.

Binding Energy:

The energy required to remove any nucleon (neutron or proton) from the nucleus is called binding energy of nucleus.

The binding energy is the energy equivalent to the mass defect.

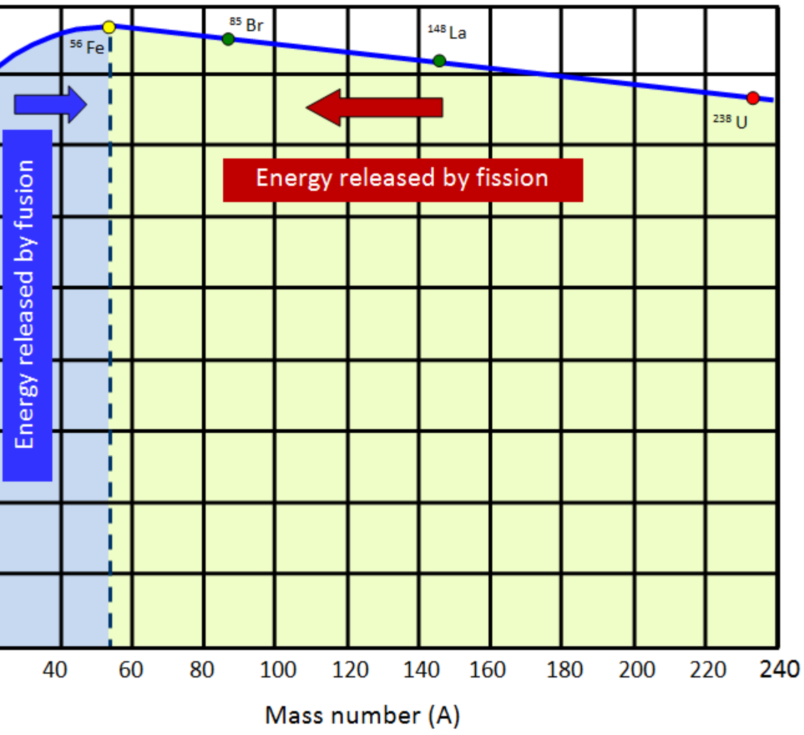
We know that the mass defect is given by

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

Where all the symbols have their usual meaning.

Now the binding energy

$$B = (\Delta M)C^2$$
$$B = \{Z.m_p + (A - Z).m_n - M\}C^2$$



Figure(3): Curve plotted between Binding energy per nucleon and mass number

The average binding energy per nucleon is found to be about 8 MeV for all elements.

Some important features from binding energy curves-

1. Binding energy of very light nuclei like ${}_1H^2$ is very small. The curve rise sharply with increase in mass number A and reaches a maximum value of 8.8 MeV for Fe. This makes iron most stable.
2. Binding energy decreases for element having $A > 138$ it is found to be decreases to 7.6 MeV for uranium.

Semi-empirical mass formula:

The actual mass is slightly less than the calculated mass of the nucleus, because some mass is lost in the form of the binding energy

This mass defect is given by

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

Where the symbols have their usual meanings.

Now the binding energy

$$B = (\Delta M)C^2$$

$$B = \{Z.m_p + (A - Z).m_n - M\}C^2$$

$$M = \left[Z.\ m_p + (A - Z).\ m_n\right] - \frac{B}{C^2}$$

On the basis of the liquid drop model the binding energy is considered to be the sum of independent different energy terms and is expressed as

$$B = B_0 + B_1 + B_2 + B_3 + B_4 \qquad \ldots \ldots \ldots \ldots$$

1. **Volume Energy:**

For most of the nuclei, the binding energy per nucleon is constant

So

$$Volume\ enerrgy \propto mass\ number$$

$$B_0 \propto A$$

$$B_0 = a_v A \qquad \ldots \ldots \ldots \ldots$$

2. **Surface Energy:**

$$B_1 \propto -Surface\ area$$

$$B_1 \propto -R^2$$

$$B_1 = -\left(R_0 A^{\frac{1}{3}}\right)^2$$

$$B_1 = -a_s A^{\frac{2}{3}} \qquad \ldots \ldots \ldots \ldots$$

Negative sign shows that the binding energy decreases due to surface energy.

3. **Coulomb's energy:**

The electrical repulsion between each pair of protons in the nucleus also contributes in decreasing its binding energy. The coulomb energy is proportional to the number of proton pair $\left[\frac{Z(Z-1)}{2!}\right]$ In the nucleus,]and inversely proportional to the nuclear radius $\left(R \propto A^{\frac{1}{3}}\right)$ So the coulomb energy $E_C = -a_3\left[\frac{Z(Z-1)}{a^{\frac{1}{3}}}\right]$ the coulomb energy is negative, because if arises from an effect that opposes nuclear stability.

4. **Asymmetric energy:**

We know that the light nuclei having same number of neutron and proton are more stable but as mass number (A) increases, the number of neutron increases more as compare to the protons, due to which the stability of nucleus decreases. Thus it is concluded that if the number of neutrons increases as compare to protons the binding energy will decrease.

$$Excess\ of\ neutrons = (N - Z)$$

$$Excess\ of\ neutrons = (A - Z) - Z$$

$$Excess\ of\ neutrons = (A - 2Z)$$

So $$Excess\ of\ neutrons = -a_a \cdot \frac{A-2Z}{A} \quad \ldots\ldots\ldots\ldots(5)$$

5. **Energy due to even odd effect:**

The nucleus having even number of neutron and proton are more stable as compared to the nucleus having odd number of neutron and proton while the nucleon having even number of proton and odd number of neutrons or even number of protons and odd number of neutrons are found to be either less stable or more stable. So

$$B_4 = \pm a_p A^{-3/4} \quad \ldots\ldots\ldots\ldots(6)$$

Here (+) sign is for the even number of neutron and protons

(-) sign is for odd number of neutron and protons

And $a_p = 0$ for even number of neutron and odd number of protons and vice-versa.

On combining all the above terms we get

$$M = Zm_P + (A-Z)m_n - \frac{1}{C^2}\left[a_v A - a_s A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_a \frac{(A-2Z)^2}{A} + B_4\right]$$

Isomerism:

The existance of the atomic nuclei those have same atomoic number and the same mass numbers but different energy states.

Magic numbers:

The nuclei which have number of protons (Z) or number of nutrons (N) equal to $2,8,20,28,50,82\ and\ 126$ are relatively stable. These numbers are called the magic numbers.

The existence of magic numbers is established by the following facts.

i) There is abundance of nuclei in nature which have number of nucleons equal to magic no.

ii) From the binding energy curve it is clear that the nuclei ${}_2He^4\ (N = 4-2 = 2)$ and ${}_8O^{16}\ (N = 16-8 = 8)$ are especially stable.

iii) The nuclei of even atomic number or atomic number more than 28 have isotopic abundance more than 60% are only ${}_{32}Sr^{82}\ (N = 88 - 38 = 50)$, ${}_{56}Ba^{138}\ (N = 138 - 56 = 82)$ and ${}_{58}Ce^{140}\ (N = 140 - 58 = 82)$

iv) There are not more than 5 isotones of all the nuclei except for $n = 50$ and $N = 82$.

v) $Sn\ (Z = 50)$ has ten stable isotopes and $Ca\ (Z = 20)$ has six stable isotopes.

vi) After $N = 126$, the $\propto -decay$ energy shows the discontinious behabiour.

vii) $\beta - decay$ energy is very large when number of protons or neutrons in a radioactive nuclear is equal to the magic number.

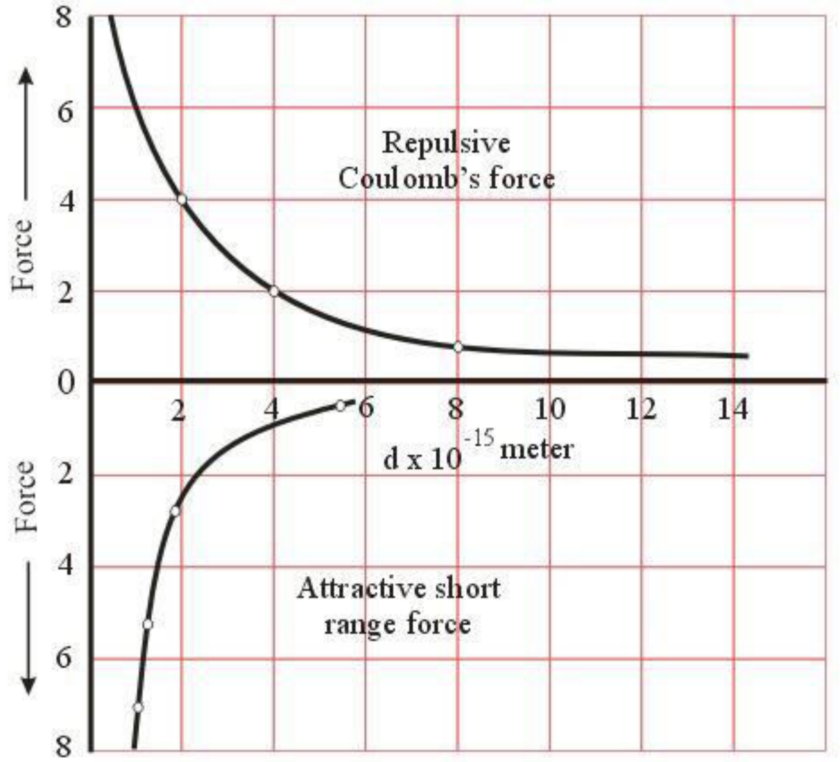
viii) The neutron absorption cross section for $Sn\ (Z = 50)$ and $Pb\ (Z = 82)$ nuclei is very small as compared to the other neighbouring nuclei.

When the average binding energy per nucleon is plotted against mass number. The curve is not smooth, but several kinks are observed. These kinks correspond to sudden increase in binding energy. Thus stability is related to higher binding energy.

Nuclear Forces:

We know that the nucleus consists of protons. Due to the positive charges on protons, there will be repulsive electrostatic force between two protons and the resulting repulsive force between protons will tend to push the nucleus apart. Therefore, for the nucleus to have a permanent existence there must be some strong attractive forces demand. Moreover, these forces cannot be gravitational forces because they are much smaller than the force required. Moreover these forces cannot be electrical forces in nature because the strong repulsive forces between protons will lead to disruption of nucleus. Actually, these forces are short range attractive forces known as Nuclear Forces. The nuclear forces have the following properties:

1) These forces are attractive forces between (proton-proton, neutron-neutron or neutron-proton).
2) These forces are strongest forces in nature.
3) They are spin dependence.
4) These forces are short rang forces, A graph of Coulomb’s law of repulsion and short range forces of attraction is shown in figure.



Figure(4): CompeResion of Colum and nuclear forces.

5) These forces are independent of charge. i.e. the nuclear forces are same for protons proton, proton-neutron, neutron-neutron.
6) In case of the nuclear forces, each nucleon attracts those nucleons which are immediate neighbouring just like the molecules in a liquid or the gas interacts with the neighbouring molecules.

Yukawa mesons theory:

Yukawa in 1935 proposed a theory to explain the binding forces between neutrons and protons known as meson theory of nuclear forces. Yukawa postulated the existence of a new particle called π meason having a rest mass greater then that of the mass of electron but less than that of a nucleon. Though this particle was discover much later, yet Yukawa showed that the interaction produced by mesons between nucleon were of the correct order of magnitude.

According to this theory, all nucleons (protons and neutrons) consist of identical cores surrounded by a cloud by one or more π mesons. The mesons may be either neutral or may carry positive or negative charge. The charge on the mesons is equal to the charge on the electronic charge and according to their charge they designated as π^0, π^+ or π^-. The idea of this theory is that it is the mesons cloud which differentiate between a neutron and a proton. The mesons are supposed to exchange rapidly between nucleons thereby changing their identity equally fast and are responsible for keeping them bound together.

Thus nuclear force between a proton and a neutron is the result of the exchange of charged mesons (π^+ and π^-) between them. When a π^+ meson jumps from a proton to a neutron, the proton is converted into a neutron and vice versa.

$p \rightarrow n + \pi^+$ or $n + \pi^+ \rightarrow p$

Similarly when a π^- meson jumps form a neutron to a proton, it is converted to a proton, and vice versa.

$n \rightarrow p + \pi^-$ or $p + \pi^- \rightarrow n$

In the same way, the forces between two protons and those between two neutrons arise due to the exchange of neutral mesons between them. In this way nucleus is an ever-changing structure. It should be remembered that numbers of protons and neutrons remains the same in the nucleus.

Nuclear Fission:

The phenomenon of braking of a heavy nucleus in to two or more light nuclei of almost equal masses together with the release of a huge amount of energy is known as nuclear fission. The process of nuclear fission was first discovered by the German scientists, Otto Hahn and Strassman, in the year 1939. In this process, when uranium nucleus (U_{92}^{235}) was bombarded with slow neutrons, this nucleus was found to split up in to two radioactive nuclei which were identified as isotopes of Barium (Ba_{56}^{144}) and Krypton (Kr_{36}^{89}). It is given by the following nuclear reaction-

$$U_{92}^{235} + {}_0^1n \rightarrow [U_{92}^{236}] \rightarrow Ba_{56}^{144} + Kr_{36}^{89} + 3\,{}_0^1n + energy$$

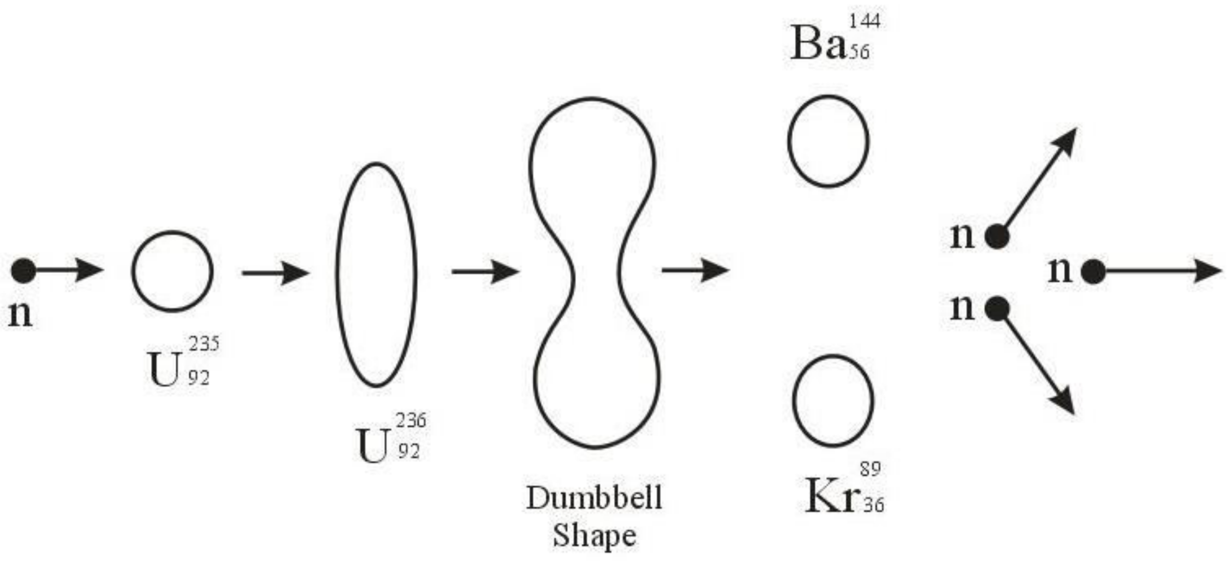


Figure (5): Liquid drop model for nuclear fission

It is not that Barium and Krypton are only isotopes to be obtained by the fission of U_{92}^{235}. Actually, this is a very complicated phenomenon and more than 100 isotopes of over 20 different elements have been obtained in it. All the elements fall in the middle 75 to 160 mass number region of the periodic table

Theory (Liquid Drop Model):

The mechanism of the nuclear fission was first explained by Bohr and Wheeler on the basis of the liquid drop model of the nucleus. According to this model, the nucleus is assumed to be similar to a liquid drop, which remains in equilibrium by a balance between the short-range, attractive forces between the nucleons and the repulsive electrostatic forces between the protons. This inter nucleon force gives rise to surface tension forces to maintain a spherical shape of the nucleus. Thus, there is a similarity in the forces acting on the nucleus and liquid drop. When nucleus drop captures slow or neutron, oscillations setup within the drop. These oscillations tend to distort the spherical shape so that the drop becomes ellipsoid in shape as shown in the figure. The surface tension forces try to make the drop return to its original spherical shape while the excitation energy tends to distort the shape still further. If the excitation energy and hence oscillations are sufficiently large, the drop attains the dumbbell shape. The Columbic repulsive forces then push the nucleus into similar drops. Then each drop tries to attain the shape for which the potential energy minimum, for example spherical shape.

Nuclear Reactor:

It is a device that produces a self-sustained and controlled chain reaction in a fissionable material. One type of nuclear reactor is shown in the figure. A modern rector has following important parts.

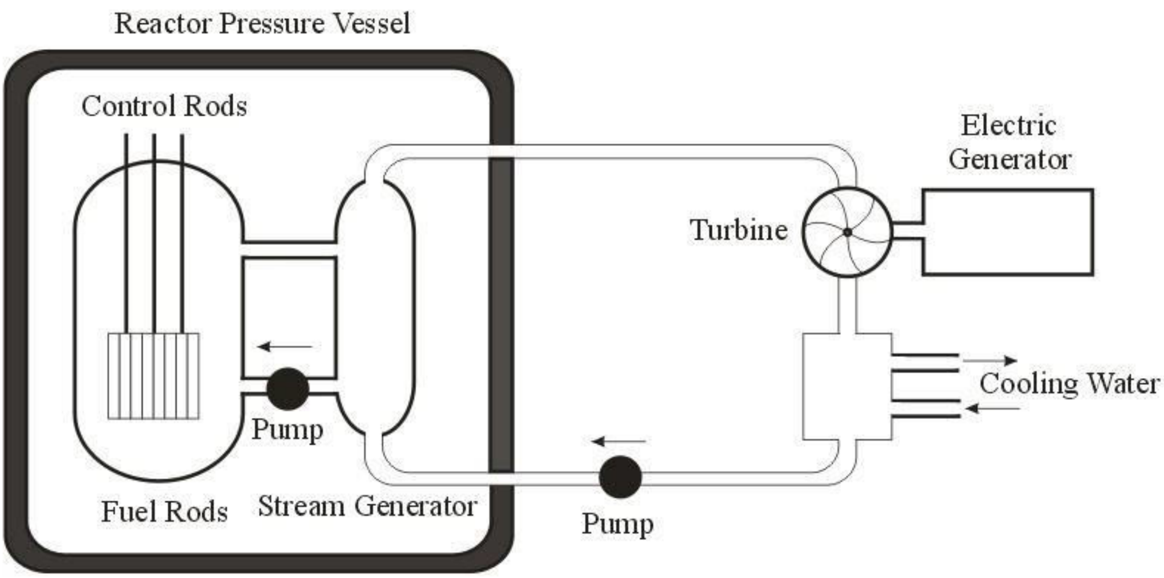


Figure (6): Nuclear reacter

1) Fuel: The fuels play the key role in the operation of the reactor. The fissionable material is known as the fuel. Generally, U_{92}^{235} and Pu_{94}^{239} can be used as fuel.

2) Moderator: It is used to slow down neutron to thermal energies by elastic collisions between its nuclei and the fission neutrons. Heavy water graphite or barium oxides are commonly used for this purpose. Heavy water is the most suitable moderator.
3) Control Rods: To control the fission rate in the reactor, we use cadmium and boron rods. Cadmium and boron are good absorber of slow neutrons. These rods are fixed in the reactor-walls. When they are pushed into the reactor, the fission rate decrease and when they are pulled out the fission rate gets increased.
4) Shield: the various types of rays, like α, β, γ, those are radioactive are emitted from the reactor. These rays may be injurious to the health of people working near the reactor. For protections the reactor is therefore surrounded by a concrete wall of about 2 meter thick and containing high protection element like iron.
5) Coolant: The reactor generates heat energy due to the fission reaction which is removed by means of cooling agent. For this purpose, air water, carbon-dioxide etc. are generally used as coolant. Coolant is circulated is circulated though the interior of the reactor by a pumping system.
6) Safety Device: If the reactor begins to go fast, a special set of control rods, known as shut-off rods insert automatically. They absorb all the neutrons so that chain reaction stops immediately.

Working of nuclear reactor: to start the reactor, no external source is required. Even a single neutron is capable of starting fission, although few neutrons are always present there. The reactor is started by pulling out the control rods. Then the neutron strikes the U_{92}^{235} nucleaus and fission it along with the emission of two or three fast neutrons. These neutrons are slow down by moderator (graphite), after which they induce further fission of U_{92}^{235}. The reaction onece starts is controlled with the help of control rods by moving them inside and outside.

Applications of Nuclear Reactor:

The nuclear reactor are used mainly for the following purpose.

1) Generations of energy
2) Production of Pu^{239}.
3) Production of neutron beam
4) Production of radioisotopes

Nuclear Fusion:

Nuclear fusion is nothing but the formation of heavier nuclide by the fussing of two light nuclei. In this process, the mass of the product nuclide is generally less than the sum of masses of the nuclides which are fused. Therefore, as per Einstein's mass energy relation $E = mc^2$, an enormous amount of energy realeased which is called nuclear energy. The first artificial fusion reaction was the hydrogen bomb which was tested in November 1952. Fusin reactions are thermonuclear reactions which occurs at extremely high temperatures. For example, in order to fuse deuterium (H_1^2) and tritium (H_1^3), the force of repulsion (called Coulomb potential barrier) of these two positively charge particles must be overcome.

The following fusion reaction is possible for the fusion of the two heavy hydrogen nucleoids H_1^2

$H_1^2 + {}_1^2H \rightarrow {}_1^3H + {}_1^1H + 4.0\ MeV$ (energy)

The nucleus of tritium H_1^3 can again fuse with heavy hydrogen nucleus

$H_1^3 + {}_1^2H \rightarrow {}_2^4He + {}_0^1n + 17.6\ MeV$ (energy)

Thus the combine form is

$H_1^2 + {}_1^2H + {}_1^2H \rightarrow {}_2^4He + {}_0^1n + {}_1^1H + 21.6\ MeV$ (energy)

From the above equation, it is clear that three deuterium nuclei fused together to form a helium nucleus and liberate 21.6 MeV energy which is obtained in the form of kinetic energy of proton (H_1^1) and neutron (n_0^1).