short life of about one or two-millionth of a second. There are several types of mesons namely π-mesons, μ-mesons and κ-mesons. Some mesons have positive charge, some have negative charge and still others are without charge. The mass of mesons ranges from 200 to 300 times the mass of electron.

***Beta rays* (${}_{-1}e^{0}$)** High-speed electrons called negative beta particles are released from the nucleus in some nuclear reactions spontaneously or artificially induced. They are not present in the nuclei of atoms as such but result from the change of neutron into a proton and an electron. The beta particles are instantly thrown out because the nucleus is not large enough to contain it. It has a charge of one electronic unit and a mass of 0.00055 amu or 9.1×10^{-31}kg at zero velocity.

***Gamma rays* (γ *ray*)** Gamma rays are electromagnetic radiations like light and radio waves. Gamma rays are released from the nucleus in some nuclear reactions spontaneously or artificially induced. In nuclear physics, gamma rays are regarded as bundles of quanta of high-energy radiations. These rays have no rest mass and no charge. They are similar to high-energy hard X-rays.

***Neutrino* (ν)** When a nucleus emits a beta particle, there is a difference in total energy and momentum before and after the decay. To remove the discrepancies in beta decay, scientists predicted the existence of a neutrino. Neutrino has no charge and is a very light particle with 2% mass of electron. Neutrinos are also formed in the decay of mesons.

Antiparticles For every fundamental particle, there exists an identical fundamental particle just opposite in some property. For example, antiproton is the antiparticle of proton. It was discovered in 1955. Its charge is negative and its mass equal to that of proton. Antineutron is the antiparticle of neutron. It was discovered in 1956. It has no charge and its mass is equal to the mass of neutron. The only difference is that if they spin in the same direction, their magnetic moments will be in opposite directions.

1.6 CLASSIFICATION OF NUCLEI

Isotopes Nuclei having the same atomic number Z but different mass number A are called isotopes. The nuclei ${}_1H^1$, ${}_1H^2$, ${}_1H^3$ are isotopes of hydrogen, ${}_{14}Si^{28}$, ${}_{14}Si^{29}$, ${}_{14}Si^{30}$, ${}_{14}Si^{32}$ are isotopes of silicon and ${}_{92}U^{235}$, ${}_{92}U^{238}$ are isotopes of uranium, since the number of charges is responsible for the characteristic property of an atom, and all isotopes of elements have the same chemical properties but different physical properties.

Isobars Nuclei having the same mass number A but different atomic number Z are called isobars. The nuclei ${}_8O^{16}$, ${}_7N^{16}$ are examples of isobars. The isobars are atoms of different elements and have different physical and chemical properties.

Isotones Nuclei having the same number of neutrons are called isotones. The nuclei ${}_6C^{14}$, ${}_7N^{15}$, ${}_8O^{16}$ have the same number of neutrons ($N = 8$) in each case.

Isomers Nuclei having the same atomic number Z and same mass number A but differ from one another in their nuclear energy states and exhibit differences in their internal structure are called isomers. The elements are distinguished from their different half-life time.

Mirror nuclei Nuclei having the same mass number A, but with the proton and neutron number interchanged are called mirror nuclei. In mirror nuclei, the number of protons in one is equal to the number of neutrons in the other. In the nucleus ${}_4Be^7$, the number of protons $Z = 4$ and number of neutrons $N = 3$ and in ${}_4Li^7$,the number of protons $Z = 3$ and number of neutrons $N = 4$.

Even–even, odd–odd, even–odd and odd–even nuclei Nuclei having even (odd) number of protons and even (odd) number of neutrons are said to be even (odd) – even (odd) nuclei. Nuclei having even (odd) number of protons and odd (even) number of neutrons are said to be even–odd (odd–even) nuclei.

1.7 PROPERTIES OF NUCLEUS

1.7.1 Representation of a Nucleus

A species of nucleus known as nuclide is represented by ${}_ZX^A$, where Z the atomic number indicates the number of protons, A the mass number, indicates the total number of protons and neutrons N ($A = Z + N$) and X is the chemical symbol of the species. For example, the chlorine nucleus is represented as ${}_{17}Cl^{35}$, where number of protons (Z) = 17, mass number (A) = 35 and number of neutrons = $A - Z = 35 - 17 = 18$.

1.7.2 Nuclear Size

Rutherford's experiment on alpha scattering showed that the mean radius of atomic nucleus is of the order of 10^{-14} to 10^{-15}m while the radius of the atom is about 10^{-10} m. Thus the nucleus is about 10,000 times smaller than the atom.

The empirical formula for the nuclear radius is $R = r_0 A^{1/3}$, where A is the mass number and $r_0 = 1.3 \times 10^{-15}$ m = 1.3 fm. Nuclear radius is measured in fermi (fm) which is an appropriate unit of length.

The radii of few elements found from the above formula are given below:

The radius of oxygen ${}_8O^{16}$ nucleus = $(1.3)\,(16)^{1/3} = 1.3 \times 2.5198 = 3.2757.6$ fm

The radius of carbon ${}_6C^{12}$ nucleus = $(1.3)\,(12)^{1/3} = 1.3 \times 2.2894 = 2.9762$ fm

The radius of uranium ${}_{92}U^{238}$ nucleus = $(1.3)\,(238)^{1/3} = 1.3 \times 6.1971 = 8.0562$ fm

The nuclear radius may be estimated from the scattering of neutrons or protons and by scattering of high-energy electrons. The fast neutrons of about 100 MeV energy with a wavelength smaller than the size of the nucleus are scattered by nuclear targets. The neutrons scattered at various angles can be used to deduce the nuclear size. The results of these experiments indicate that the radius of nucleus is given by $R = r_0 A^{1/3}$ where r_0 =1.3 to 1.4 fm. The scattering experiment may be done with proton beams as well.

The scattering experiment can be done with fast electrons of energy as high as 10^4 MeV with a wavelength of 0.1 fm. The advantage of scattering with high-energy electrons is that the charge density of a nucleus can be directly measured. The results of this experiment are in agreement with

Thus, binding energy is equivalent to the energy that must be supplied from the external sou
to dissociate the nucleus into protons and neutrons. It is therefore analogous to the ionization energ
of atoms which must be supplied to remove electrons from them.

1.8.1 STABILITY AND BINDING ENERGY PER NUCLEON

As the total binding energy of a nucleus increases with its complexity, we usually express it a
binding energy per nucleon, E_A/A, where, E_A is the total binding energy of the nucleus and A is th
atomic mass number.

$$\text{Binding energy per nucleon} = \frac{\text{Total binding energy of nucleus}}{\text{Mass number}}$$

The binding energy per nucleon (E_A/A) values plotted as a function of mass number A is show
in Figure 1.5.

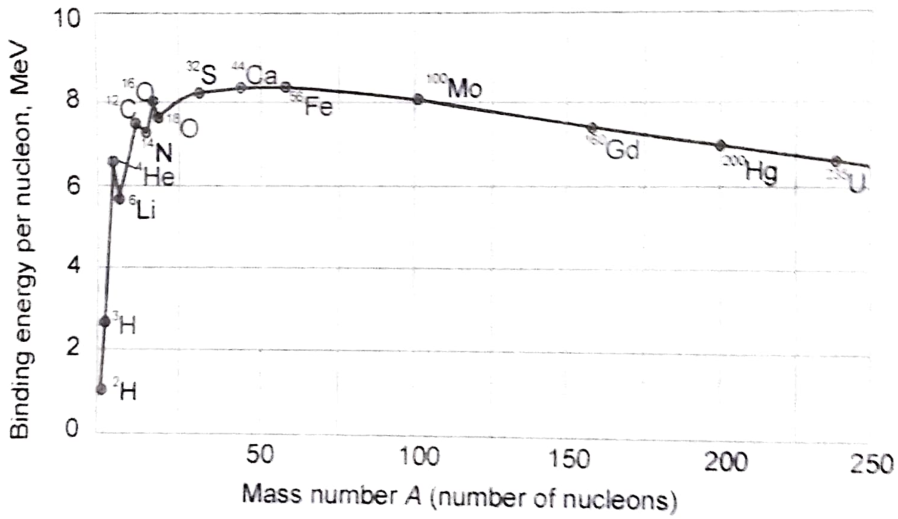


Figure 1.5 Binding energy per nucleon as a function of mass number

When the curve rises steeply in the beginning, certain peaks are observed for the nuclei $_2He^4$, $_4Be^8$, $_6C^{12}$, $_8O^{16}$ and $_{10}Ne^{20}$. This signifies that these nuclei are more stable compared to their neighbours because they have multiples of helium nuclei.

The binding energy curve increases sharply at first and then more gradually until it reaches a maximum of 8.79 MeV for a mass number of 56 corresponding to iron nuclei.

The curve is almost flat for mass numbers between 40 and 120. Evidently the nuclei of intermediate mass numbers are more stable, since the binding energy per nucleon is more for these nuclei. Hence, greater amount of energy must be supplied to liberate each of their nucleons.

For higher mass numbers, the curve drops slowly to about 7.6 MeV for uranium nucleus. Hence, these nuclei are unstable and radioactive.

The lesser amount of binding energy for lighter and heavier nuclei explains the nuclear fusion and fission processes respectively.

Table 1.2 gives atomic masses of some light nuclei.

1.8.3 NUCLEAR STABILITY

Isotopes of the same element have the same chemical properties because they have the same number and arrangement of electron. However, isotopes may not have the same nuclear properties. For instance, some isotopes of an element may be stable while the others may be radioactive. The carbon atom with $A = 12$ may be stable and the same carbon of isotope with $A = 14$ is radioactive. There are nearly 280 stable isotopes occurring in nature. But there are 800 natural and artificially made unstable radioisotopes available now.

Out of the 272 stable isotopes available in nature, 160 isotopes have even number of protons and even number of neutrons in their nuclei, 52 isotopes have even number of protons and odd number of neutrons, 52 isotopes have odd number of protons and even number of neutrons and only 4 isotopes have odd number of protons and odd number of neutrons.

The number of neutrons $N (= A - Z)$ required for maximum stability is plotted as a function of proton number Z in Figure 1.7. It is observed from the graph that for those isotopes with $Z < 20$, having equal number of protons and neutrons, there is a straight line showing the stability of the isotopes. But for those isotopes with $Z > 20$, the number of neutrons is more than the number of protons, the curve bends slightly showing the instability of isotopes.

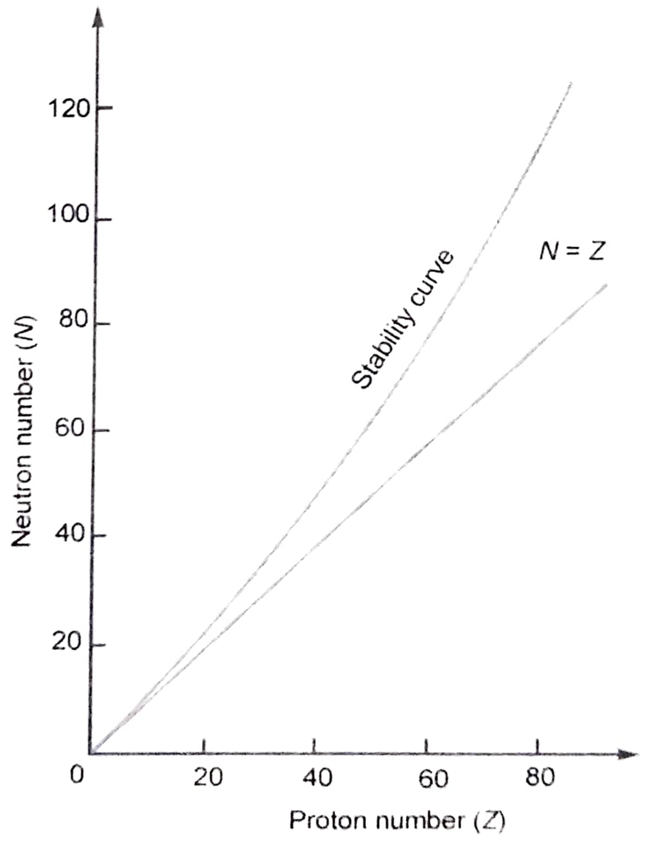


Figure 1.7 Stable isotopes curve based on number of neutrons and protons

Evidently, in isotopes of higher atomic number Z, the Coulomb electrostatic repulsive force becomes predominant, and hence the number of neutrons must be made greater to compensate the repulsive effect. Thus the curve of Figure 1.7 bends more and more when Z increases.

For maximum stability of the isotopes, there must be an optimum value of neutron/proton rati It is concluded that for the light stable nuclei such as $_6C^{12}$ and $_8O^{16}$ the neutron/proton ratio is For nuclei heavier than $_{20}Ca^{40}$ the ratio increases slowly towards 1.6. All nuclei with $Z > 83$ ar $A > 209$ spontaneously transform themselves into lighter ones after emitting alpha or beta particl followed by a gamma emission.

1.9 NUCLEAR FORCES

A nucleus consists of positively charged protons and neutrally charged neutrons. Due to the positi charges of protons, there will be repulsive electrostatic forces between protons and eventually th nucleus will become unstable.

Since the* nucleus is stable with protons and neutrons, there should be certain forces acting c the nucleons to bind them inside the nucleus. These forces are known as nuclear force
* These nuclear forces are strongly attractive in order to overcome the electrostatic attractive force c repulsion between the protons.

* There are three kinds of attractive forces in the nucleus namely, (i) neutron–neutron (n–n) forc
ii) neutron–proton (n–p) force and proton–proton (p–p) (iii) force. The nuclear* forces have the followin characteristics.

1. *The nuclear forces are short range forces*. Nuclear forces are effective within the nucleus c radius 10^{-15}m and the Coulomb repulsive force becomes predominant outside the nucleus The distance 10^{-15}m is known as the range of nuclear forces. A graph of Coulomb repulsive an short-range forces of attraction is shown in Figure 1.8.

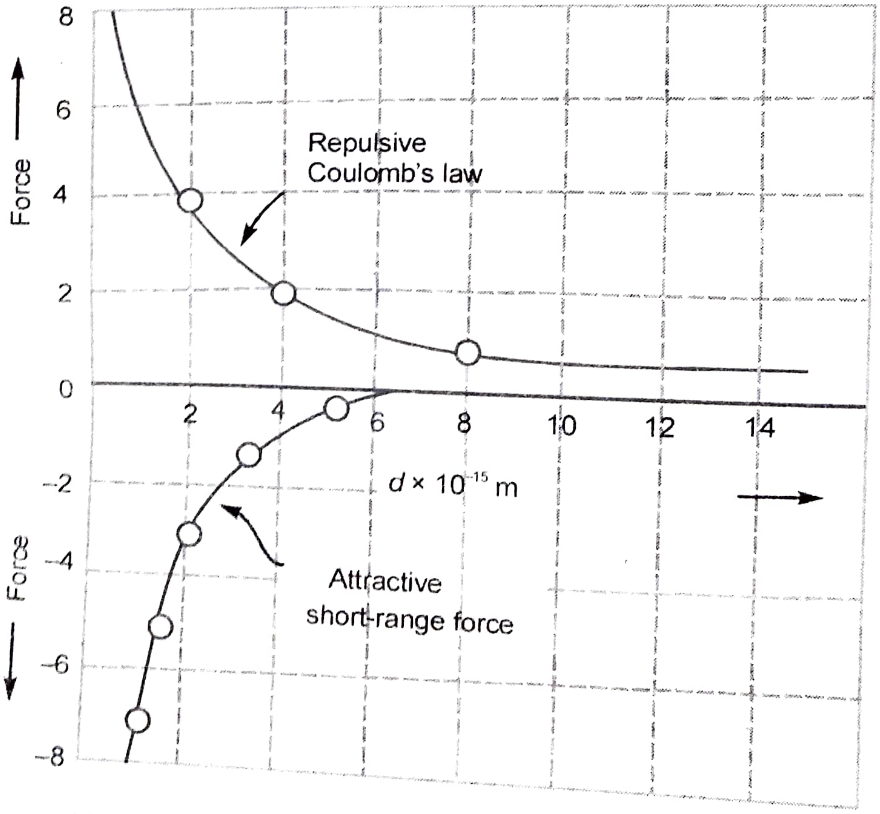


Figure 1.8 Coulomb repulsive and short-range forces of attraction

2. *Nuclear forces are charge-independent.* The nuclear forces acting between two protons or between two neutrons or between a proton and neutron are the same. Hence, it is understood that nuclear forces are charge-independent and they are not electric in nature.

3. *Nuclear forces are the strongest forces.* Nuclear forces are the strongest ever known forces. They are stronger than other known forces like electrostatic force and gravitational force. Nuclear forces are 10^{40} times stronger than gravitational force.

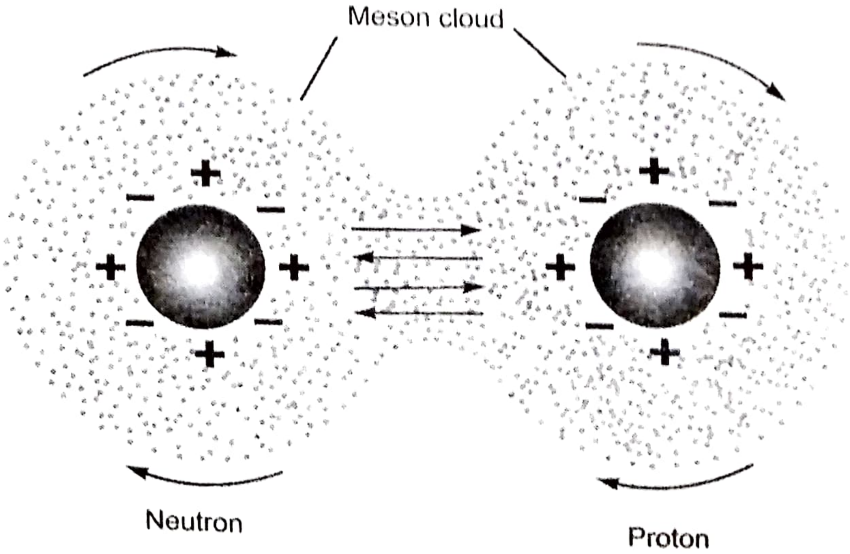
4. *Nuclear forces have saturation property.* Nuclear forces are limited in the range. As a result, each nucleon interacts with only a limited number of nearest neighbours in just the same way as molecules in a liquid interact with neighbouring molecules. This effect is known as the saturation effect of nuclear forces.

1.9.1 MESON THEORY OF NUCLEAR FORCES

1* In 1935, Yukawa proposed a theory to explain the binding forces between neutrons and protons known as meson theory of nuclear forces. According to this theory, there exists a meson cloud surrounding the neutrons and protons as 2* shown in Figure 1.9.

3* According to Yukawa's theory every nucleon continually emits and re-emits π-mesons. If another nucleon is nearby, an emitted π-meson may shift across to it instead of returning to its parent nucleon. The associated transfer of momentum is equivalent to the action of force.

4 Nuclear forces are attractive when the nucleons are at shorter distances and are repulsive when they are at greater distances. One of the strengths of the meson theory of such forces is that it can account for both attractive and repulsive properties. There is no simple way to explain this notion formally, but a rough analogy may make it less mysterious.



Story Telling

Figure 1.9 Nucleus surrounded by meson cloud

Let us imagine two boys exchanging basket ball. If they throw the balls to each other, the boys move backwards and when they catch the balls thrown at them, their backward momentum increases. Thus this method of exchanging basket ball yields the same effect as the repulsive force between the boys (as shown in Figure 1.10).

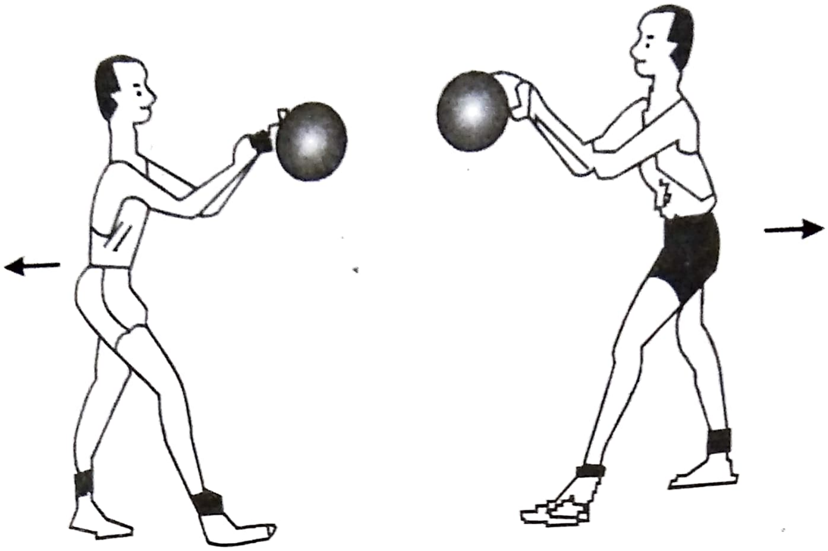


Figure 1.10 Repulsive force

If the boys snatch the basket balls from each other's hands, the result will be equivalent to an attractive force acting between them (as shown in Figure 1.11).

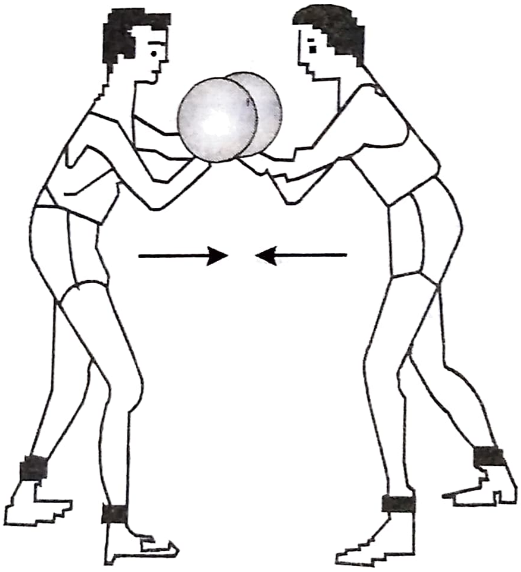


Figure 1.11 Attractive force

There are three kinds of mesons existing in the meson cloud namely positively charged, negatively charged and neutrally charged mesons. The theory also predicts that protons and neutrons do not have their independent existence inside the nucleus. The mesons are supposed to exchange between nucleons, thereby changing their identity equally fast and responsible for making the nucleons to be bound inside the nucleus.

Interaction of π-mesons Yukawa assumed that the mesons are exchanged between the nucleons and this exchange is responsible for the nuclear binding forces. The forces between one neutron and another (*n–n* force) and between one proton and another (*p–p* force) are the result of the exchange of neutral mesons (π^0) between them. The forces between a neutron and proton is the result of exchange of charged mesons (π^+ and π^-) between them.

$$\because \left[\mu = \frac{mc}{h/2\pi}\right] \qquad \left[\nabla^2 - \frac{m^2c^2}{h/2\pi} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right]\phi = 0 \text{ ①}$$

2 Thus a neutron emits a π⁻ meson and is converted into a proton.

$$\left[\nabla^2 - \mu^2\right]\phi(r) = 0 \text{ ②}$$

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

3 The absorption of the π⁻ meson by a proton converts it into a neutron.

$$\phi(r) = -g\frac{e^{-\mu r}}{r} \text{ ③}$$

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

$$\text{Potential} = V(r) = -g^2\frac{e^{-\mu r}}{r} \text{ ④}$$

4 In the reverse process, a proton emits a π⁺-meson and is converted into a neutron.

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

5 Similarly, the absorption of the π⁺-meson by a neutron converts it into a proton.

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

Thus in the nucleus of an atom, there exist three kinds of attractive forces between neutron and neutron and proton and proton and proton and neutron. These forces are responsible for the stability of the nucleus. The π-mesons remain free for an extremely short time and are undetectable. During the very short period of time, they violate the law of conservation of energy and that is why π-mesons are called virtual mesons.

Mass of mesons in nucleus According to uncertainty principle, $\Delta E.\Delta t \geq \frac{h}{2\pi}$ ✓

$$m_\pi c^2 \Delta t \geq \frac{h}{2\pi} \quad \text{where, } \Delta E = m_\pi c^2$$

If mesons travel with the velocity of light as might be expected for a field particle, and the range of nuclear force is $R = 1.4 \times 10^{-15}$ m, then the mass of the meson can be calculated as

$$m_\pi = \frac{h/2\pi}{c^2\Delta t} = \frac{h/2\pi}{Rc} \quad \text{where } \Delta t = \frac{R}{c}$$

In terms of electronic mass, the mass of meson is found as

$$m_\pi = \frac{h/2\pi}{c^2\Delta t} = \frac{h/2\pi}{Rc}$$

$$\frac{m_\pi}{m_e} = \frac{h/2\pi}{m_e Rc} = \frac{1.054 \times 10^{-34}}{(9.1 \times 10^{-31})(1.4 \times 10^{-15})(3 \times 10^8)} = 275$$

Hence, $m_\pi = 275 m_e$

✓ The mass of meson is thus calculated to have a value 275 times the mass of an electron. In 1947, Powell discovered that the mass of π-meson is about 273 times the mass of an electron. This particle showed strong interaction with nucleons and is recognized as the Yukawa particle.

The discovery of the meson of mass 273 times the electron mass and the existence of positive, negative and neutral mesons has given some support to the meson theory of nuclear forces.

Magnetic moment of neutron The experimental value of magnetic moment of a free neutron have some support to the meson theory of nuclear forces. A free neutron is for part of its life time dissociated into a proton and negatively charged meson. This combination will have a negative magnetic moment. It follows that though uncharged, a neutron will have a negative magnetic moment.

1.10 NUCLEAR MODELS

To explain various nuclear phenomena, various nuclear models have been proposed. Out of these models, the two which are more important and widely accepted are liquid drop model and shell model. The liquid drop model is designed based on the extrinsic analogy between the properties of atomic nuclei and the liquid drop. The shell model is proposed based on the electronic shell structure. These nuclear models explain many of the salient features of the nucleus like, nuclear stability, fission process, spin, parity, magnetic moment, nuclear isomerism, stripping reaction, etc.

1.10.1 Liquid Drop Model

In 1936, Neils Bohr proposed the liquid drop nuclear model. In liquid drop model, the forces acting inside the nucleus are assumed to be analogous to the molecular forces in a droplet of liquid (Figure 1.12). Neils Bohr has observed that there are certain similarities between an atomic nucleus and a liquid drop. Using liquid drop model, the calculation of atomic masses and binding energies can be done with good accuracy. In 1939, Bohr and Wheeler have given the first thorough theoretical treatment of the fission process based on the liquid drop model. However, this model fails to explain the extraordinary stability of certain nuclei, spin and magnetic moment.

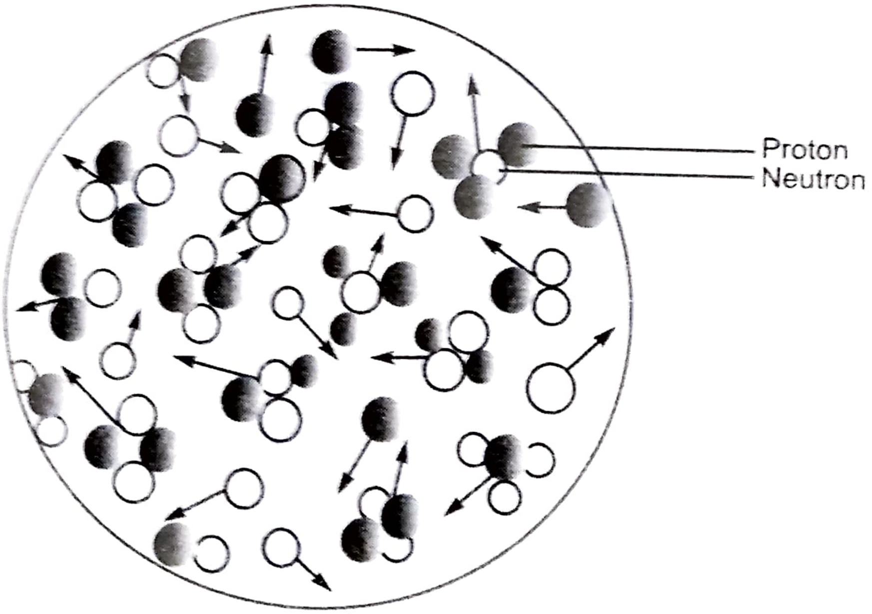


Figure 1.12 Liquid drop model

Spherical shape The nucleus is supposed to be spherical in shape in the stable state, just as the liquid drop is spherical due to the symmetrical surface tension forces.

Surface effect The force of surface tension acts on the surface of the liquid drop. Similarly, there is a potential barrier at the surface of the nucleus.

1.10.2 WIEZSÄCKER SEMI-EMPIRICAL MASS FORMULA FOR BINDING ENERGY

The liquid drop model can be applied to obtain expression for the binding energy of the nucleus. Wiezsäcker proposed the semi-empirical mass formula for binding energy for a nucleus of mass number A containing Z protons and N neutrons. The proposed Weizsäcker mass formula is written as

$$\text{Binding energy} = aA - bA^{2/3} - \frac{cZ(Z-1)}{A^{1/3}} - \frac{d(N-Z)^2}{A} \pm \frac{\delta}{A^{3/4}}$$

where a, b, c, d and δ are constants. The best values of the constants expressed in MeV are $a = 15.760$, $b = 17.810$, $c = 0.711$, $d = 23.702$ and $\delta = 34$. The formula is not an exact expression but is fairly valid for mass numbers $A > 15$. According to Wiezsäcker, the total binding energy of a nucleus consists of volume energy, surface energy, Coulomb energy, asymmetry energy and pairing energy.

Volume energy The first term in the above formula is called the volume energy of a nucleus which is is given as $E_V = aA$. Thus, the volume energy is more for a nucleus with higher mass number. The larger the total number of nucleons A, the more difficult it will to remove the identical protons and neutrons from the nucleus.

Surface energy Nucleus of an atom has some nucleons on its surface. The nucleus on the surface is attracted less strongly compared to nucleons in the interior, since the nucleons in the interior of a liquid is attracted equally in all directions due to other surrounding nucleons. It is concluded that the nucleons at the surface of the liquid are bound less tightly giving rise to a slight reduction in the total binding energy of the nucleus. The number of nucleons on the surface depends on the surface area of the nucleus. A nucleus of radius R has a surface area of $4\pi R^2 = 4\pi r_0^2 A^{2/3}$. Hence, the surface energy reduces the binding energy by $E_s = bA^{2/3}$. The surface energy is more significant for light nuclei, since a greater fraction of their nucleons are on the surface.

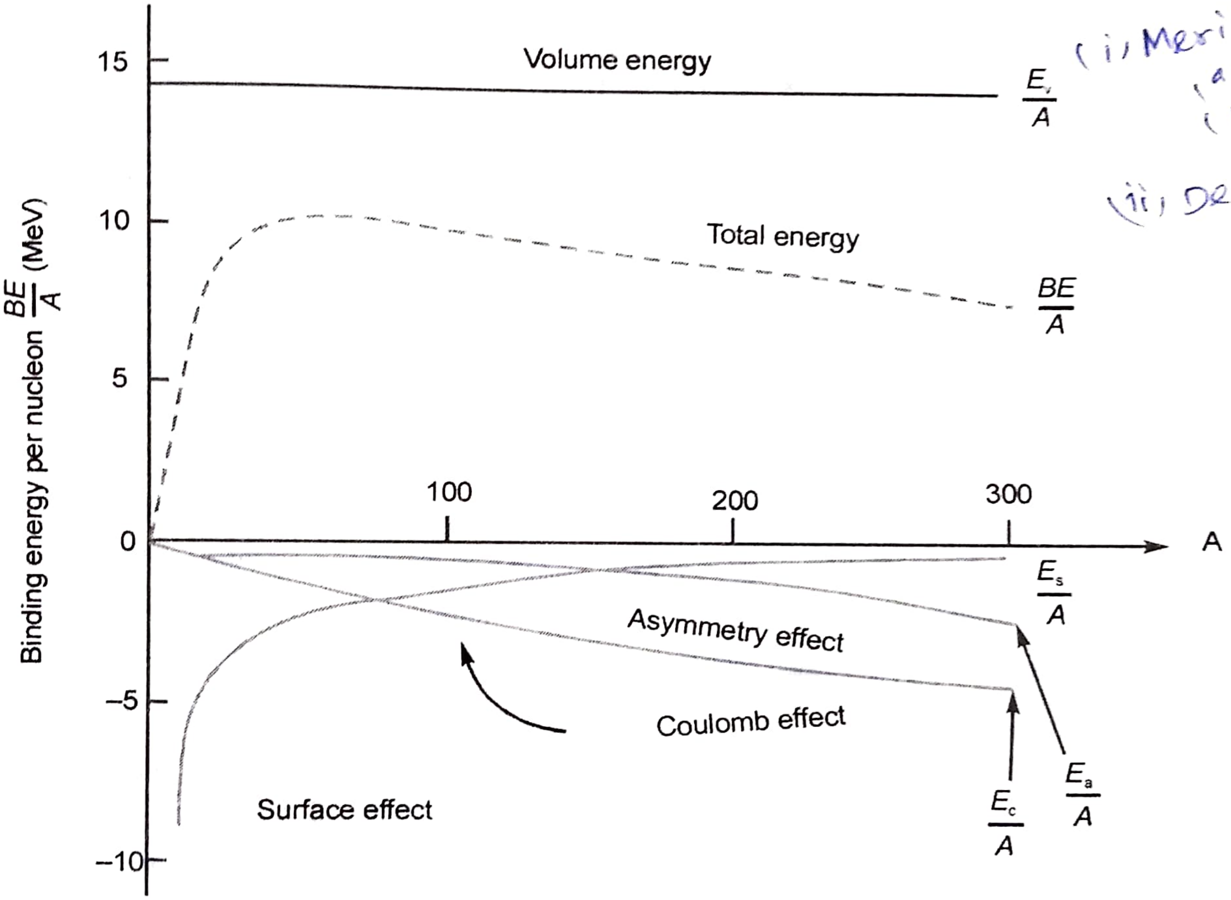
Coulomb energy The Coulomb electrostatic repulsive forces are produced due to the mutual repulsion of protons which are positively charged particles of the nucleus. These repulsive forces reduce the binding energy of the nucleus. Assuming that the nuclear charge Ze is uniformly distributed throughout the nuclear volume, the electrostatic potential energy is given by $\frac{3}{5}\frac{Z^2e^2}{R}$. The Coulomb repulsive force is proportional to the electrostatic potential energy and hence the Coulomb repulsive energy E_c is written as $E_c = \text{constant} \times \frac{3}{5}\frac{Z^2e^2}{R} = \text{constant} \times \frac{3}{5}\frac{Z^2e^2}{r_o A^{1/3}} = c\frac{Z(Z-1)}{A^{1/3}}$. The Coulomb energy E_c is negative because it arises from the force that opposes the nuclear stability.

Asymmetry energy It has been observed that nuclei are stable when nucleus contains equal number of protons and neutrons. Hence, the condition for a nucleus to be stable is $Z = N$. But in the nuclei of elements of higher atomic number, the number of neutrons is more than the number of protons. The excess number of neutrons over protons = $(N - Z)$. This increase in number of neutrons reduces the binding energy of the nuclei and this effect is called the asymmetry effect. It has been observed that the contribution of asymmetry effect to the binding energy of the nucleus is given by

$E_a = d\dfrac{(N-Z)^2}{A}$. The asymmetry energy is zero for nuclei having equal number of protons and neutrons ($N = Z$).

Pairing energy It has been observed that nuclei containing even number of protons and even number of neutrons are most stable. On the other hand, nuclei containing odd number of protons and odd number of neutrons are least stable. Moreover, nuclei containing even number of protons and odd number of neutrons or vice versa have intermediate stability. Hence, the pairing energy is positive for even–even nuclei, is negative for odd–odd nuclei and zero for odd A.

The contributions of the various effects in Weizäcker's empirical formula are represented schematically in Figure 1.14.



(i) Merits
(a)
(b)
(ii) De-merits
(a)
(b)

✓

Figure 1.14 The contributions of the various effects in Weizsäcker's formula

1.10.3 SHELL MODEL

The nuclear shell model is able to explain several nuclear phenomena like nuclear stability, spin, magnetic moment, parity, nuclear isomerism, ~~stripping reaction,~~ etc.

In 1933, W.M.Elsasser first proposed the shell model. In 1948, Maria Goeppert Mayer developed the model and in 1949, O.Haxel, J.H.D.Jensen and H.E.Suess independently showed that the nuclei containing the following protons or neutrons exhibited very high stability.

Protons	2	8	20	28	50	82	
Neutrons	2	8	20	28	50	82	126

The numbers 2, 8, 20, 28, 50, 82 and 126 are popularly known as magic numbers and ar analogous to the atomic numbers of the inert gases. According to shell model, the nucleus is consistin of definite energy levels or shells similar to electron shells in an atom. The total number of proton and neutrons are distributed in different sets of energy levels (Figure 1.15). The number of proton and neutrons in each shell is limited based on Pauli's exclusion principle. The shells are considere to be filled when they contain specific number of protons or neutrons. The shell model is als referred to as independent particle model.

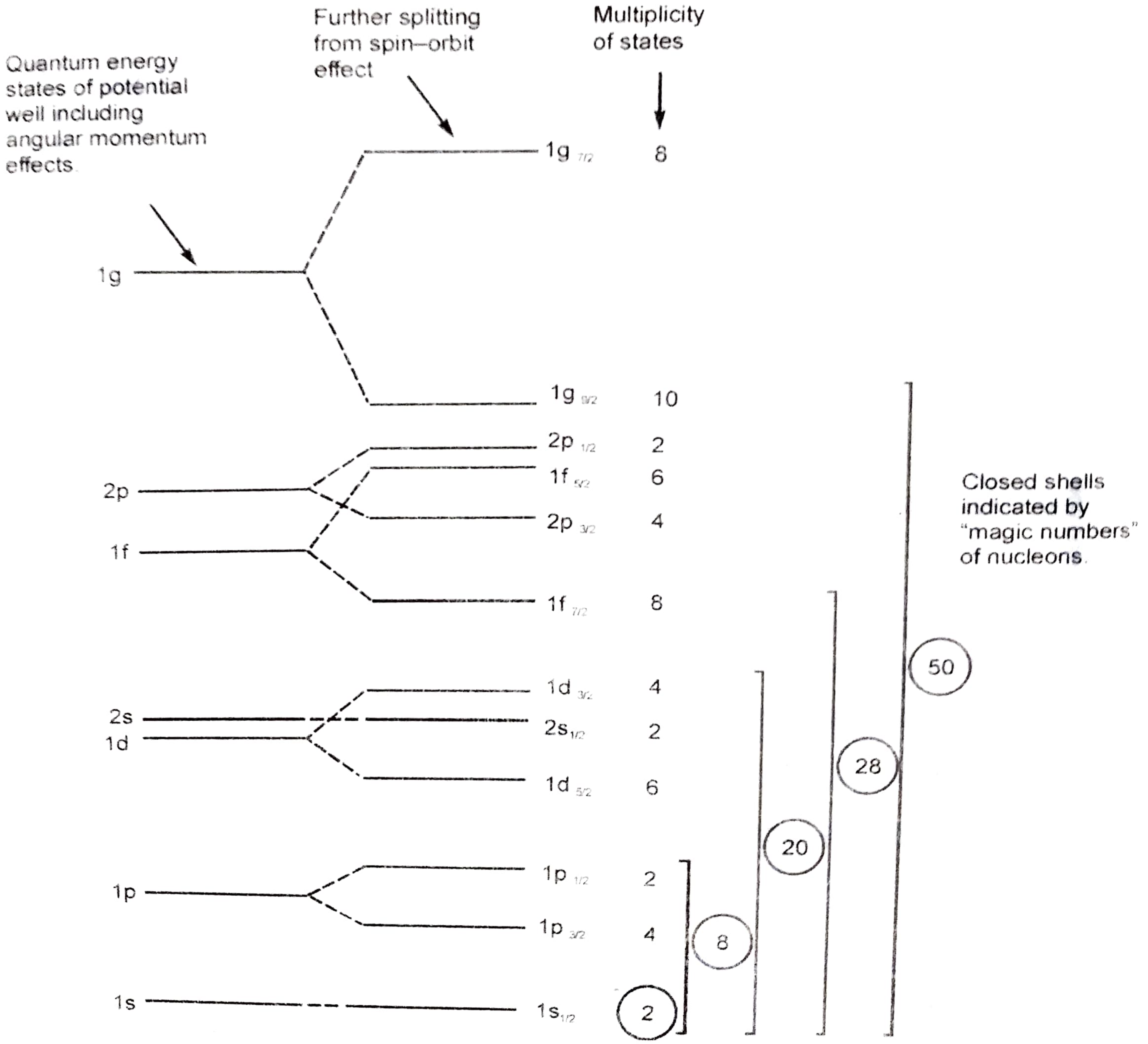


Figure 1.15 Sequence of energy levels

$$_{92}U^{238} + {_8O^{16}} \rightarrow {_{100}Fm^{252}} + 2\,{_0n^1}$$

$$_{92}U^{238} + {_8O^{16}} \rightarrow {_{100}Fm^{250}} + 4\,{_0n^1}$$

The name Fermium was given in honour of scientist Fermi.

Mendelvium (Md) 101 In 1955, Seaborg and others discovered this element by bombarding einsteinium with alpha particle of 48 MeV. The reaction is given below.

$$_{99}Es^{253} + {_2He^4} \rightarrow {_{101}Md^{256}} + {_0n^1}$$

The name Mendelivium was given in honour of scientist Mendeleev.

Nobelium (No) 102 In 1958, Ghiorso, Sikkeland and others discovered this element by bombarding $_{96}Cm^{246}$ with $_6C^{12}$ ions. The reaction is given below.

$$_{96}Cm^{246} + {_6C^{12}} \rightarrow {_{102}No^{254}} + 4\,{_0n^1}$$

The name Nobelium was given in honour of scientist Alfred Nobel.

Lawrencium (Lw) 103 In 1961, this element is discovered in Lawrence laboratory in California by bombarding Californium with $_5B^{11}$ ions. The reaction is given below.

$$_{98}Cf^{249} + {_5B^{11}} \rightarrow {_{103}Lw^{257}} + 3\,{_0n^1}$$

The name Lawrencium was given in honour of scientist Lawrence.

Kurchatovium (Kv) 104 In 1965, Flerov and others discovered this element by bombarding $_{94}Pu^{242}$ with accelerated $_{10}Ne^{22}$ ions. The reaction is given below.

$$_{94}Pu^{242} + {_{10}Ne^{22}} \rightarrow {_{104}Kv^{260}} + 4\,{_0n^1}$$

Hahnium (Ha) 105 In 1970, Ghiorso and others discovered this element at Lawrence radiation laboratory by bombarding $_{98}Cf^{249}$ with $_7N^{15}$ ions. The reaction is given below.

$$_{98}Cf^{249} + {_7N^{15}} \rightarrow {_{105}Ha^{260}} + 4\,{_0n^1}$$

The name Hahnium was given in honour of scientist Otto Hahn.

2.6 RADIOACTIVE LAW OF DISINTEGRATION

Rutherford and Soddy found that the rate of disintegration is independent of physical and chemical conditions. The rate of disintegration at any instant is directly proportional to the number of atoms of the element present at that instant. This is known as radioactive law of disintegration.

Let N_0 be the number of radioactive atoms present initially and N, the number of atoms at a given instant t. Let dN be the number of atoms undergoing disintegration in a small interval of time dt.

Then, the rate of disintegration $-\frac{dN}{dt}$ is proportional to N

or

$$-\frac{dN}{dt} = \lambda N \qquad (\;$$

where λ is a constant known as the disintegration constant or decay constant of th radioactive element.

$$\lambda = \frac{\left(-\frac{dN}{dt}\right)}{N} \qquad (\;$$

The decay constant is defined as the ratio of the amount of substance which disintegrates in un time to the amount of substance present.

Equation (1) can be written as

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

Integrating the above equation, we get

$$\log_e N = -\lambda t + C \qquad (3$$

where C is a constant of integration.

When time $t = 0$, the number of radioactive atoms present in the specimen at that instant N should have been N_0 only, hence when $t = 0, N = N_0$. Substituting this condition in equation (3) we get,

$$\log_e N_0 = C$$

Substituting the value of C in equation (3) we get,

$$\log_e N = -\lambda t + \log_e N_o$$

or

$$\log_e \frac{N}{N_o} = -\lambda t \qquad (4)$$

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

From the above equation, it is understood that the number of atoms of a given radioactive substance decreases exponentially with time (Figure 2.7).

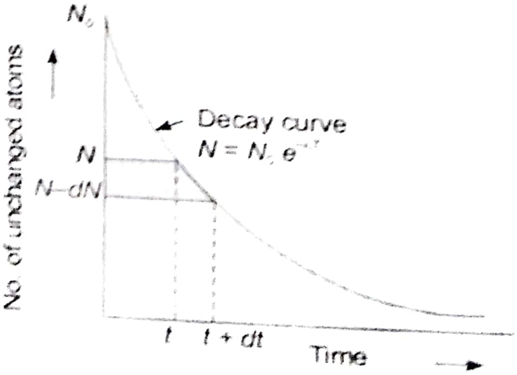


Figure 2.7 Radioactive disintegration curve

$$\lambda = \frac{\left(\frac{-dN}{dt}\right)}{N}$$

where,

dN/dt is the ratio of amount of substance which disintegrates in unit time and N is the amount of substance present at that instant.

2.6.2 HALF-LIFE PERIOD

The half-life period of a radioactive substance is defined as the time required for one half of a radioactive substance to disintegrate.

In a radioactive element at the end of one half-life period $T_{1/2}$, 50% of the radioactive atoms remain radioactive, at the end of $2T_{1/2}$, 25% of the atoms remain radioactive, after $3T_{1/2}$, only 12.5%, after $4T_{1/2}$,6.25% and so on.

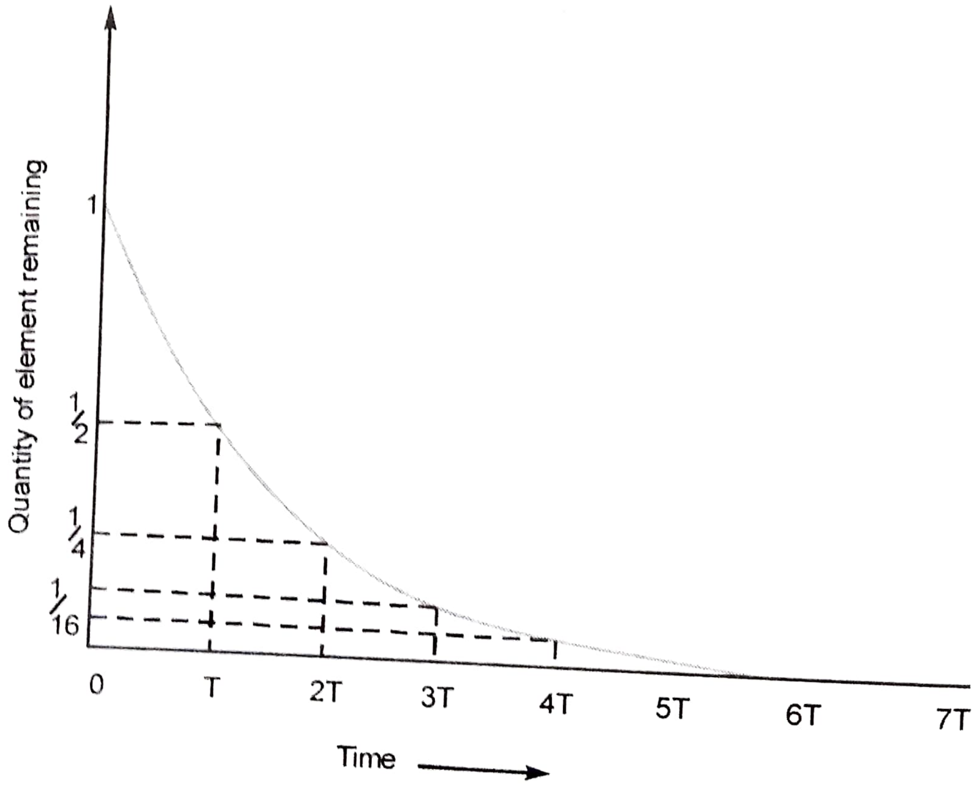


Figure 2.8 Radioactive disintegration with half-lives

According to the radioactive law of disintegration,

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

If $T_{1/2}$ is the half-life period, then at $t = T_{1/2}$, $N = \frac{N_0}{2}$, the above equation becomes

$$\lambda = \frac{1}{5}\log_e\left(\frac{1}{0.9979}\right) = \frac{2.3026}{5}\log_{10}\left(\frac{1}{0.9979}\right) = 41.45\times10^{-5} \text{ per year}$$

$$\text{Half-life period } T_{1/2} = \frac{0.6931}{41.45\times10^{-5}} = 1672 \text{ years.}$$

2.6.3 THE MEAN-LIFE PERIOD

When the radioactive substance is undergoing disintegration, the atom which disintegrates first has zero life and that which disintegrates last has infinite life. Thus, the actual life of each atom ranges from zero to infinity.

The mean-life of a radioactive substance is defined as the ratio of total life time of all the radioactive atoms to the total number of atoms in it.

$$\text{Mean-life of radioactive element} = \frac{\text{Total lives of all the radioactive atoms}}{\text{Total number of atoms}}$$

Let dN atoms disintegrate between the time t and $t + dt$. It means that dN atoms have lived for a time t and therefore the total life of dN atoms is $(dN)t$. The possible life of the total number of atoms to disintegrate varies from zero to infinity.

$$\text{The total life of all the atoms in the element} = \int_0^\infty t\,dN$$

$$\text{The total number of radioactive atoms} = N_0$$

$$\text{Mean-life period} = \frac{\int_0^\infty t\,dN}{N_0}$$

Let N_0 be the total number of radioactive atoms in the beginning and N be the number of atoms of that element after time t. Then,

$$N = N_0 e^{-\lambda t}$$

$$\frac{dN}{dt} = -\lambda N_0 e^{-\lambda t}$$

$$dN = -\lambda N_0 e^{-\lambda t}\,dt$$

The negative sign is omitted because it merely indicates the decrease in the number of atoms with time.

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The mean-life period $\bar{T} = \dfrac{\int_0^\infty t\lambda N_o e^{-\lambda t}\,dt}{N_o} = \lambda\int_0^\infty te^{-\lambda t}\,dt$

Integrating by parts,

$$\bar{T} = \lambda\left[\frac{te^{-\lambda t}}{-\lambda} - \int\frac{e^{-\lambda t}}{-\lambda}dt\right]_o^\infty = \lambda\left[\frac{te^{-\lambda t}}{-\lambda} - \frac{e^{-\lambda t}}{-\lambda^2}\right]_0^\infty = \lambda\left(\frac{1}{\lambda^2}\right) = \frac{1}{\lambda}$$

Thus the mean-life period of a radioactive substance is the reciprocal of the decay constant. From the equations of half-life and mean-life period, we can write

Half-life period $T_{1/2} = \dfrac{0.6931}{\lambda} = 0.6931\bar{T}$ = 69.3% of mean-life period (where $\bar{T}$ is mean-life period).

Example 2.5 The disintegration constant of a radioactive element is 0.00231 per day. Calculate its half-life and mean-life.

Solution The disintegration constant $\lambda = 0.00231$

$$\text{The half-life period } = T_{1/2} = \frac{0.6931}{\lambda} = \frac{0.6931}{0.00231} = 300 \text{ days}$$

$$\text{The mean-life period } = \bar{T} = \frac{1}{\lambda} = \frac{1}{0.00231} = 432.9 \text{ days}$$

Example 2.6 1 g of a radioactive substance disintegrates at the rate of 3.7×10^{10} disintegrations per second. The atomic weight of the substance is 226. Calculate the mean-life.

Solution The number of atoms disintegrated in 1 second = 3.7×10^{10}

$$\text{The mass of the substance disintegrated in 1 second } = \frac{3.7\times10^{10}\times226}{6.023\times10^{23}} = 1.38\times10^{-11}\text{ g}$$

Here, $N = 1\text{ g}$ and $\dfrac{dN}{dt} = 1.38\times10^{-11}\text{ g}$

$$\text{The disintegration constant } \lambda = \frac{\left(\frac{dN}{dt}\right)}{N} = \frac{1.38\times10^{-11}}{1} = 1.38\times10^{-11}\text{ per second}$$

$$\text{The mean-life } \bar{T} = \frac{1}{\lambda} = \frac{1}{1.38\times10^{-11}} = 7.197\times10^{10}\text{ s} = \frac{7.197\times10^{10}}{86400\times365}\text{ years}$$

The mean-life = 2262 years.

2.7 LAW OF SUCCESSIVE DISINTEGRATION

Successive disintegration means a process in which a radioactive substance disintegrates to form a new substance, which again disintegrates to form another substance and so on. Consider a radioactive substance A which after an interval t decays to form another substance B. Let the substance B decay to form another substance C and so on. In a radioactive series, any two adjacent elements are considered as parent and daughter. Evidently, the parent of the present element should have been the daughter of the previous element.

Radioactive decay and growth At time $t = 0$, the number of initial atoms present in element A = N_0 and the number of initial atoms present in element B = 0.

At time t, the number of atoms present in element A = N_1 and the number of atoms present in element B = N_2.

Let λ_1 and λ_2 be the decay constants of elements A and B respectively. Every time an atom of element A disappears and an atom of element B is produced.

∴ The rate of formation of daughter element B = $\lambda_1 N_1$.

The rate at which the element B decays = $\lambda_2 N_2$

The net increase in the number of atoms in element B $= \frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2$

Hence, $\frac{dN_2}{dt} = \lambda_1 N_0 e^{-\lambda_1 t} - \lambda_2 N_2$ since $N_1 = N_0 e^{-\lambda_1 t}$

$$\frac{dN_2}{dt} + \lambda_2 N_2 = \lambda_1 N_0 e^{-\lambda_1 t}$$

Multiplying both sides by the factor $e^{\lambda_2 t}$

$$\frac{dN_2}{dt} e^{\lambda_2 t} + \lambda_2 N_2 e^{\lambda_2 t} = \lambda_1 N_0 e^{(\lambda_2 - \lambda_1)t}$$

$$\frac{d}{dt}\left[N_2 e^{\lambda_2 t}\right] = \lambda_1 N_0 e^{(\lambda_2 - \lambda_1)t}$$

Integrating the above equation, we get

$$N_2 e^{\lambda_2 t} = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_0 e^{(\lambda_2 - \lambda_1)t} + C \qquad (1)$$

When $t = 0$, $N_2 = 0$, substituting this condition in the above equation we get,

$$C = \frac{-\lambda_1 N_0}{\lambda_1 - \lambda_2}$$

Substituting the value of C in equation (1) we get, Hence, the potential barrier for an alpha particle with charge 2e is found to be approximately 30 MeV.

Frequency of wave of alpha particles The escape of alpha particles from a radioactive nucleus can be explained on the basis of quantum mechanics. According to quantum wave mechanics, particles with very high speed will behave like a waveform. Thus the alpha particles in unstable nuclei behave like waveform. Then the frequency of alpha particles with energy 4 MeV is calculated as follows.

$$E = h\nu = 4\ \text{MeV} = 4\times 10^{6}\times 1.6\times 10^{-19}\ \text{J}$$

$$\nu = \frac{E}{h} = \frac{4\times 10^{6}\times 1.6\times 10^{-19}}{6.625\times 10^{-34}} = 0.9660\times 10^{21}\ \text{Hz}$$

According to the above calculation, the frequency of the wave of alpha particles with energy 4 MeV is found to be 10^{21} Hertz. It means that the wave of the alpha particles is able to hit the walls of the potential barrier of the nucleus again and again for 10^{21} times per second until the conditions are ripe for penetration or leakage. Eventually the alpha particles are emitted from the nucleus. This effect is known as the tunnelling effect.

3.1.9 GAMOW'S THEORY OF ALPHA DECAY

Classical physics fails to explain the emission of alpha particles. Quantum mechanics provides a successful explanation for the problem of alpha emission. According to the quantum wave mechanics, the alpha particles are in constant motion inside the nucleus and bounces back and forth from the walls of the potential barrier.

In short, the alpha particles behave like a wave form inside the nucleus. In each collision with the walls of the potential barrier, there is a probability that the particle leak through the barrier. Gamow gave the theory of alpha decay by deriving an expression for the probability of alpha emission.

Tunnelling effect Figure 3.8 illustrates the variation of potential energy with respect to distance from 0 to radius of the nucleus (R) and above (R_1). In the figure, $V(r)$ represents the height of potential barrier and T represents the kinetic energy of alpha particle. As the height of potential barrier is very much higher than the kinetic energy of the alpha particle, according to classical physics the probability of alpha emission is zero.

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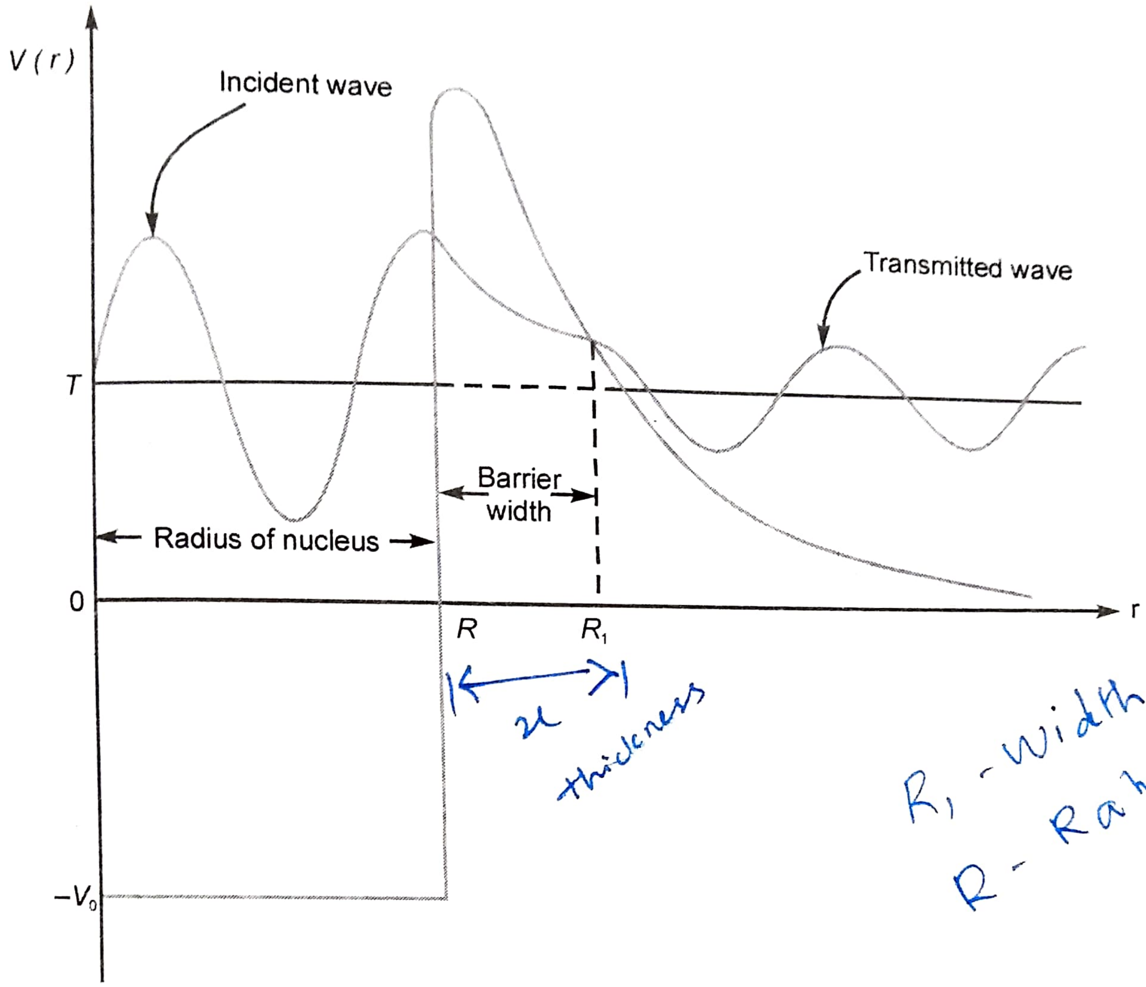
✓ But in quantum mechanics, a moving particle is ~~regarded as a wave and~~ bounces back and forth from the wall of the potential barrier. In each collision with the wall of the potential barrier, there is a definite probability that the alpha particles leak through the barrier. This effect is known as the tunnelling effect.

The probability P can be calculated quantum mechanically using WKB perturbation theory.

Probability of alpha emission Let ν be the frequency with which the alpha particle collides with the walls of the potential barrier in order to escape from the nucleus. The frequency of the alpha particles is given by the relation $\nu = v/2R$, where v is the velocity and $2R$ is the nuclear diameter.



R_1 - width of P.B
R - Radn

Figure 3.8 Alpha particle tunnelling

Let P be the probability of transmission in each collision. Then the decay probability per unit time is given by $\lambda = \nu P$, where, λ is disintegration constant.

According to this theory

$$\log_e P = \frac{-2}{(h/2\pi)} \int_R^{R_1} \sqrt{2m(V-T)}\,dx$$

Where m is the mass of alpha particle and $V = \dfrac{2Ze^2}{4\pi\varepsilon_o x}$ is the electrostatic potential energy of an alpha particle of charge $2e$ at a distance x from the centre of a daughter nucleus of charge Ze, R is the radius of the nucleus, T is the kinetic energy of the particle which is less than the potential energy and the region from $x = R$ to R_1 is called the thickness of the barrier or barrier width.

$$\log_e P = \frac{-2}{(h/2\pi)} \int_R^{R_1} \sqrt{2m\left(\frac{2Ze^2}{4\pi\varepsilon_o x} - T\right)}\,dx$$

When $x = R_1$, $T = V$ and $T = \dfrac{2Ze^2}{4\pi\varepsilon_o R_1}$, the above equation becomes,

$$\log_e P = \frac{-2}{(h/2\pi)} \int_R^{R_1} \sqrt{2m\left(\frac{2Ze^2}{4\pi\varepsilon_o x} - \frac{2Ze^2}{4\pi\varepsilon_o R_1} T\right)} dx$$

$$\log_e P = \frac{-2}{(h/2\pi)} (2mT)^{1/2} \int_R^{R_1} \left(\frac{R_1}{x} - 1\right)^{1/2} dx$$

$$\log_e P = \frac{-2}{(h/2\pi)} (2mT)^{1/2} R_1 \left[\cos^{-1}\left(\frac{R}{R_1}\right)^{1/2} - \left(\frac{R}{R_1}\right)^{1/2} \left(1 - \frac{R}{R_1}\right)^{1/2}\right]$$

The width of the potential barrier is very large compared with the nuclear radius, that is $R_1 \succ R$.

Since, $$\left[\cos^{-1}\left(\frac{R}{R_1}\right)^{1/2} = \frac{\pi}{2} - \left(\frac{R}{R_1}\right)^{1/2}\right] \text{and} \left[1 - \left(\frac{R}{R_1}\right)^{1/2} = 1\right]$$

We have, $$\log_e P = \frac{-2}{(h/2\pi)} (2mT)^{1/2} R_1 \left[\frac{\pi}{2} - 2\left(\frac{R}{R_1}\right)^{1/2}\right]$$

Substituting $R_1 = \dfrac{2Ze^2}{4\pi\varepsilon_o T}$ in the above equation, we get

$$\log_e P = \frac{4e}{(h/2\pi)} \left(\frac{m}{\pi\varepsilon_o}\right)^{1/2} Z^{1/2} R^{1/2} - \frac{e^2}{(h/2\pi)\varepsilon_o} \left(\frac{m}{2}\right)^{1/2} ZT^{-1/2}$$

Substituting the values of constants, we get

$$\log_e P = 2.97 Z^{1/2} R^{1/2} - 3.95 Z T^{-1/2}$$

where R is in fermi and T is in MeV.

Thus from the above equation the probability of alpha emission from a radioactive element can be calculated by substituting the values of nuclear radius R, atomic number Z and the kinetic energy T of the alpha particle.

Disintegration constant The equation for disintegration constant can be derived based on the equation for the probability of alpha emission. From the equation for the disintegration constant, it is possible to find many parameters of the radioactive source material.

Disintegration constant $\lambda = \nu P$

Taking logarithm on both sides, we get,

$$\log_e \lambda = \log_e \nu + \log_e P = \log_e\left(\frac{\nu}{2R}\right) + \log_e P$$

$$\log_e \lambda = \log_e\left(\frac{\nu}{2R}\right) + 2.97Z^{1/2}R^{1/2} - 3.95ZT^{-1/2}$$

Changing the base of log from e to the base 10

$$\log_e \lambda = \log_e\left(\frac{\nu}{2R}\right) + 0.4343(2.97Z^{1/2}R^{1/2} - 3.95ZT^{-1/2})$$

$$\log_e \lambda = \log_e\left(\frac{\nu}{2R}\right) + 1.29Z^{1/2}R^{1/2} - 1.72ZT^{-1/2}$$

3.2 THE BETA RAYS

Beta particles emitted from a radioactive substance consist of fast moving electrons which are of nuclear origin without having any orbital motion. The mass of beta particle is 9.11×10^{-31} kg and the charge is 1.6×10^{-19} Coulomb. They are represented as ${}_{-1}e^0$ (Figure 3.9).

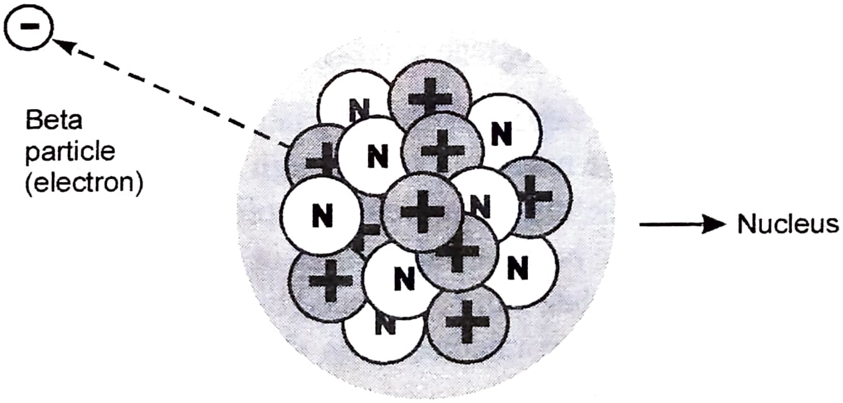


Figure 3.9 Representation of beta particle emission

Since beta particles consist of electrons, they are deflected by electric and magnetic fields. Their greater deflection in the electric field indicates that they are lighter than alpha particles.

The beta particles emitted from radioactive nucleus have a wide range of velocities. The velocities of beta particles range from 1% to 99% of the velocity of light. At high velocities, the e/m of beta particle is found to decrease indicating an increase in mass of the particle according to Einstein's equation $m = \dfrac{m_0}{\sqrt{1 - v^2/c^2}}$, where m_0 is the rest mass of electron, m is the mass of electron moving with velocity v and c is the velocity of light.

The first anomaly in beta decay is that the electrons emitted from the radioactive substance possess a continuous range of energies. That is, beta ray spectrum is a continuous spectrum. This violates the fact that nucleus exists in discrete energy states as stated in alpha decay.

The second anomaly in beta decay is that the angular momentum is not conserved. We know that beta particles are fermions and have a spin value of half. Thus when they are emitted from the nucleus, it should change the nuclear spin by half. But it is found that a nucleus has the same spin or an integral change of spin is observed. Thus the law of conservation of angular momentum is violated in beta decay.

The third anomaly in beta decay is that the law of conservation of linear momentum is violated.

Pauli's neutrino hypothesis In order to explain the anomalies mentioned above, in 1930 Pauli proposed a hypothesis known as neutrino hypothesis. According to this hypothesis, in the process of beta decay, another particle, which has a negligible mass as compared to electron, zero charge and spin half, is emitted with beta particles.

Neutrino travels with the velocity of light. This particle carries a part of available energy and momentum and is called neutrino. There are two kinds of neutrino involved in beta decay, one is antineutrino and the other is neutrino. Only in 1956 after 26 years, Pauli's hypothesis of existence of neutrino in beta decay has been experimentally proved.

3.2.4 FERMI THEORY OF BETA DECAY

Continuous spectrum In 1934, Fermi developed a theory to explain the continuous beta ray spectrum. This theory is called the neutrino theory of beta decay. According to this theory, a beta particle and a neutrino are created in the nucleus and both are emitted simultaneously.

In beta disintegration, the amount of energy released is equal to the end point energy. The energy is shared between beta particle and neutrino (Figure 3.12).

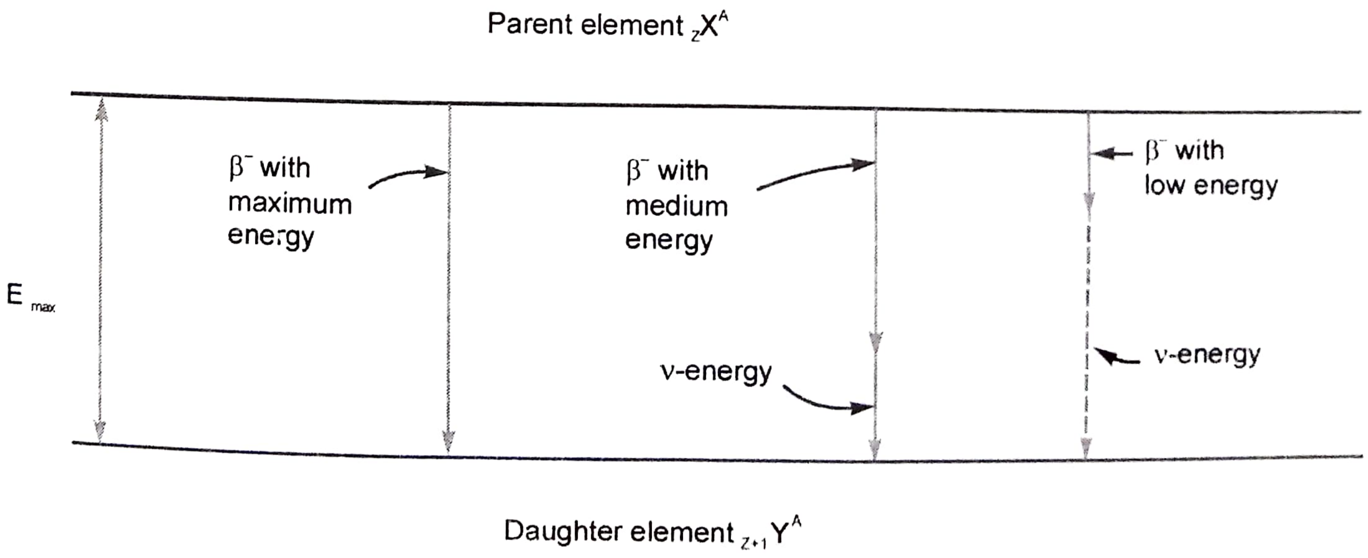


Figure 3.12 The sharing of the total disintegration energy between the beta particle and the neutrino

When neutrino gets no energy, beta particles are emitted with maximum energy or end point energy. When beta particles are emitted with medium energy, the neutrino gets some energy. In the lower limit of continuous spectrum, a greater amount of energy is shared by neutrino than the beta particles. Figure 3.12 explains how the total disintegration energy is shared between the beta particle and the neutrino. Thus the energy carried by neutrino varies continuously leaving beta particles of continuously varying energy and hence continuous spectrum.

Conservation of angular momentum When beta particles (electrons) are emitted from the nucleus, it should change the nuclear spin by half. But it is found that a nucleus has the same spin or an integral change of spin is involved. According to neutrino theory, in the process of beta decay, another particle which has a negligible mass as compared to electron, zero charge and spin half, is emitted with beta particles. Hence during beta decay, electron and neutrino are emitted both with spin half can carry zero or one unit of angular momentum when their spins are antiparallel and parallel respectively and the nuclear state have the same spin or differ by one unit.

Conservation of linear momentum When beta decay results in three particles namely a beta particle, a neutrino and a daughter nucleus, the available energy can be shared among the particles in a variety of ways still conserving the linear momentum.

The negative beta decay During negative beta decay, a nucleon shifts from the neutron quantum state to the proton quantum state, electron and antineutrino are emitted. This process is represented by

$$n \rightarrow {}_{-1}e^{0} + \bar{\nu}$$

Thus, negative beta decay can be represented by the following reaction.

$${}_{Z}X^{A} \rightarrow {}_{Z+1}X^{A} + {}_{-1}e^{0} + \bar{\nu}$$

The positive beta decay During positive beta decay, a nucleon shifts from the proton quantum state to the neutron quantum state, positron and neutrino are emitted. This process is represented by

$$p \rightarrow {}_{+1}e^{0} + \nu$$

Thus, negative beta decay can be represented by the following reaction.

$${}_{Z}X^{A} \rightarrow {}_{Z-1}X^{A} + {}_{+1}e^{0} + \nu$$

The electron, neutrino and the product nucleus share among them the energy, angular momentum and linear momentum available from the nuclear transitions. Thus, the neutrino theory of beta decay successfully explains the continuous spectrum of beta decay, angular momentum and linear momentum violations.

3.2.5 *K*-ELECTRON CAPTURE

In an excited nucleus, there is a possibility that a proton may be absorbing an electron and turning into a neutron. In an alternate case, an orbiting electron of the parent nucleus usually an electron in

4.3 IONIZATION COUNTERS

Ionization counters are designed based on the property that the radiating particles produce intense ionization in a gas through which they pass. The ionization counter consists of a gas-filled cylinder in which a wire is stretched at the centre. A high voltage is applied between the wall of the cylinder and the stretched wire. The radiating particles passed on to the gas-filled chamber ionize the gas molecules. The total charges produced by ionization are collected and measured. There are different types of ionization chambers devised based on the amount of voltage applied to the centre electrode and the consequent nature of the ionizing events.

If the voltage is high enough for the primary electron-ion pair to reach the electrodes but not high enough for secondary ionization, the device is called an ionization chamber.

The collected charge is proportional to the number of ionizing events, and such devices are typically used as radiation dosimeters. At a higher voltage, the number of ionizations associated with particle detection rises steeply because of secondary ionizations, and the device is often called a proportional counter.

A single event can cause a voltage pulse proportional to the energy loss of the primary particle. At a still higher voltage, an avalanche pulse is produced by a single event in the devices called Geiger counters.

4.3.1 Ionization Chamber

Principle The principle of ionization chamber is that charged particles in motion produce ionization in gases. The ionization varies with the nature and velocity of the charged particles. Hence, the number of pairs produced by the incident particles gives the information about the nature of the particles and their energy.

Types of ionization chambers The ionization chambers are of two types namely non-integrating or pulse type and integrating or current-measuring type. The non-integrating or pulse type of ionization chamber measures voltage pulses due to the entry of individual ionizing particles. The integrating or current-measuring type of ionization chamber measures the total quantity of charges due to the entry of ionization particles over a certain time interval.

Non-integrating ionization chamber

Description of the apparatus The non-integrating chamber consists of a hollow metallic cylindrical chamber closed at one end and the other end with a window through which incident particles enter. (Figure 4.1). A metal rod well insulated from the cylinder is mounted coaxially within the cylinder. The chamber is filled with a gas like sulphur dioxide or methyl bromide at a pressure of one atmosphere. A suitable voltage (250 V) is applied between the chamber like sulphur dioxide or methyl bromide and the central electrode so that the chamber wall acts as cathode and the central electrode acts as anode.

Working When the charged particles pass through the gas chamber, through the window the gas gets ionized and positive ion-electron pairs are produced. The positive ions go to the chamber walls and electron to the central electrode. This gives rise to an extremely short electric pulse of the order of 10^{-12} to10^{-15} ampere. This small electric pulse can be amplified by the amplifier and then passed on to a suitable electronic counter.

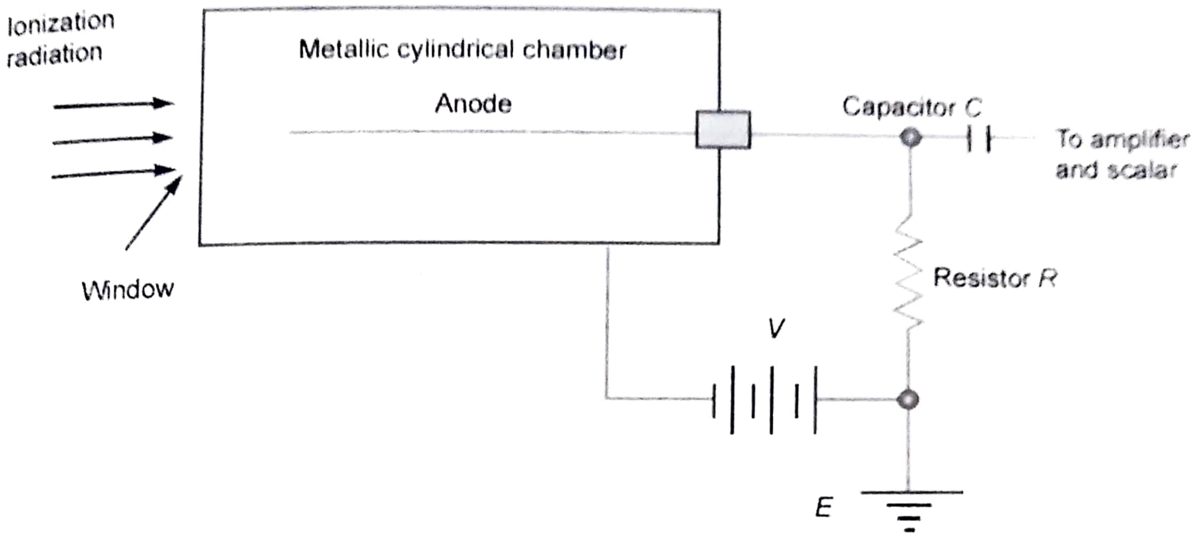


Figure 4.1 Pulse ionization chamber

Working voltage for ionization chamber When the applied voltage is low, many ions recombine before reaching the central wire and hence the current is small. But when the voltage is increased (250V), more and more ions reach the central wire and the current increases. When all the ions are collected by the central electrode, the current reaches the saturation value. The ionization chamber is designed to work in this voltage range.

Ionization chamber can be used to study alpha, beta, gamma particles, protons, electrons, X-rays and nuclei of lighter elements. Ionization chambers have been extensively used in the early studies of comic ray phenomenon.

Detection of neutron The ionization chamber can also be used to detect neutrons by filling the chamber with boron trifluoride vapour and the chamber walls are lined inside with a boron compound in the form of a paste. The incoming neutron causes the emission of alpha particle by bombarding with boron trifluoride molecule. The alpha particle is recorded as usual.

Integrating ionization chamber

Description of the apparatus The integrating chamber consists of a hollow metallic cylindrical chamber with two electrodes A and B placed at some distance from each other (Figure 4.2). A suitable potential difference is maintained between two electrodes by means of a battery. A resistance R is included between two electrodes.

Working When charged particles pass through the chamber through the window, they produce ionization of gas which results in ion pair formation. The ions are collected at the electrodes due to the potential established between them. Now a very weak and continuous current flows through the resistance R, and the current can be measured by a sensitive instrument. The strength of the current is found to be directly proportional to the rate at which ionization resistance (alpha, beta and gamma) is entering the ionization chamber.

Working voltage for proportional counter When the applied voltage is low, many ions recombine before reaching the central wire and hence the current is small. But when the voltage is increased (250 V), more and more ions reach the central wire and the current increases. When all the ions are collected by the central electrode, the current reaches the saturation value. The ionization chamber is designed to work in this voltage range.

When voltage is further increased (250 to 750 V), the electrons produced in primary ionization gain sufficient kinetic energy to produce secondary electrons by collisions with the atom of the gas. In this case, the current would be very large so that considerably less external amplification is required. Thus, the ionization counter is improved and proportional counter is designed to work in this voltage range.

Detection of neutron The proportional counter can also be used to detect neutrons by filling the chamber with boron trifluoride vapour and the chamber walls are lined inside with a boron compound in the form of a paste. The incoming neutron causes the emission of alpha particle by bombarding with boron trifluoride molecule. The alpha particle is recorded as usual.

4.3.3 GEIGER–MÜLLER COUNTER

Description of the apparatus The Geiger–Müller counter consists of a hollow metallic cylindrical chamber closed at one end and the other end with a window through which incident particles enter (Figure 4.4). A metal rod well insulated from the cylinder is mounted coaxially within the cylinder.

The chamber is filled with a mixture of 90% argon gas at 10 cm pressure and 10% ethyl alcohol vapour at 1 cm pressure. A suitable voltage (750 to 1500 V) is applied between the chamber and the central electrode so that the chamber wall acts as cathode and the central electrode as anode.

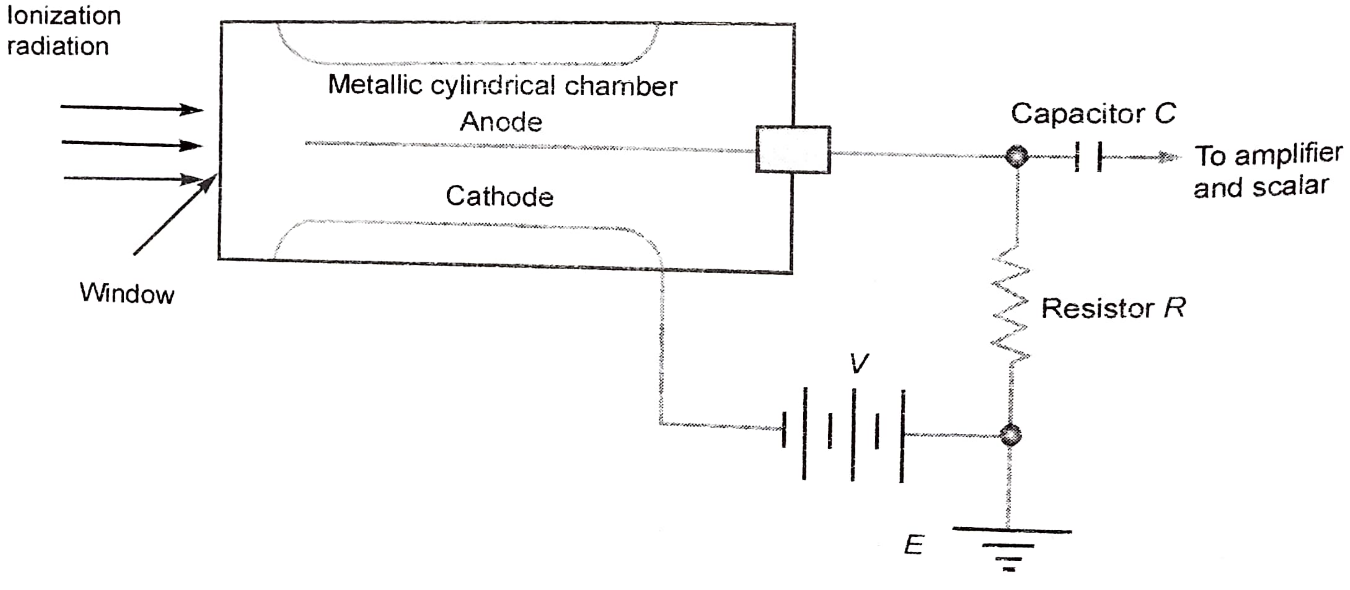


Figure 4.4 Geiger–Müller counter

Working When an ionizing particle enters the counter through the window, ionization takes place and a few ions are produced. If the applied voltage is increased, the ions are multiplied by further collisions. An avalanche of electrons move towards the central wire and this is equivalent to a small current impulse which flows through the resistance R. The potential difference developed across R is amplified and then passed on to a suitable electronic counter.

Working voltage for GM counter The ionization chamber works in the voltage range of 250 V, counts the incoming radiation particles with an amplifier. So an improved version of proportional counter has been designed. The proportional counter works in the voltage range of 250–750 V, counts the incoming radiation particles with an improved internal amplification. Since in the proportional counter, it is difficult to measure a weak source of ionizing radiation, the Geiger–Müller counter is designed to work in the voltage range 750 to 1500 V. The successful operation of Geiger–Müller counter depends upon the proper voltage to the electrodes. Figure 4.5 represents the counts per minute as a function of voltage.

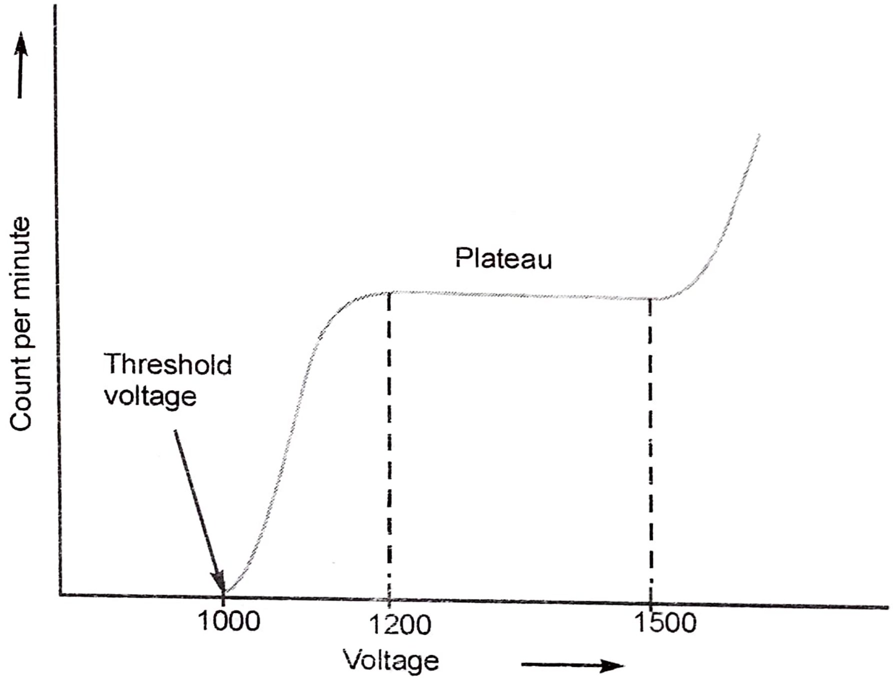


Figure 4.5 Variation of applied voltage with the current pulses

It is obvious from the figure that until the voltage reaches 1000 V, the value called starting voltage or threshold voltage, small pulses produced from weak source of ionizing radiation cannot be detected. But with increasing potential, the gas amplification increases and pulses are recorded in increasing numbers. Hence when the Geiger threshold voltage is reached, the number of pulses per minute becomes essentially constant. The range of potential over which the number of pulses per minute remains constant is called Geiger plateau. The voltage is further increased from this region, continuous discharge takes place and counting is not possible.

The voltages of the plateau range depend upon the design of the counter and the nature and pressure of gas it contains.

4.4 SCINTILLATION DETECTORS

Scintillation detectors are designed based on the property that the radiating particles emit light when they are passed on to certain materials. This property of light emission when radiating particles fall on certain materials is called scintillations.

Advantages

- The emulsion is relatively light and cheap. Because of their lightness they can be sent in balloons, spaceships, etc., for high altitude cosmic ray experiments. The cosmic ray event once recorded can be studied by developing the exposed plates conveniently in the laboratory. Emulsions are widely employed in cosmic ray studies and led to the discovery of the π-mesons and κ-mesons.
- The high density of the emulsion gives it a stopping power about a thousand times that of standard air. Unstable high energy particles are brought to rest in the emulsions and their decay schemes can thus be studied.
- The emulsion is continuously sensitive and is consequently always available to record events. But the cloud chamber is sensitive only for a fraction of a second after an expansion and remains ineffective for several seconds between successive expansions.

Limitations The main drawback of nuclear emulsions is that their sensitivity and thickness are affected by temperature, humidity, age of emulsions before development and the condition under which they are developed. The scanning of the plates and the analysis of the tracks obtained are also laborious when done manually.

4.7 SOLID-STATE TRACK DETECTORS

The principle of solid state track detectors is rather very simple. If a high energy charged particle passes through a solid, it causes a continuous damage to the material due to excitation and ionization of its atoms along the path of the particle. In some materials, this path can be etched by strong acid or alkaline solutions that preferentially attack the damaged region to make the path visible. The usual solids are mica, glass, other minerals, etc., or commercially available plastics such as cellulose nitrate, polycarbonates, etc. The commonly used reagents for etching are hydrofluoric acid for mica and glass, and caustic soda for plastics.

4.7.1 SEMICONDUCTING DETECTORS

Construction and working A p–n junction used as a particle detector is shown in Figure 4.12. The semiconductor detector consists of a p–n junction between p-type and n-type silicon. Contact is made with the n-type silicon layer by a thin evaporated film of gold. In order to minimize the current flowing in the detector when no radiation is striking it, a reverse biased diode is always used. The positive bias applied to the gold film will push all the positive charge carriers away from the junction and produce a depletion layer, indicated in the figure. The depletion layer contains almost no carriers of either sign. When an energetic charged particle travels through the depletion layer, it interacts with the electrons in the crystal produces electron-hole pairs. There is an electron-hole pair for every 3.5 eV of energy lost by the charged particle. The electron-hole pairs are swept away by the applied electric field and registered as a voltage pulse over the resistor R.

Advantages

- The number of charge carrier pairs produced in a semiconductor material is approximately 10 times larger as the number of ion pairs produced in gas ion chamber. That is, the energy extended per pair is about 3.5 eV in silicon compared to about 30 eV for gases. The voltage pulse will therefore be about 10 times larger. Hence, this detector has much better energy resolution than other radiation detectors.

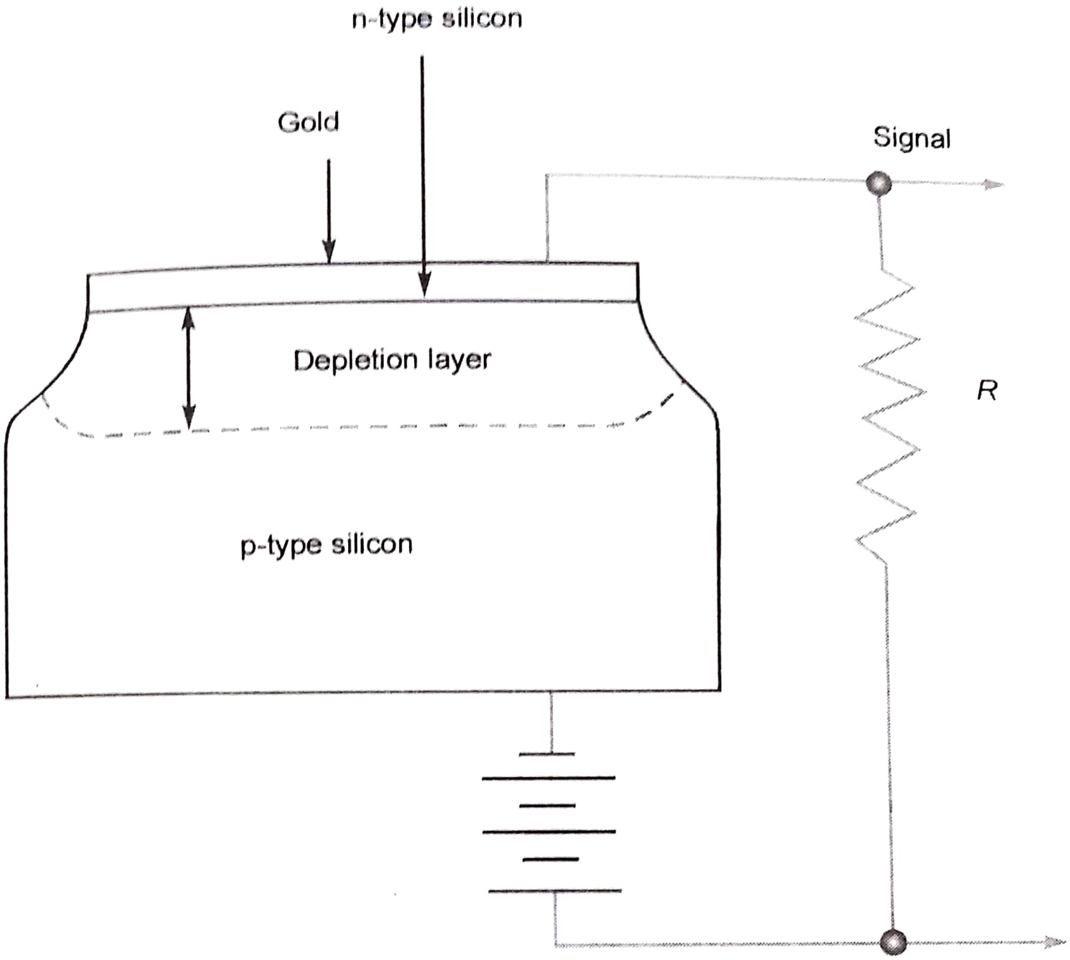


Figure 4.12 Semiconducting detector

- In solid state detectors for charged particles, silicon has been used most because of its low intrinsic conductivity. This means that the detector can be operated at room temperature without excessive leakage current. For gamma ray work, germanium are much better than silicon because of the large density of germanium.

4.8 CERENKOV COUNTER

4.8.1 CERENKOV RADIATION

When a charged particle moves through a transparent dielectric medium with a velocity greater than the velocity of light medium, a cone of light waves is emitted. These light waves are known as Cerenkov radiation.

4.8.2 CERENKOV DETECTOR

Principle In a dielectric medium of refractive index n, photons move with a velocity c/n. Consider a charged particle moving with a velocity v through the dielectric medium. Figure 4.13 shows the interaction when $v > c/n$.

The leakage of charge from the sphere can be reduced by enclosing it in a gas-filled steel chamber at a very high pressure. The high voltage produced in this generator can be used to accelerate positive ions (protons, deuterons) for the purpose of nuclear disintegration.

8.4 LINEAR ACCELERATOR

In linear accelerators, high energy particles are produced without employing high potential differences by using the principle of synchronous acceleration. The direct acceleration of particles by potentials above 10 million volts is a difficult problem due to insulation difficulties. In linear accelerators, the particles are accelerated to very high energies in small successive steps. In such machines, the potential difference between different parts of the machine and the machine and earth is maintained low compared to the potential difference corresponding to the ultimate energy acquired by the particle.

Description and working The schematic diagram of linear accelerator is shown in Figure 8.3. It consists of a series of coaxial hollow metal cylinders or drift tubes 1,2,3,4, etc. They are arranged linearly in a glass vacuum chamber. The alternate cylinders are connected together, the odd-numbered cylinders being joined to one terminal and even-numbered ones to the second terminal of a high frequency oscillator. Thus in one half cycles, if tubes 1 and 3 are positive, 2 and 4 will be negative. After the half cycle, the polarities are reversed. That is, 1 and 3 are negative and 2 and 4 will be positive. The ions are accelerated only in the gap between the tubes where they are acted by the electric field present in the gaps. The ions travel with constant velocity in the field free space inside the drift tubes.

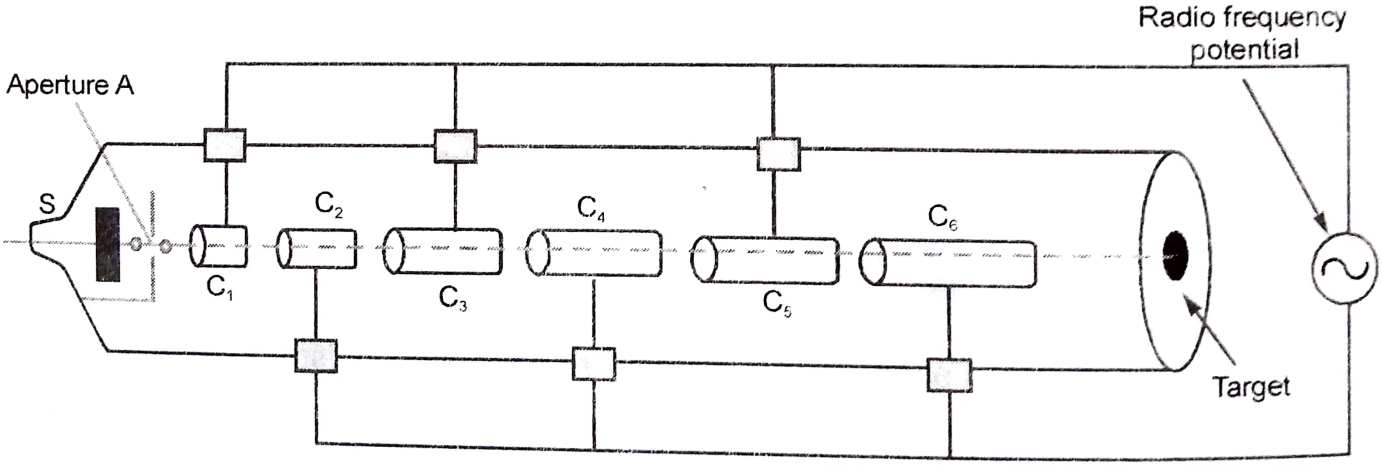


Figure 8.3 Linear accelerator

Theory The positive ions to be accelerated enter along the axis of the accelerator from an ion source through an aperture A. Suppose a positive ion leaves A and is accelerated during the half cycle, when the drift tube 1 is negative. Let e be the charge, m the mass of the ion and V the potential of drift tube 1 with respect to A.

Then, the velocity v_1 of the ion reaching the drift tube 1 is given by

$$\frac{1}{2}mv_1^2 = eV$$

$$v_1 = \sqrt{\frac{2eV}{m}}$$

The length of the tube 1 is so adjusted that as the positive ions come out of it, the tube has a positive potential and the next tube (tube no.2) has a negative potential, that is, the potentials change sign. The positive ion is again accelerated in the space between the tubes 1 and 2.

Then, the velocity v_2 of the ion reaching the drift tube 2 is given by

$$\frac{1}{2}mv_2^2 = 2eV$$

$$v_2 = \sqrt{2}\sqrt{\frac{2eV}{m}} = \sqrt{2}v_1$$

This shows that the velocity v_2 of the ion reaching the drift tube 2 is $\sqrt{2}$ times the velocity v_1 of the ion reaching the drift tube 1. Since $v_2 = \sqrt{2}v_1$, the length of the tube 2 must be $\sqrt{2}$ times the length of the tube 1. Hence to have successive acceleration in successive gaps, the tubes 1,2,3, etc. must have lengths $l_1 : l_2 : l_3$, etc., proportional to 1, $\sqrt{2}$, $\sqrt{3}$, etc.

Energy of the ion If n is the number of gaps that the ion travels in the accelerator and v_n is the final velocity acquired by the ion, then

$$\text{The velocity of ion as it emerges out of } n\text{th tube} = \sqrt{n}\sqrt{\frac{2eV}{m}}$$

$$\text{The kinetic energy acquired by the ion} = \frac{1}{2}mv_n^2 = neV$$

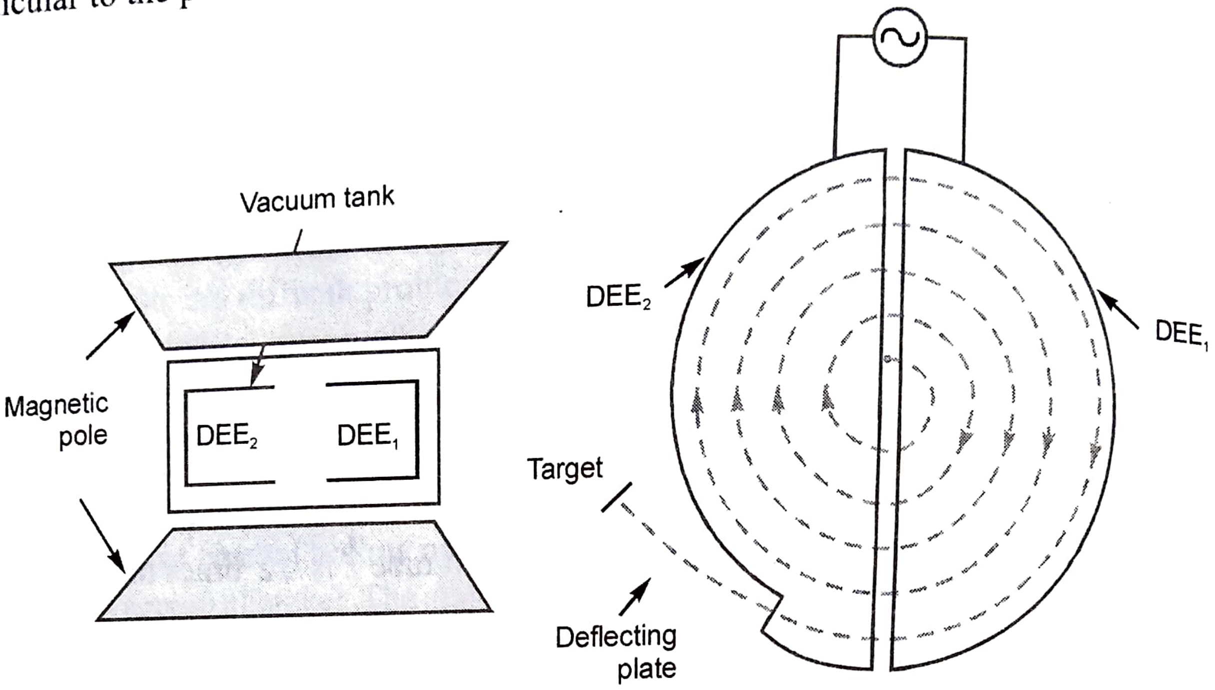
Thus, the final energy of the ions depends upon the total number of gaps and the energy gained in each gap.

Limitation The limitation of this accelerator is that the length of the accelerator becomes invariably large and is difficult to maintain vacuum in a large chamber. The ion current available is in the form of short interval impulses because the ions are injected at an appropriate moment.

8.5 THE CYCLOTRON

In 1932, Professor E.O. Lawrence and M.S. Livingston devised the first cyclotron at the University of California at Berkeley. The cyclotron is a device to accelerate positively charged particles in successive steps under combined influence of electric and magnetic fields along circular or spiral trajectories.

Construction The schematic diagram of cyclotron is shown in Figure 8.4. The cyclotron consists of two hollow semicircular metal boxes D_1 and D_2 called dees. A source of ions is located near the midpoint of the gap between the dees. The dees are insulated from each other and are enclosed in other vacuum chamber. The dees are connected to a powerful radio frequency oscillator. The whole apparatus is placed between the pole pieces of a strong electromagnet. The magnetic field is perpendicular to the planes of the dees.



(a) Side view (b) Top view

Figure 8.4 Cyclotron

Theory Suppose a positive ion leaves the ion source at the centre of the chamber at the instant, when the dees D_1 and D_2 are at the maximum negative and positive AC potentials respectively. The positive ion will be accelerated towards the negative dee D_1 before entering it. The ions enter the space inside the dee with a velocity v and a kinetic energy $\frac{1}{2}mv^2 = eV$, where V is the applied voltage, e is the charge and m is the mass of the ion respectively. When the ion is inside the dee it is not accelerated since this space is field-free. Inside the dee under the action of the applied magnetic field, the ions travel in a circular path of radius r, the centripetal force is equal to the applied magnetic force.

$$Bev = \frac{mv^2}{r}$$

where, B is the flux density of the magnetic field.

$$\text{or } r = \frac{mv}{Be}$$

The angular velocity of the ion in its circular path $\omega = \frac{v}{r} = \frac{Be}{m}$

The time taken by the ion to travel semicircular path $t = \frac{\pi}{\omega} = \frac{\pi m}{Be}$

The strength of the magnetic field B or the frequency f of the oscillator are so adjusted that by the time the ion has described a semicircular path and just enters the space between D_1 and D_2, D_2

must have become negative with respect to D_1. The ion is then accelerated towards the dee D_2 and enters the space inside with a greater velocity. Since the ion is now moving with greater velocity, it will describe a semicircle of greater radius in the second dee. But from the equation, $t = \frac{\pi m}{Be}$, it is clear that the time taken by the ion to describe a semicircle is independent of both the radius (r) of the path and the velocity (v) of the ion. Hence the ion describes all semicircles whatever be their radii, in exactly the same time. This process continues until the ion reaches the periphery of the dees. The ion thus spirals round in circles of increasing radius and acquires high energy. The ion will finally come out of the dees in the direction indicated through the window.

Energy of the ion Let r_m be the radius of the outermost orbit described by the ion and v_m the maximum velocity gained by the ion in its final orbit. Then the equation for the motion of the ion in a magnetic field is given by

$$Bev_m = \frac{mv_m^2}{r_m}$$

or

$$v_m = \frac{Ber_m}{m}$$

The energy of the ion

$$E = \frac{1}{2}mv_m^2 = \frac{B^2e^2r_m^2}{2m}$$

Limitations of the cyclotron The energies of the particles which are accelerated in a cyclotron are limited by the relativistic increase of mass with velocity.

The relativistic increase in mass of a particle moving with a velocity v is $m = \frac{m_o}{\sqrt{1-\left(\frac{v^2}{c^2}\right)}}$,

where m_o is the rest mass and c is the velocity of light.

The time taken by the ion to travel in a semicircular path $t = \frac{\pi}{\omega} = \frac{\pi m}{Be} = \frac{T}{2}$

The frequency of the ion $f = \frac{1}{T} = \frac{Be}{2\pi m} = \frac{Be\sqrt{1-\left(\frac{v^2}{c^2}\right)}}{2\pi m_o}$

Therefore the frequency of rotation of the ion decreases with increase in velocity. The ions take longer time to describe their semicircular paths than the fixed period of the oscillating electric field. Thus, the ions lag behind the applied potential and finally they are not accelerated further. Due to this reason, the energy of the ions produced by the cyclotron is limited. This limitation can be overcome in the following two ways.

Field-variation (Principle of synchrotron) The frequency of the ion can be kept constant by increasing the magnetic field (B) at such a rate that the product $B\sqrt{1-\left(\frac{v^2}{c^2}\right)}$ remains constant. For this purpose, the value of the magnetic field B should increase as velocity of the ion increases so that the product $B\sqrt{1-\left(\frac{v^2}{c^2}\right)}$ remains unchanged. This type of machine in which the frequency of electric field is kept constant and magnetic field is varied is called synchrotron.

Frequency-modulation (Principle of synchrocyclotron) In another form of apparatus, the frequency of the applied AC is varied so that it is always equal to the frequency of rotation of the ion. This type of machine in which magnetic field is kept constant and the frequency of the applied electric field is varied is called frequency-modulated cyclotron or synchrocyclotron.

Example 8.1 Deuterons in a cyclotron describe a circle of radius 0.32 m just before emerging from the dees. The frequency of the applied emf is 10 MHz. Find the flux density of the magnetic field and the velocity of deuteron emerging out of the cyclotron. Mass of deuteron $m = 3.32 \times 10^{-27}$ kg and charge $e = 1.6 \times 10^{-19}$ C.

Solution Mass of deuteron $m = 3.32 \times 10^{-27}$ kg, Charge $e = 1.6 \times 10^{-19}$ C, The frequency of the applied emf = 10 MHz = 10^7 Hz and of radius $r = 0.32$ m

The frequency of the applied emf $f = \dfrac{Be}{2\pi m}$

The magnetic flux density $B = \dfrac{2\pi m f}{e} = \dfrac{2 \times 3.14 \times 3.32 \times 10^{-27} \times 10^{7}}{1.6 \times 10^{-19}} = 1.303$ weber/m^2

The equation of motion of ion $Bev_m = \dfrac{mv_m^2}{r_m}$

The velocity of deuteron emerging out of the cyclotron $v_m = \dfrac{Ber_m}{m}$

$$v_m = \frac{Ber_m}{m} = \frac{1.303 \times 1.6 \times 10^{-19} \times 0.32}{3.32 \times 10^{-27}} = 2.009 \times 10^{7}\ \text{m/s}.$$

Example 8.2 A cyclotron in which the flux density is 1.4 weber/m^2 is employed to accelerate protons. How rapidly should the electric field between the dees be reversed? Mass of proton $m = 1.67 \times 10^{-27}$ kg and charge $e = 191.6 \times 10^{-19}$ C.

Solution Mass of proton $m = 1.67 \times 10^{-27}$ kg, Charge $e = 1.6 \times 10^{-19}$ C, The magnetic flux density $B = 1.4$ weber/m^2.

The time of reversing electric field $t = \dfrac{\pi m}{Be} = \dfrac{3.14 \times 1.67 \times 10^{-27}}{1.4 \times 1.6 \times 10^{-19}} = 2.342 \times 10^{-8}$ s

8.6 THE SYNCHROCYCLOTRON

Principle The synchrocyclotron is a modified form of the Lawrence cyclotron. The energies of the particles which are accelerated in a cyclotron are limited by the relativistic increase of mass with velocity. Therefore the frequency of rotation of the ion decreases with increase in velocity. Thus, synchrocyclotron is designed in such a way that the frequency of the applied AC is varied so that it is always equal to the frequency of rotation of the ion.

Construction and working The synchrocyclotron consists of only one dee placed in a vacuum chamber between the poles of the electromagnet as shown in Figure 8.5. Instead of second dee, opposite the opening of the dee, there is a metal sheet connected to the earth. The alternating potential difference is applied between the dee and the metal plate. The alternating potential applied to the dee is made to rise and fall periodically, instead of remaining constant. The frequency is changed at such a rate that as the ion lags a little due to the increase in mass caused by the increase in velocity, the electric field frequency automatically lags in variation. Hence the particle always enters the dee at the correct moment, when it can experience maximum acceleration.

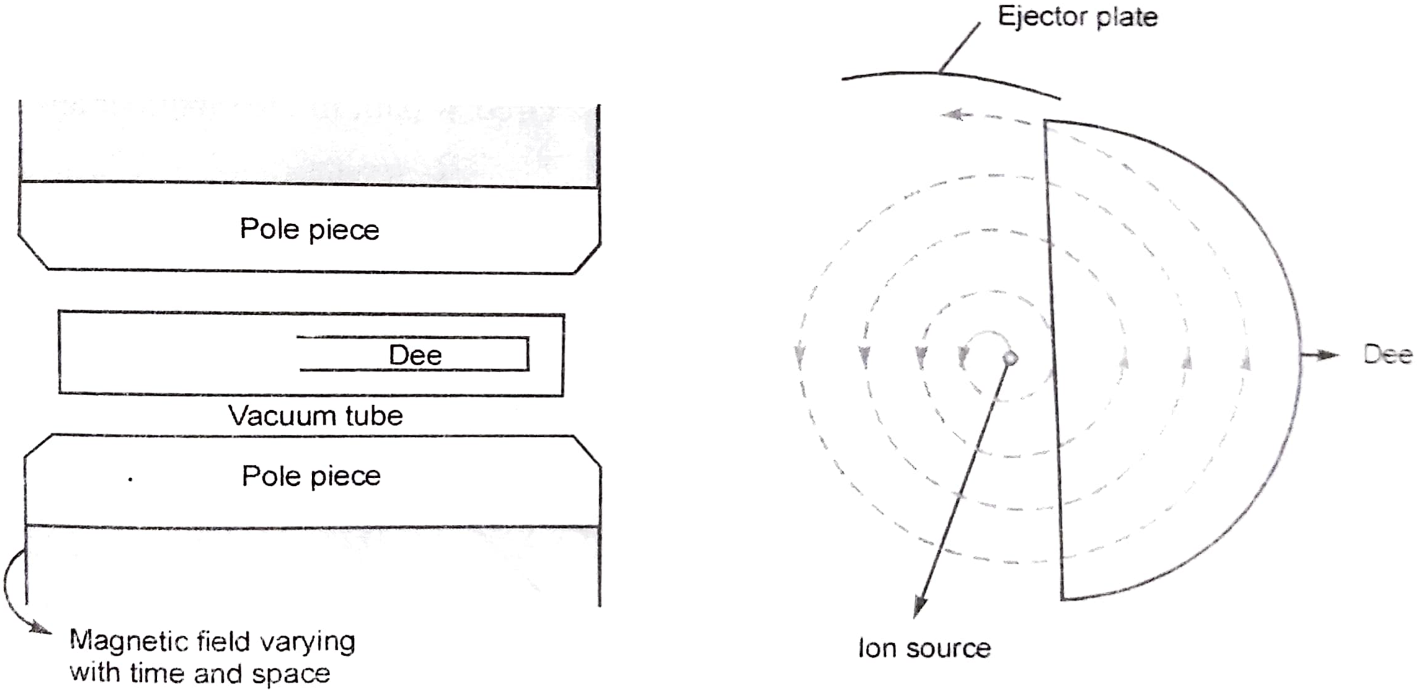


Figure 8.5 Synchrocyclotron

Advantage The advantage of using one dee is that it leaves sufficient space in the vacuum chamber for the ion source and the target. The pole pieces of the magnet are of suitable shape such that the field decreases outwards from the centre. This ensures good focusing of the accelerated ions.

Disadvantage The disadvantage of synchrocyclotron is that the output beam current is relatively small because only a small fraction of ions is captured in the phase-stable orbit of maximum radius and energy.

8.7 THE BETATRON

In cyclotron, the maximum energy that could be imparted to a particle is limited by the relativistic increase in mass that disturbs the synchronization. In particular, the cyclotron cannot be used to accelerate electrons as their relativistic mass increase even at low energies. The above difficulty is overcome in a betatron designed and developed by D.W. Kerst in 1941 at University of Illinois. The name itself suggests that betatron is specifically meant for accelerating electrons only.

Principle ~~The basic principle of betatron is~~ to accelerate electrons in a stable orbit ~~of~~ with essentially constant radius by ~~the application of~~ an alternating magnetic field called the induction field. The induction field produces two effects, first the increasing magnetic flux produces an electromagnetic ① force that accelerates the electrons along their orbits and thus increases their energy in each successive orbital revolution and secondly the varying magnetic field acting perpendicular to the electron orbit ~~simultaneously constrains~~ the electrons move in a circular trajectory of constant radius.

Construction and working It consists of a doughnut-shaped vacuum chamber placed between the pole pieces of an electromagnet. The magnet produces a strong magnetic field in the doughnut. The electrons are produced by the electron gun and are allowed to move in a circular orbit of constant radius in the vacuum chamber as shown in Figure 8.6. The magnetic field varies very slowly compared with the frequency of vibration of the electrons in the equilibrium orbit. The varying magnetic field acting parallel to the axis of the vacuum chamber produces the following effect. The changing flux due to the electromagnet produces the induced emf which is responsible for the acceleration of the electrons and bends the electrons in a circular path in the chamber and confines them to the region of the changing flux.

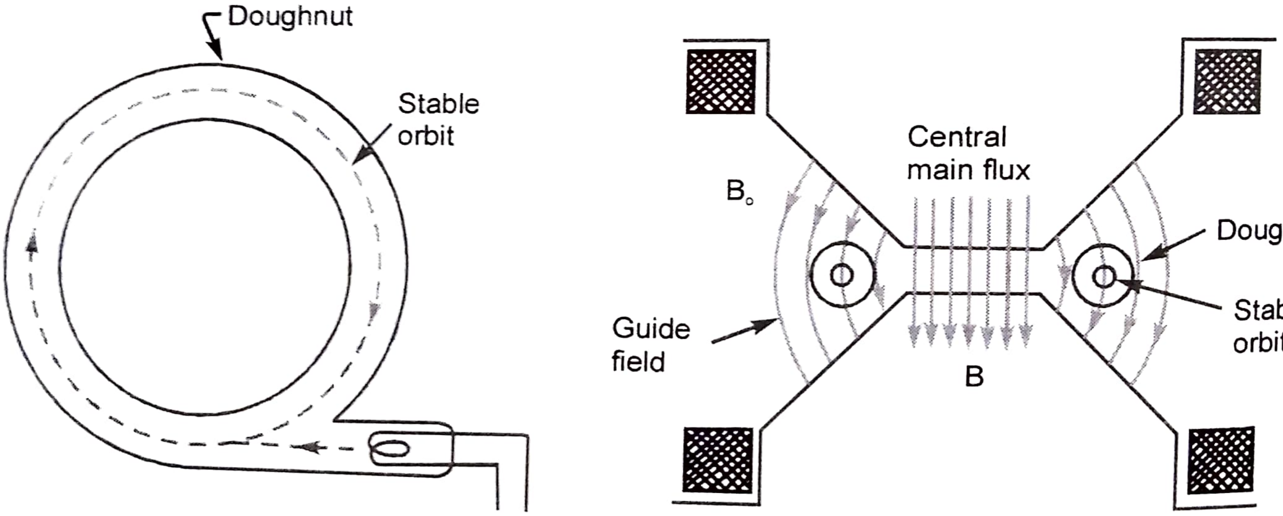


Figure 8.6 Betatron

Theory Consider the electron moving in a circular orbit of radius r as shown in Figure. Let ϕ be the flux linked with the circular orbit. The flux increases at the rate of $\frac{d\phi}{dt}$ and the induced emf in the circular orbit is given by

$$E = -\frac{d\phi}{dt} \qquad (1)$$

The work done on an electron in one revolution $= Ee = -e\frac{d\phi}{dt}$ (2)

Let F be the tangential electric force acting on the orbiting electron. The path length is $2\pi r$ for one revolution.

The work done on the electron in one revolution $= F \times 2\pi r$ (3)

Comparing equations (2) and (3) we have,

$$F \times 2\pi r = -e\frac{d\phi}{dt}$$

$$F = -\frac{e}{2\pi r}\cdot\frac{d\phi}{dt} \tag{4}$$

During the revolution, when the velocity of electron increases due to the above force, it will try to move into an orbit of larger radius. The magnetic flux perpendicular to the plane of the circular orbit influences the electron to experience a radial force inward which is given by

$$Bev = \frac{mv^2}{r} \tag{5}$$

where, B is the value of the magnetic field at the electron orbit of constant radius r, v is the velocity of the electron and m is the mass of electron. From equation (5) we have,

The moment of the electron $= mv = Ber$ (6)

From Newton's law of motion,

$$F = \frac{d}{dt}(mv) = er\frac{dB}{dt} \tag{7}$$

To maintain the constant radius of the orbit, the values of F given in equation (4) and (7) must be numerically equal.

$$\frac{e}{2\pi r}\cdot\frac{d\phi}{dt} = er\frac{dB}{dt}$$

$$\text{or} \qquad d\phi = 2\pi r^2 dB$$

Integrating the above equation we have,

$$\int_0^\phi d\phi = \int_0^B 2\pi r^2 dB$$

$$\phi = 2\pi r^2 B \tag{8}$$

The equation (8) represents the condition under which a betatron works and is called betatron condition. This distribution of magnetic flux is obtained by the special pole pieces where the magnetic field is greater at the centre of the orbit than at the circumference.

The Figure 8.7 shows the variation of magnetic field with time. Electrons are injected into the chamber, when magnetic field just begins to rise. The electrons are then accelerated by the increasing

- Another problem is to test whether transmutation has really taken place. If the fragments of the broken nucleus are very heavy, they move too slowly and remain lost in the mass of the element. In consequence, they cannot be detected by any external device. Hence unless the transmutation is accompanied by the production of light particles like proton, neutron or alpha particle the whole reaction may be missed.

9.2 BOHR'S THEORY OF NUCLEAR DISINTEGRATION

Introduction Bohr assumed that the nucleus is like a liquid drop. When a particle strikes the nucleus, it is captured by the nucleus and a compound nucleus is formed. The compound nucleus resembles a heated-up liquid drop. The projectile particle loses its identity and all its energy is distributed among all the particles of the newly formed compound nucleus. The compound nucleus is in an excited state and of course, initially no particle has sufficient energy to escape from the compound nucleus. The compound nucleus persists in its excited state until a particular nucleon momentarily happens to gain high excitation energy to escape from the compound nucleus, thus leading to a disintegration or transmutation. This process is similar to slow evaporation of particles from the surface of a liquid drop.

A nuclear reaction may be represented as,

$$a + X \rightarrow Y + b$$

This nuclear reaction signifies that a particle 'a' interacts with the nucleus 'X' to yield the nucleus 'Y' and particle 'b'. The above reaction is usually abbreviated and written as X (a, b) Y. For example, ${}_6C^{12}$ (d, n) ${}_7N^{13}$ stands for the nuclear reaction between an incident deuteron (${}_1H^2$) and a ${}_6C^{12}$ nucleus to produce ${}_7N^{13}$ nucleus with the emission of a neutron.

Compound nucleus In 1936, Bohr proposed the theory of compound nucleus which is extremely useful in the correlation and interpretation of nuclear reactions. Bohr assumed that a nuclear reaction takes place in two steps.

1. The incident particle is absorbed by the initial or target nucleus to form a compound nucleus.
2. The compound nucleus disintegrates by ejecting a particle proton, neutron, alpha particle, etc., or a gamma ray leaving the final product nucleus.

Bohr assumed that the mode of disintegration of the compound nucleus is independent of the way by which the latter is formed and depends only on the properties of the compound nucleus itself such as its energy and angular momentum.

9.3 NUCLEAR REACTIONS

The process of changing the structure of nucleus by bombarding them with fast moving charged or uncharged particles is known as nuclear reactions. Nuclear reactions are generally produced by exposing the target nucleus with the help of fast moving nuclear projectiles (nuclear particles). The nuclear particles may be charged particles like protons (${}_1H^1$), alpha particles (${}_2He^4$), deuterons (${}_1H^2$), etc., or uncharged particles like neutrons (${}_0n^1$), high-energy photons (γ), etc.

According to Bohr, the general scheme of nuclear reaction is

$$A + B \rightarrow C \rightarrow P + O$$

The projectile B strikes the target nucleus A and combines with it to form the compound nucleus C. The compound nucleus then splits into an outgoing particle O and a residual product nucleus P.

The same projectile may form different product element out of the same nucleus. The bombarding agents may be neutral or charged particles. The uncharged particles like neutrons are most effective in nuclear reactions, since they can easily enter an atomic nucleus without experiencing any repulsion. The charged particles like protons. deuterons, alpha particles, etc., have to be accelerated to overcome the potential barrier of the target nucleus.

9.3.1 TYPES OF NUCLEAR REACTIONS

Elastic scattering In elastic scattering, the incident particle strikes the target nucleus and leaves without energy loss but, in general, with altered direction of motion. Scattering of alpha particles in gold is a good example of this process.

$${}_{2}\text{He}^{4} + {}_{79}\text{Au}^{197} \rightarrow {}_{79}\text{Au}^{197} + {}_{2}\text{He}^{4}$$

Inelastic scattering In inelastic scattering, the scattering particle may lose kinetic energy in excess of that required for an elastic collision with the nucleus. This loss in kinetic energy corresponds to increase in internal energy of the product nucleus which is excited to a higher quantum state.

Lithium nucleus goes to an excited state when bombarded with proton is a good example for inelastic scattering process.

$${}_{3}\text{Li}^{7} + {}_{1}\text{H}^{1} \rightarrow \left({}_{3}\text{Li}^{7}\right)^{*} + {}_{1}\text{H}^{1}$$

The star (*) symbol is used to indicate that after scattering, the nucleus is left in an excited state. In this present example, the excess energy is radiated away in terms of gamma radiation.

Disintegration In the disintegration process of nuclear reaction, when striking the target nucleus, the incident particle is absorbed and a different particle is ejected and the product nucleus is different from the target nucleus.

The incident particle may be alpha particle, proton, neutron, etc., the product particle may be a charged particle or neutron. The typical reaction of disintegration type is given below.

$${}_{7}\text{N}^{14} + {}_{2}\text{He}^{4} \rightarrow {}_{8}\text{O}^{17} + {}_{1}\text{H}^{1}$$

Photodisintegration In photodisintegration, the gamma rays are absorbed by the target nucleus, exciting it to higher energy state. If the energy is high enough, one or more particle may be liberated. The example of photodisintegration reaction is

$${}_{1}\text{H}^{2} + \gamma \rightarrow {}_{1}\text{H}^{1} + {}_{0}\text{n}^{1}$$

Radiative capture In radiative capture, a particle may combine with a nucleus to produce a new nucleus or a compound nucleus in an excited state. The excess energy in compound nucleus is emitted in the form of gamma radiation. The process of radiative capture is explained with the following example.

$${}_{12}\mathrm{Mg}^{26} + {}_{1}\mathrm{H}^{1} \rightarrow {}_{12}\mathrm{Mg}^{26} + {}_{1}\mathrm{H}^{1} \rightarrow {}_{13}\mathrm{A}^{27} + \gamma$$

Direct reactions The direct reactions have two types namely pickup reaction and stripping reaction. In pickup reaction, the collision of an incident particle with the nucleus may immediately pull one of the nucleons out of the target nucleus.

In the inverse process known as stripping reaction, a bombarding particle composed of more than one nucleon may loss one of the nucleon to the target nucleus. The example for a stripping reaction is

$${}_{29}\mathrm{Cu}^{63} + {}_{1}\mathrm{d}^{2} \rightarrow {}_{29}\mathrm{Cu}^{64} + {}_{1}\mathrm{H}^{1}$$

Heavy ion reaction In heavy ion reaction, the nuclear reactions are induced by heavy ions exhibit the characteristics of both compound nucleus and of the stripping and pickup reaction mechanisms. The best example of heavy ion reaction is

$${}_{7}\mathrm{N}^{14} + {}_{82}\mathrm{Pb}^{207} \rightarrow {}_{7}\mathrm{N}^{13} + {}_{82}\mathrm{Pb}^{208}$$

Spontaneous decay The alpha and beta decay processes may be regarded as spontaneous decay type of nuclear reactions. In these reactions, the total energy of the system cannot be controlled, because it is a natural process.

Spallation reaction When a target nucleus captures an incident particle, the compound nucleus may split into several smaller nuclei with product particles. This process is known as spallation reaction.

The example for a spallation reaction is the nuclear fission process in which heavy nucleus splits into several smaller nuclei with product particles. The following is an example for spallation reaction.

$${}_{92}\mathrm{U}^{235} + {}_{0}\mathrm{n}^{1} \rightarrow {}_{40}\mathrm{Zr}^{98} + {}_{52}\mathrm{Te}^{136} + 2\,{}_{0}\mathrm{n}^{1}$$

High energy reactions In the energy range of about 150 MeV, spallation process merges into a new kind of reaction in which new kinds of particles like mesons, strange particles, etc., are produced along with neutrons and protons. This type of nuclear reaction is known as high energy reactions.

9.3.2 CONSERVATION LAWS

The principal properties of nuclei are mass, charge, spin, linear and angular momenta statistics, parity, etc. In any nuclear reaction, some of these properties must be conserved. Using these conservation laws, it is possible to make an analysis of nuclear reactions. We shall list the various conservation laws that appear to be valid in ordinary nuclear interactions.

Conservation of mass number The total number of neutrons and protons in the nuclei in a nuclear reaction remains unaltered after the reaction. That is, in the reaction X(x, y)Y, the sum of the mass numbers of the X and x must be equal to the sum of mass of numbers of Y and y.

Conservation of atomic number The total number of protons in a nuclear reaction remains unaltered after the reaction. That is, in the reaction X(x, y)Y, the sum of atomic numbers of X and x equals to the atomic numbers of Y and y.

Conservation of energy The total energy of the products including both mass energy and kinetic energy of the particle plus the energy involved must be equal to the mass energy of the initial ingredients plus the kinetic energy of the bombarding particles.

Conservation of linear momentum The total linear momentum of the products must be equal to the linear momentum of the bombarding particle since the target nucleus is usually considered to be at rest.

Conservation of angular momentum The total angular momentum comprising of the vector sum of the intrinsic angular momentum and the relative orbital angular momentum of the products must be equal to the total angular momentum of the target nucleus and initial particles.

Conservation of charge The total electric charge of the products must be equal to the total electric charge of target nucleus and initial particles.

Conservation of parity The parity of the system determined by the target nucleons and bombarding particle must be conserved throughout the reactions. The total parity of the system is the product of intrinsic parities of the target nucleus and bombarding particle. Although parity does not appear to be conserved in weak interactions, no violation of parity has been observed in nuclear reactions (strong nuclear interactions).

9.3.3 ENERGY BALANCE IN NUCLEAR REACTIONS AND *Q*-VALUE

In all nuclear reactions, the sum of mass and energy is conserved. Thus in the equation $A + B \rightarrow P + O$, the target nucleus is supposed to be at rest, and let its mass be m_1. The projectile has a mass m_2 and kinetic energy is E_2. The product nucleus has a mass m_3 and kinetic energy E_3 and the outgoing particle has mass m_4 and kinetic energy E_4. The equation representing the conservation of energy is written as

$$m_1c^2 + m_2c^2 + E_2 \rightarrow m_3c^2 + E_3 + m_4c^2 + E_4$$

$$Q = E_3 + E_4 - E_2 = (m_1 + m_2 - m_3 - m_4)c^2$$

The quantity Q is called the energy balance or the Q-value of the reaction. If the kinetic energy of the products of transmutation is greater than the kinetic energy of the reactants, then the Q-value is positive and energy is released in the process and the reaction is exothermic or exoergic.

If the kinetic energy of products of transmutation is smaller than the kinetic energy of the reactants, then Q-value is negative and energy is absorbed in the process and the reaction is endothermic or endoergic.

Example 3 A nuclear reaction is given by ${}_7N^{14} + {}_0n^1 \rightarrow {}_6C^{14} + {}_1H^1 + 0.55$ MeV. Find the mass of ${}_6C^{14}$ in amu. The atomic masses the nucleus and particles are $N^{14} = 14.003074$, $n^1 = 1.008665$ and $H^1 = 1.007825$ amu.

Solution

The nuclear reaction is

$${}_7N^{14} + {}_0n^1 \rightarrow {}_6C^{14} + {}_1H^1 + 0.55 \text{ MeV}$$

Mass of interacting nucleus and particle $= 14.003074 + 1.008665 = 15.011739$ amu

Mass of ${}_1H^1$ + mass equivalent of 0.55 MeV $= 1.007825 + 0.55/931 = 1.0084156$ amu

Mass of ${}_6C^{14}$ in amu $= 15.011739 - 1.0084156 = 14.0033203$ amu.

9.3.4 THRESHOLD ENERGY OF AN ENDOERGIC REACTION

In an endoergic reaction, the Q-value is negative and energy is needed to excite the reaction. This energy is supplied by the kinetic energy of the incoming particle. But complete kinetic energy of the projectile particle is not available for the nuclear reaction because part of the energy is used to give the kinetic energy to the compound nucleus.

Hence, for a reaction in which an amount of energy Q is to be absorbed, the incident particle should supply some energy in addition to the Q-value. Thus, the minimum kinetic energy which the projectile should posses so that the nuclear reaction may take place is called the threshold energy.

Let m_i and v_i be the mass and initial velocity of the projectile. Let m_c and v_c be the mass and velocity of the compound nucleus.

Applying conservation of momentum principle, $m_i v_i = m_c v_c$

The velocity of compound nucleus $v_c = \dfrac{m_i v_i}{m_c}$

Kinetic energy of compound nucleus $= \dfrac{1}{2} m_c v_c^2 = \dfrac{1}{2} m_c \left(\dfrac{m_i}{m_c}\right)^2 v_i^2$

Energy available for the reaction $= \dfrac{1}{2} m_i v_i^2 - \dfrac{1}{2} m_c v_c^2 = \dfrac{1}{2} m_i v_i^2 \left(1 - \dfrac{m_i}{m_c}\right)$

But $m_c = m_i + m_t$, where m_t is the mass of target nucleus.

$$\therefore \quad \frac{1}{2} m_i v_i^2 - \frac{1}{2} m_c v_c^2 = \frac{1}{2} m_i v_i^2 \left(\frac{m_t}{m_i + m_t}\right)$$

or

$$-Q = \frac{1}{2} m_i v_i^2 \left(\frac{m_t}{m_i + m_t} \right)$$

The threshold energy $= E_{th} = \frac{1}{2} m_i v_i^2 = -Q \left(\frac{m_i + m_t}{m_t} \right)$

9.4 NUCLEAR CROSS SECTION

The probability or efficiency of a nuclear reaction can be defined in terms of the number of particles emitted or number of nuclei undergoing transmutation for a specific number of incident particles. The interaction probability is expressed by means of a quantity called nuclear cross section. The concept of nuclear cross section can be easily visualized as the cross sectional area or target area presented by a nucleus to an incident particle. If the nucleus is considered as a sphere of radius R and the incident particle as point projectiles, then the target area or cross section σ of each nucleus is $\sigma = \pi R^2$. The magnitude of of cross section falls within 10^{-27} m^2 and 10^{-28} m^2. Due to this small value, it has been found convenient to use unit for cross section as barn (1 barn = 10^{-28} m^2). Any incident particle that is directed to the nuclear cross sectional area interacts with the target nucleus. Hence, greater the cross section, greater is the likelihood of an interaction.

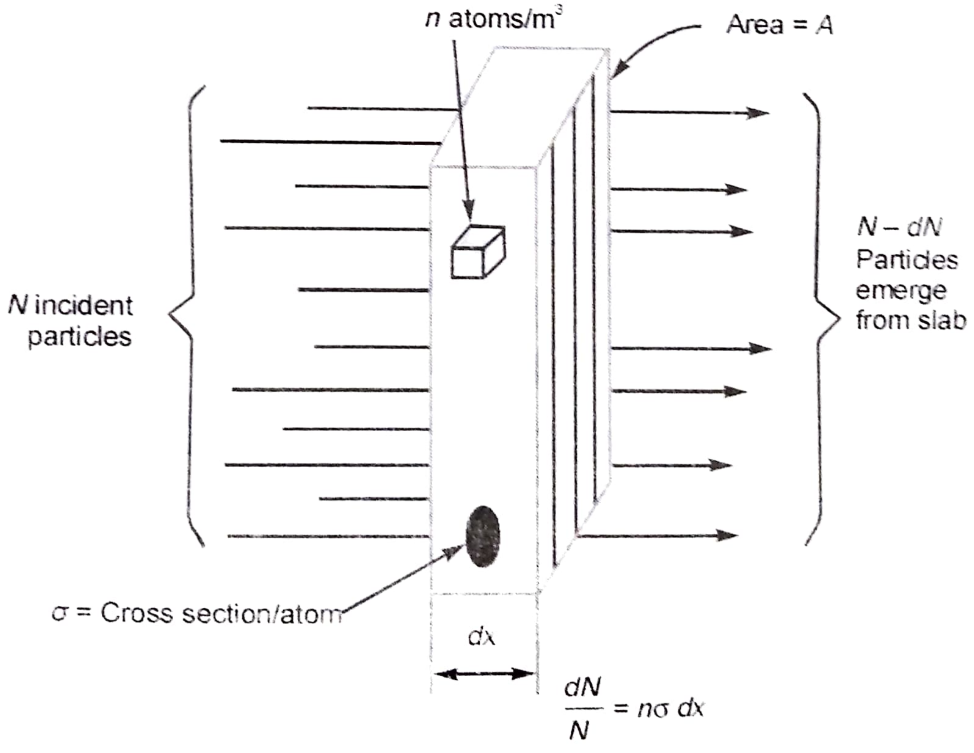


Figure 9.3 Nuclear cross section

Nuclear interaction cross section The nuclear interaction cross section is the measure of probability of the scattering of the projected particles. In fact it denotes the effective area around the nucleus so that a bombarding particle or an incident radiation entering into this area is either scattered or absorbed so as to produce a particular nuclear reaction. When the likelihood of an interaction is high, the cross section is said to be large and when the likelihood is low, the cross section is said to be small.

The interaction cross section of a target nucleus depends upon the nature of the process involved and varies with the energy of the incident particle or radiation.

Consider a slab of some material whose area is A and thickness dx. Its volume is $A.dx$. If the target material contains n nuclei per unit volume, the total numbers of nuclei in the slab is $n.A.dx$. Each nucleus has a cross section of σ for some particular interaction, so that the aggregate cross section of all the nuclei in the slab is $\sigma.n.A.dx$.

Let N be the number of incident particles in a bombarding beam and dN be the number of particles that interact with nuclei in the slab then,

$$\text{Probability of incoming particle to hit a nuclear target} = \frac{\text{Total nuclear target area of cross section}}{\text{Total target area}}$$

$$\frac{dN}{N} = \frac{\sigma.n.A.dx}{A} = \sigma.n.dx$$

Now the rate of decrease of bombarding particle and the probability of incoming particle hitting the nuclear target can be written as $-\frac{dN}{N} = n.\sigma.dx$

Let us calculate the total rate of decrease of bombarding particle or the total probability of incoming particle hitting the nuclear target nucleus with thickness x.

Let N_0 be the number of bombarding particle and N be the number of particles coming out of the target nucleus after bombardment.

$$\int_{N_o}^{N} \frac{dN}{N} = -\sigma.n\int_{0}^{x} dx$$

$$\log_e N - \log_e N_o = -\sigma.n.x$$

$$N = N_o\ e^{-\sigma n x}$$

The number of surviving particles N decreases exponentially with increasing slab thickness x. Here σ is the cross section per nucleus or the microscopic cross section or absorption cross section and n is the number of nuclei per unit volume. The product $n\sigma$ is called the macroscopic cross section or absorption coefficient of the target (nucleus) material. If the material has a greater absorption coefficient then it is more effective in stopping the incident particles. It has been observed that the absorption cross section of various nuclei is in the range 10^{-28} m^2.

The unit of cross section is termed as barn. 1 barn = 10^{-28} m^2. Nuclear cross section is ordinarily given in milli barn, abbreviated mb. The product $n\sigma$ is denoted as Σ.

Thus

$$N = N_o\ e^{-\Sigma x}$$

If the incident flux beam intensity is I_0 and the flux after penetrating distance x is I then,

NUCLEAR FISSION AND FUSION

10.1 INTRODUCTION

The discovery of nuclear fission started with the attempts of Enrico Fermi and his co-workers in 1934 to produce transuranic elements by bombarding uranium with neutrons. In 1938, Hahn and Strassman showed when uranium is bombarded by neutrons, radioactive elements of barium with atomic number $Z = 56$ (${}_{56}\mathrm{Ba}^{141}$) and krypton with atomic number $Z = 36$ (${}_{36}\mathrm{Kr}^{92}$) were produced. Meitner and Frisch suggested that the process by which uranium splits into two lighter nuclei barium and krypton, when bombarded with neutron is known as nuclear fission process. The process is called nuclear fission process since it resembled division of cells in biology.

10.2 NUCLEAR FISSION

The process of breaking up of the nucleus of a heavy element into two or more equal fragments with the release of large amount of energy is known as nuclear fission.

When uranium is bombarded with neutron, the uranium nucleus captures a slow neutron forming an unstable compound nucleus. The compound nucleus disintegrates into two nearly equal fragments with some neutrons. The schematic representation of this process is given as

$${}_{92}\mathrm{U}^{235} + {}_{0}\mathrm{n}^{1} \rightarrow {}_{92}\mathrm{U}^{236*} \rightarrow \mathrm{X} + \mathrm{Y} + \text{neutrons}$$

The compound nucleus ${}_{92}\mathrm{U}^{236*}$ is a highly unstable isotope and X and Y are the fission fragments. The fission fragments are not uniquely determined, because various combinations of fragments are possible and a number of neutrons released. The typical fission reaction is given as

$${}_{92}\mathrm{U}^{235} + {}_{0}\mathrm{n}^{1} \rightarrow {}_{92}\mathrm{U}^{236*} \rightarrow {}_{56}\mathrm{Ba}^{141} + {}_{36}\mathrm{Kr}^{92} + 3\,{}_{0}\mathrm{n}^{1} + \mathrm{Q}$$

where, Q is the energy released in the nuclear reaction. The above fission process is taking place when uranium is bombarded with slow neutrons, the uranium nucleus absorbs the neutron and becomes unstable and splits into two or more fission fragments. The other type of fission reaction is given as

$$_{92}U^{235} + {_0}n^1 \rightarrow {_{92}}U^{236*} \rightarrow {_{54}}Xe^{141} + {_{38}}Sr^{94} + 2\,{_0}n^1 + Q$$

Bohr and Wheeler successfully explained the phenomenon of nuclear fission by liquid drop model.

10.2.1 ENERGY RELEASED IN NUCLEAR FISSION

In the process of nuclear fission, a large amount of energy is released. This energy is produced because the sum of masses of the target nucleus and the bombarding particle is greater than the sum of masses of the product nuclei and the particles released. The difference between the masses before and after the fission is converted into energy according to Einstein's mass energy equation $E = mc^2$.

The energy liberated per fission can be calculated as follows. Let us consider the following nuclear fission reaction.

$$_{92}U^{235} + {_0}n^1 \rightarrow {_{92}}U^{236*} \rightarrow {_{56}}Ba^{141} + {_{36}}Kr^{92} + 3\,{_0}n^1 + Q$$

Let us estimate the actual masses before and after the nuclear fission reaction.

Mass of $_{92}U^{235}$ = 235.045733 amu
Mass of $_0n^1$ = 1.008665 amu
Total mass before fission = 236.054398 amu
Mass of $_{56}Ba^{141}$ = 140.917700 amu
Mass of $_{36}Kr^{92}$ = 91.885400 amu
Mass of $3\,{_0}n^1$ = 3.025995 amu
Total mass after fission = 235.829095 amu
Mass decrease before and after fission = 0.2253 amu

This decrease in mass is converted into energy. The amount of energy released when one uranium atom is bombarded with a neutron in the nuclear fission process = 0.2253 × 931 = 209.8 MeV. (since 1 amu = 931 MeV).

Energy released in 1 kg of uranium In the nuclear fission process of one uranium nucleus, 200 MeV of energy is released. Now let us calculate the amount of energy released during fission process of 1 kg of uranium.

$$\text{Number of atoms in 1 kg of uranium} = \frac{6.023 \times 10^{26}}{236}$$

Energy released in the fission process = 200 MeV

$$\text{Energy produced by 1 kg of uranium} = \frac{6.023 \times 10^{26}}{236} \times 200 = 5.128 \times 10^{26}\ \text{MeV}$$

$$\text{Energy produced} = \left(5.128 \times 10^{26}\right) \times \left(1.6 \times 10^{-19}\right) \text{J} (\text{since } 1\ \text{MeV} = 1.6 \times 10^{-19}\ \text{J})$$

$$\frac{\text{Escape rate}}{\text{Production rate}} \propto \frac{1}{r}$$

The larger the size of the body, the smaller is the escape rate. Thus it is clear that increase in the volume of the system, reduces the loss of neutrons by escape. The greater the size of the system, the lesser is the probability of the escape of neutrons. In this case, the production of neutrons will be more than the loss due to other causes and chain reaction can be maintained.

Critical mass The critical size of a system containing fissile material is defined as the minimum size for which the number of neutrons produced in the fission process just balances those lost by leakage and non-fission capture. The mass of the fissionable material at this size is called critical mass. If the size is less than the critical size, a chain reaction is not possible.

10.3.1 ATOM BOMB

Atom bomb is based on the principle of uncontrolled fission chain reaction. Natural uranium consists of 99.28% of ${}_{92}U^{238}$ and 0.72% of ${}_{92}U^{235}$. The isotope ${}_{92}U^{238}$ is fissionable only by fast neutrons. Hence, it is essential in an atom bomb that either ${}_{92}U^{235}$ or ${}_{94}Pu^{239}$ should be used, because they are fissionable by neutrons of all energies.

An atom bomb consists of two hemispheres of ${}_{92}U^{235}$ or ${}_{94}Pu^{239}$, each smaller than the critical size which are kept apart by a separator aperture as shown in Figure 10.2.

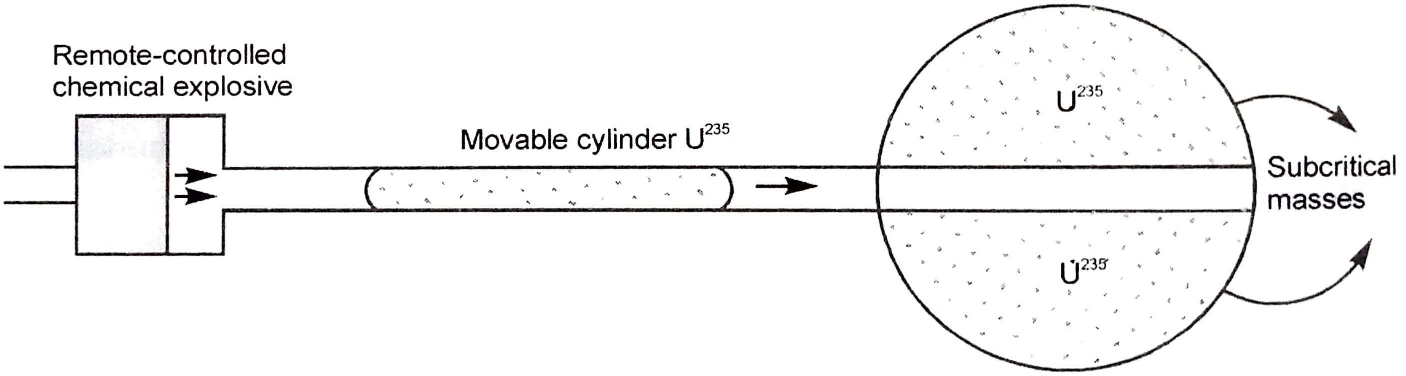


Figure 10.2 Atom bomb

When the bomb has to be exploded, a third well-fitting cylinder of ${}_{92}U^{235}$ or ${}_{94}Pu^{239}$ whose mass is less than the critical mass, is propelled so that it fuses together with the other two pieces. Now the total quantity is greater than the critical mass and an uncontrolled chain reaction takes place resulting in a great explosion.

The explosion of an atom bomb releases tremendous amount of energy in the form of heat, light and radiation. A temperature of millions of degree Celsius and pressure of millions of atmospheres are produced. Such explosions produce shock waves. They are very dangerous because the waves spread radiations in air and cause loss of life.

The release of dangerously radioactive gamma rays, neutrons and other radiations produce health hazards over the surroundings for a long time. The radioactive fragments and isotopes formed out of explosion adhere to dust particles thrown into space and fall back to earth causing a radiation fall-out even at distant places.

These types of atom bombs were used in world war II and were exploded over Hiroshima and Nagasaki in Japan.

Hiroshima and Nagasaki

On August 6, 1945, a uranium fission bomb was detonated over the Japanese city of Hiroshima. The bomb, called little boy was a gun-type device which used an explosive charge to force two subcritical masses of ${}_{92}U^{235}$ together. It was 28 inches in diameter and 120 inches long, a relatively small package to deliver an explosive force of some 20,000 tons of TNT by converting about 1 g of matter into energy. This could be accomplished with a sphere of ${}_{92}U^{235}$ about the size of a baseball.

This kind of device had never been tested, except the plutonium bomb which was dropped on Nagasaki three days later. Casualties included both direct blast victims plus those who died from radiation-induced cancer in subsequent years. The bomb was triggered to explode at a height of 550 m (1800 ft), a height calculated to cause the widest area of damage. In the detonation of the uranium fission bomb over Hiroshima, about 130,000 people were reported killed, injured, or missing. Another 177,000 were made homeless.

On August 9, 1945 a plutonium fission bomb was detonated over the Japanese city of Nagasaki, three days after a uranium fission bomb was dropped on Hiroshima. The bomb, called fat man, was 128 inches long and had a diameter of 60.5 inches. It used implosion to compress the sub-critical assembly of plutonium. This kind of device had been tested less than a month before the drop, and was the subject of several other weapons tests after World War II. The explosive yield was about 20,000 tons of TNT, generated in about a microsecond. The bomb was triggered to explode at a height of 550 m (1800 ft), a height calculated to cause the widest area of damage.

10.4 NUCLEAR REACTOR

A chain reaction is a self-propagating process in which large amount of energy is released within an extremely short interval of time. There are two types of chain reactions namely controlled and uncontrolled chain reactions. An atom bomb is an example for uncontrolled chain reaction. A nuclear reactor is an example for controlled chain reaction in which the nuclear fission reaction takes place in a self-sustained and controlled manner. In 1942, the first nuclear reactor was built at Chicago, USA.

The nuclear reactors are classified into research reactors, production reactors and power reactors depending on the purpose for which the reactors are used. Research reactors are used primarily to supply neutrons for research purpose and for production of radioisotopes. The purpose of production reactors is to convert fertile (non-fissile but abundant) material into fissile material. The power reactor converts nuclear fission energy into electric power. The schematic diagram of a nuclear reactor is shown in Figure 10.3.

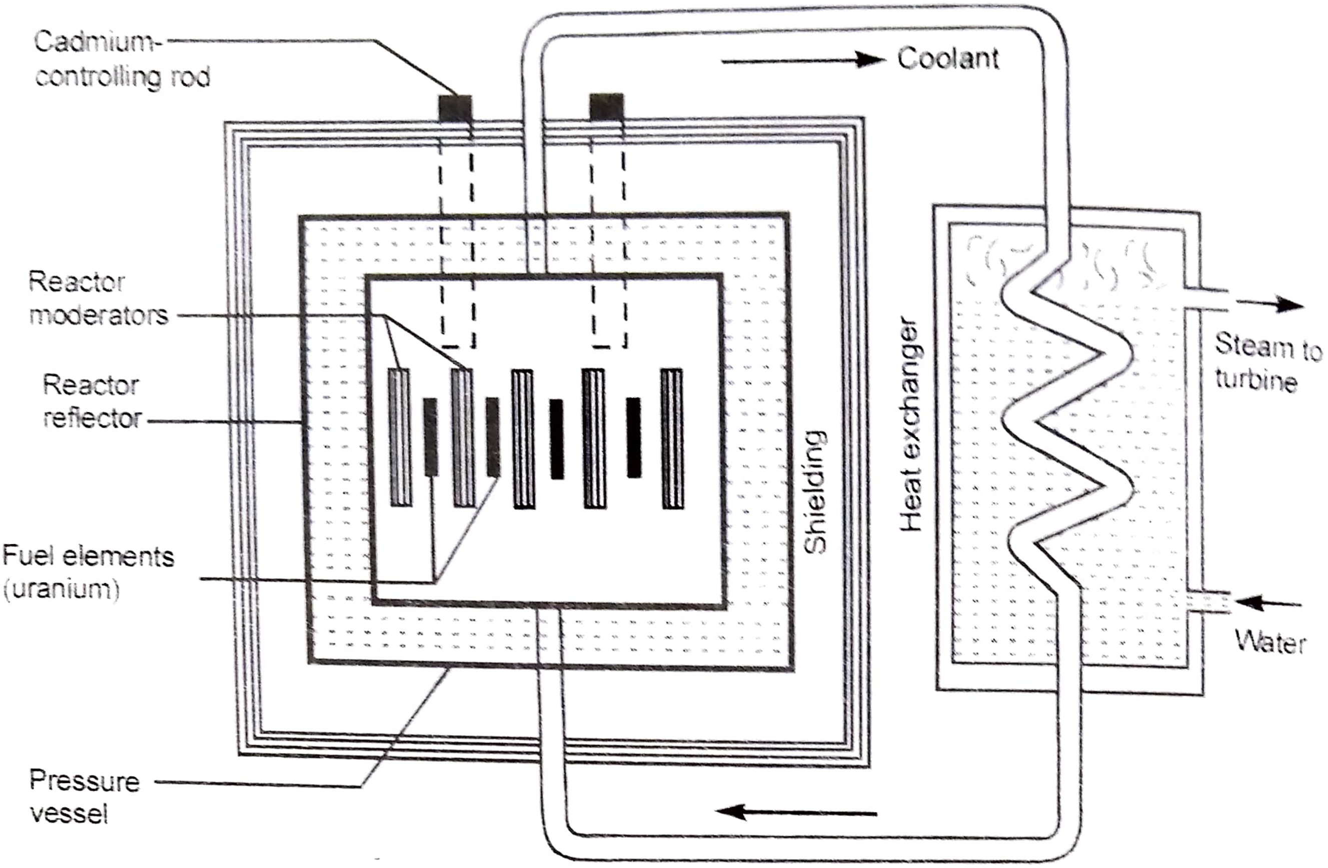


Figure 10.3 Nuclear reactor

The essential components of nuclear reactors are reactor core, moderator, neutron source, control system, coolant system, neutron reflectors and shielding.

Reactor core Reactor core is the main part of a nuclear reactor which contains fissionable material called the nuclear fuel. The commonly used fissile material or nuclear fuel is $_{92}U^{235}$ and the other fissile isotopes used as fuel in some reactors are U^{233} and Pu^{239}. The reactor core consists of an assemblage of fuel elements, control rods, coolant and moderator. Reactor cores generally have a shape similar to a right circular cylinder with a diameter of few metres. The fuel elements are made as plates or rods of uranium metal. The nuclear reaction takes place in the reactor core and a huge quantity of heat is generated.

Moderator The function of a moderator is to slow down fast neutrons (2 MeV of energy) produced in the fission process to thermal neutrons (0.025 eV of energy), which are in thermal equilibrium with the moderator. A good moderator slows down neutrons by elastic collisions and it does not remove them by absorption. The moderator is present in the space between the fuel rods in channels.

The good moderator should have high boiling point, large scattering cross section, small absorption cross section and low atomic number. The commonly used moderators are water, heavy water, graphite and beryllium oxide. In fast breeder reactors, the fission chain reaction is sustained by fast neutrons and hence no moderator is required.

Neutron source A source of neutron is required to initiate the fission chain reaction for the first time. A mixture of beryllium with plutonium or radium or polonium is commonly used as a source of neutron.

Control system The control system is necessary to prevent the chain reaction from becoming violent and uncontrolled. The effective multiplication factor of the reactor is always kept greater than unity in order to increase the neutrons in successive generations. The reactor is likely to be damaged unless the increase in number of neutrons and the neutron flux density is controlled at some stage.

The control system works on the principle of absorbing the excess neutrons with the help of control rods and controls the chain reaction. The commonly used control rods are made up of elements like boron or cadmium. These materials have a very large absorption cross section of thermal neutrons and have the advantage of not becoming radioactive due to neutron capture. The control rods are inserted into the core and they pass through the space in between the fuel tubes and through the moderator. By pushing control rods in or pulling out, the reaction rate can be controlled.

Cooling system The cooling system removes the heat generated in the reactor core. The commonly used coolants are water, heavy water and liquid sodium. A good coolant must possess large specific heat capacity and high boiling point. The coolant passes through the tubes containing the fuel bundle and carries the heat from the fuel rods to the steam generator through heat exchanger. The steam runs the turbines to produce electricity in power reactors. The coolant and the moderator are the same in the pressurized heavy water reactor (PHWR) and pressurized water reactor (PWR). In fast breeder reactors, liquid sodium is used as the coolant since a high temperature is produced in the reactor core of the fast breeder reactors. The best coolant is the liquid metal, like molten sodium, since it is a very good conductor of heat and remains in the liquid state for a very high temperature as its boiling point is 1000°C.

Neutron reflectors Neutron reflectors prevent the leakage of neutrons to a large extent, by reflecting them back into the reactor. In pressurized heavy water reactors, the moderator itself acts as the reflector. In the fast breeder reactors, the reactor core is surrounded by depleted uranium (uranium which contains less than 0.7% of ${}_{92}U^{238}$) or thorium (${}_{90}Th^{232}$) which acts as neutron reflector. Neutrons escaping from the reactor core convert these materials into Pu^{239} or U^{233} respectively.

Shielding The reactor shielding is an important component in a reactor installation. The shielding is provided to weaken the intensity of gamma rays and neutrons coming out from reactor. In high power reactors, thermal shield and biological shield are provided.

Thermal shield The thermal shield is fixed very close to the reactor core which consists of thick iron or steel covering. It absorbs most of the harmful rays and also protects the biological shield from overheating.

Biological shield The biological shield is a layer of concrete wall of thickness about 2 to 2.5 m surrounding the thermal shield and reactor core. Its function is to absorb the gamma rays and neutrons coming out from the first shield to a considerable extent.

10.4.1 BREEDER REACTOR

Natural uranium, ${}_{92}U^{238}$, and thorium, ${}_{90}Th^{232}$, are not fissile materials but are abundant in nature. In the reactor, these can be converted into fissile material, ${}_{94}Pu^{239}$ and ${}_{92}U^{233}$ respectively, by absorption of neutrons. The reactor of this type produces its own fissionable fuel. The reactions are as follows:

Narora Atomic Power Station (NAPS) , January 1,1991	Uttar Pradesh 1	PHWR	220
Narora Atomic Power Station (NAPS) , July 1,1992	Uttar Pradesh 2	PHWR	220
Kakrapar Atomic Power Station (KAPS), May 6, 1993	Gujarat 1	PHWR	220

Example 10.2 Calculate the power output of a nuclear reactor which consumes 10 kg of ${}_{92}U^{235}$ per day. Given that the energy released per fission is 200 MeV.

Solution

The number of atoms in 10 kg of ${}_{92}U^{235}$ $= \dfrac{10 \times 6.023 \times 10^{26}}{235} = 2.56 \times 10^{26}$ atoms

Energy released per fission = 200 MeV = $200 \times 1.6 \times 10^{-13}$ J = 3.2×10^{-11}J

Energy released in 10 kg of ${}_{92}U^{235}$ $= 2.56 \times 10^{26} \times 3.2 \times 10^{-11} = 819 \times 10^{12}$ J

The power output of nuclear reactor in 1 day = $\dfrac{819 \times 10^{12}}{24 \times 3600} = 9.48 \times 10^{9}$ W

Since 1 watt = 1 joule per sec

The power output of nuclear reactor in 1 day = 9.48×10^{3} MW.

10.5 NUCLEAR FUSION

The process of fusing two or more light nuclei to form a single heavy nucleus with the release of large amount of energy is known as nuclear fusion process.

For example, when four hydrogen nuclei are fused together, a helium nucleus is formed. The mass of the single nucleus formed is less than the sum of masses of the individual light nuclei. The difference in mass is converted into energy according to Einstein's mass energy relation $E = mc^2$.

Similarly when two deuterium nuclei are fused together, a helium nucleus is formed. The energy released during the nuclear fusion process is calculated as follows. The mass of deuterium ${}_1H^2$ = 2.014102 amu, mass of helium ${}_2He^4$ = 4.002604 amu.

$${}_1H^2 + {}_1H^2 \rightarrow {}_2He^4 + Q$$

The initial mass of two deuterium = 2 × 2.014102 = 4.0028204 amu. Mass of helium ${}_2He^4$ = 4.002604 amu. The decrease in mass = 4.0028204 – 4.002604 = 0.025600 × 931.3 MeV. Thus the energy released in fusion is 23.84 MeV. Table 10.1 gives the distinction between nuclear fission and fusion reaction.

Table 10.1 Distinctions between fission and fusion reaction

Fission reaction	**Fusion reaction**
In fission reaction, large amount of energy is liberated.	In fusion reaction, large amount of energy is liberated.
A heavy nucleus is split into two lighter nuclei.	Two lighter nuclei are fused into a heavier nucleus.
The fission process is possible even at room temperature.	The fusion process is possible only at very high temperature.
The links of this process are neutrons.	The links of this process are protons.
The energy produced per nucleon is 200 MeV per nuclide.	The energy per nucleon is 6.75 MeV.
The fission reaction leaves large amount of radioactive wastes.	The fusion reaction does not leave any radioactive wastes.

10.5.1 SOURCES OF STELLAR ENERGY

The temperatures of stars are very high and they radiate tremendous amount of energy. The sun is one of the innumerable stars. The sun radiates 3.8×10^{26} joules of energy each second. The origin of such a tremendous amount of energy in sun and stars is the nuclear fusion reaction taking place in them. In 1939, Bethe suggested the following carbon–nitrogen cycle and proton–proton cycle as the most important nuclear reactions for the release of energy by fusion.

Carbon–nitrogen cycle The carbon–nitrogen cycle is given below. In this cycle, carbon acts as a catalyst to drive the reaction. Initially, the carbon nucleus absorbs the protons in succession and ultimately discharges alpha particle becoming carbon nucleus again.

$$_6C^{12} + {}_1H^1 \rightarrow {}_7N^{13*} + \gamma$$

$$_7N^{13*} \rightarrow {}_6C^{13} + {}_1e^0 + \gamma$$

$$_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14} + \gamma$$

$$_7N^{14} + {}_1H^1 \rightarrow {}_8O^{15*} + \gamma$$

$$_8O^{15*} \rightarrow {}_7N^{15} + {}_1e^0 + \gamma$$

$$_7N^{15} + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4$$

Though the above reaction is called carbon–nitrogen cycle, the actual reaction cycle is essentially based on the following reaction.

$$4\,{}_1H^1 \rightarrow {}_2He^4 + 2\,{}_1e^0 + 2\,\nu + Q$$

The loss in mass is calculated as follows.

$$4\,{}_1H^1 = 4.031300 \text{ amu}, \; {}_2He^4 + 2\,{}_1e^0 = 4.002603 + 0.001098 = 4.003701 \text{ amu}.$$

10.5.3 HYDROGEN BOMB

Hydrogen bomb is devised, based on the principle of nuclear fusion. The very high temperature required for an uncontrolled thermonuclear reaction is obtained by the detonation of an atom bomb.

In hydrogen bomb, the central part of the device is a fission bomb containing $_{92}U^{235}$ and $_{94}Pu^{239}$ and is surrounded by an atmosphere of deuterium and tritium. The fission bomb produces very high temperature at which the thermonuclear reactions start resulting in the fusion of hydrogen nuclei to form helium. A greater energy per unit mass is obtained from a hydrogen bomb than from a nuclear fission bomb.

The fusion reactions based on deuterium–deuterium and deuterium–tritium are known as wet hydrogen. The first successful hydrogen bomb was exploded in the island Eniwetok Atoll in the pacific ocean on 1st November 1952. The explosion not only melted the whole island but boiled it away. There is no limit to the size of the hydrogen bomb as there is no need for any critical mass in the process.

10.5.4 CONTROLLED THERMONUCLEAR REACTIONS

The devices producing controlled thermonuclear reactions use plasma containing hydrogen isotopes $_1H^1$, $_1H^2$ and $_1H^3$. The plasma is a neutral assembly of ionized atoms, molecules and electrons and could be produced by high temperatures or by high frequency electric discharges.

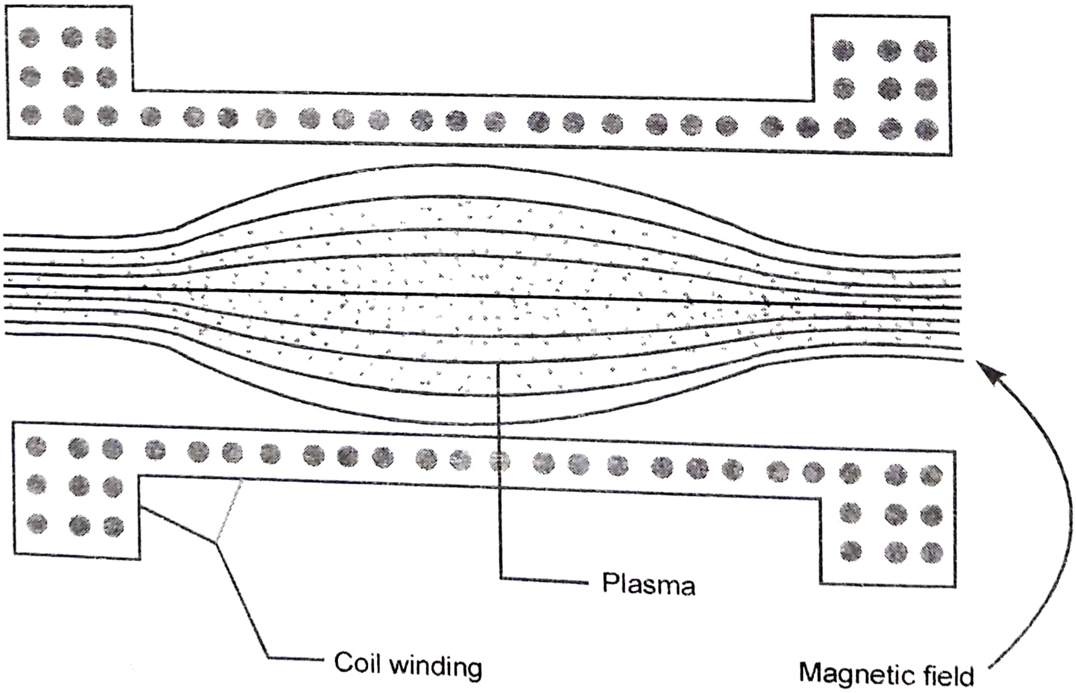


Figure 10.6 Controlled nuclear fusion reaction

The plasma contained in a vessel is the major problem because if it hits the walls of the vessel, the wall will get vaporized and the loss of heat will prevent the rise of temperature of the plasma. If a device is fabricated to prevent plasma from the leakage to the walls, hot cloud of plasma gases consisting of positively charged nuclei and electron move randomly according to Maxwellian law of distribution. Some of the nuclei which are close together in the range of nuclear forces fuse together and liberate energy. The schematic diagram of machine constructed to produce fusion reaction in a controlled manner is shown in the Figure 10.6.

The plasma is held in suspension in space by the lines of force of an electromagnet, the so-called magnetic bottle. High-pressure hot plasma under appropriate conditions develops a magnetic field of its own and this field may be strong enough to exclude the external applied field. Hence, the particles would move in such plasma in straight lines except at the boundary, hence, they would be deflected. So the strong magnetic field will confine the plasma like a gas in a bottle known as magnetic bottle. This is the basic principle of this magnetic confinement of plasma. The ${}_1H^1$, ${}_1H^2$ and ${}_1H^3$ nuclei which are close together in the range of nuclear forces fuse together and liberate energy.

The nuclear fusion as an energy source is preferred when compared to nuclear fission as an energy source because of the following reasons.

- Hydrogen is enormously available everywhere in this planet in various forms whereas fissile material ${}_{92}U^{235}$ is available only in a very small amount.
- The lightness of the reactant nuclei makes the energy yield per unit mass of the reacting material much greater than that in nuclear fission process.
- A fusion reaction does not leave any radioactive waste as in fission reaction. Hence, the problem of radioactive waste disposal does not arise in the case of fusion process.

Example 10.3

A deuterium reaction that occur in experimental fusion reaction is H^2 (*d, p*)H^3 and H^3(*d, n*)He^4. Calculate the energy release in these reactions. The data given are H^1 = 1.007825 amu, H^2= 2.014102 amu, H^3 = 3.016049 amu, He^4 = 4.002604 amu and ${}_0n^1$ = 1.008665 amu.

Solution

The fusion reaction H^2 (*d, n*) H^3 is given as

$${}_1H^2 + {}_1H^2 \rightarrow {}_1H^3 + {}_1H^1 + Q$$

The mass decrease in the reaction

$$\Delta m = (2.014102 + 2.014102 - 3.016049 - 1.007825)\text{ amu} = 0.00433\text{ amu}$$

Energy released = 0.00433 × 931.3 = 4.032 MeV

The fusion reaction H^3 (*d, n*) He^4 is given as

$${}_1H^3 + {}_1H^2 \rightarrow {}_2He^4 + {}_0n^1 + Q$$

The mass decrease in the reaction

$$\Delta m = (3.016049 + 2.014102 - 4.002604 - 1.008842)\text{ amu} = 0.018842\text{ amu}$$

Energy released = 0.18842 × 931.3 = 17.58 MeV.

ELEMENTARY PARTICLES

12.1 INTRODUCTION

The study of structure of atom gives the opinion that perhaps electron, proton and neutron are the only building blocks of matter. Recently, the studies on high energy cosmic ray particles with the help of high-energy accelerators have revealed the existence of numerous new nuclear particles. There are more than two hundred subatomic or elementary particles that have been discovered so far. These particles are elementary in the sense that they are structureless which cannot be explained as a system of other elementary particles.

12.2 CLASSIFICATION OF ELEMENTARY PARTICLES

Elementary particles are broadly classified into four groups namely photons (mass-less bosons), baryons (heavy particles), leptons (light particles) and mesons (particles having masses between electron and nucleon). The elementary particles are described in terms of their mass, charge, spin, half-life, decay mode, etc., the properties of various particles are intimately connected with properties of the interacting force fields.

Photons The photon is a quantum of electromagnetic radiations. These particles come under the mass-less boson group. Photon has a rest mass equal to zero and spin unity. Since photon has a zero rest mass, its range is infinite. There is another mass-less boson called graviton which has a spin of two units associated with gravitational interaction. The photon and graviton have their own antiparticles. Photon is a stable particle and can interact with electromagnetic field of the nucleus and give rise to electron-positron pair production. Conversely, photon can be produced by annihilation of an electron and positron.

Table 12.1 gives the summary of characteristics of some elementary particles.

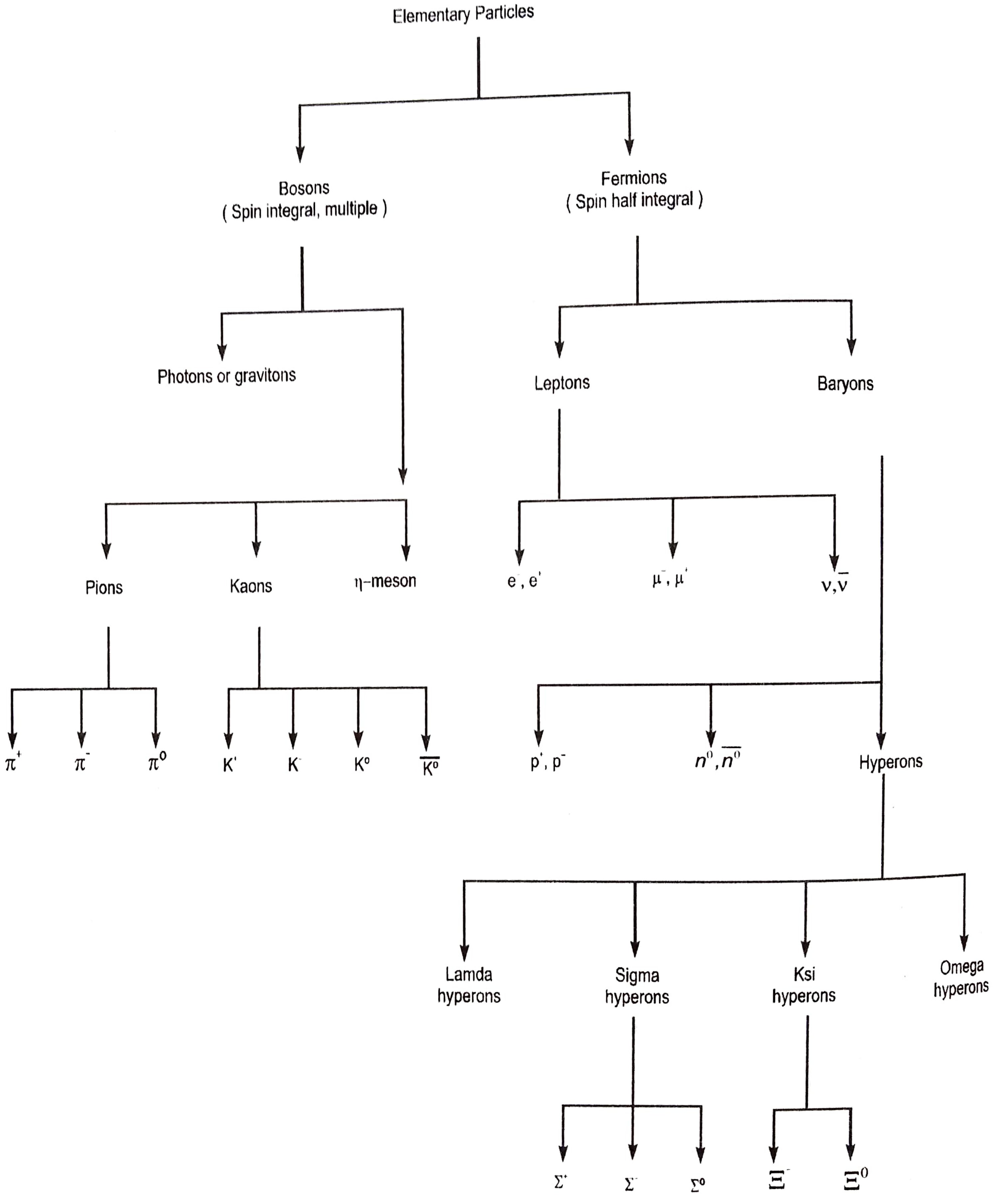


Figure 12.1 Classification of elementary particles

Baryons or heavy particles Baryons are subjected to all three types of interactions namely strong, weak and electromagnetic. The members of baryons are nucleons (proton and neutron), omega hyperon, Xi hyperon, sigma hyperon and lamda hyperon.

Hyperons are special type of baryons characterized by a time decay of 10^{-10} second and mass value intermediate between neutron and deuteron. Their decay time is very much greater than the time of their formation (10^{-3} sec). There are four types of hyperons namely Lamda, Sigma, Xi and Omega.

Since, there are some unsolved problems in the characteristics of these particles, they are also called strange particles.

Leptons Particles which do not respond to strong interaction, but only to weak and electromagnetic interactions are called leptons. They are all fermions, the particles which are obeying Fermi–Dirac statistics. They have spin $\frac{1}{2}$ and have mass lesser than that of nucleons. This group contains electron (e^-), positron (e^+), muons (μ^+, μ^-), mu-neutrino (ν_μ), mu-antineutrino ($\overline{\nu}_\mu$), e-neutrino (ν_e), e-antineutrino ($\overline{\nu}_e$).

Mesons Mesons are subjected to all the three types of interactions namely strong, weak and electromagnetic. They are all bosons, the particles which are obeying Bose–Einstein statistics. They have zero or integral spins, that is, 0, 1, 2, etc. The rest mass of these particles varies between 250 m_e and 1000 m_e. This group contains π-mesons ($\pi^+ \cdot \pi^\circ \cdot \pi^-$), K-mesons (K^+, K^-, K_1°, K_2°) and η-mesons (η^o). The three types of mesons π°, π^- and π^+ are responsible for the interaction between protons and neutrons inside the nucleus. Baryons and mesons are also called as hadrons and are the particles of strong interaction.

12.3 PARTICLES AND ANTIPARTICLES

Electron and positron In 1932, Anderson discovered positron, the antiparticle of electron. The existence of positron, the antiparticle of the electron was predicted by Dirac based on the symmetry equation of the relativistic quantum theory of electron. The particle and antiparticle electron and positron have the same mass and spin but opposite charge. When electron and positron come in contact with each other, they annihilate with the emission of photon.

Proton and antiproton In 1955, Segre, Chamberlain and their collaborators established the existence of the antiparticle antiproton. Antiprotons were produced by bombarding protons in a target with 6 GeV protons and thereby inducing the reaction. The kinetic energy of the bombarding proton is converted into a proton and antiproton pair with four residual protons. Antiprotons interact strongly with matter and annihilate with proton. In a typical annihilation reaction, the rest mass of the proton and antiproton pair appears as five pions.

Neutron and antineutron In 1956, Cork, Lamberton and Wenzel discovered antineutron, the antiparticles of neutron. Neutron and antineutron have zero charge and same mass. However, since neutron is having an internal charge distribution, it is expected that the antineutron also has an internal charge distribution opposite to that of the neutron. Antineutron is quickly annihilated either by a proton or neutron with the production of several pions.

Neutrino and antineutrino In a negative beta decay, the neutron decays into a proton, positron and antineutrino. Similarly in a positive beta decay, the proton in the nucleus decays into a neutron, electron and neutrino. Thus the antineutrino and neutrino form the antiparticles. Neutrino and antineutrino have no charge, spin $\frac{1}{2}$, are very light particles with 2% mass of electron and magnetic moments smaller than 10^{-8} Bohr magneton or nearly zero. The neutrino and antineutrino have finite energy and momentum in flight and travel with the velocity of light. They do not cause ionization on passing through matter. A neutrino possesses a left-handed helicity and the antineutrino possesses a right-handed helicity and hence neutrino and antineutrino differ only in the sense of their helicity.

12.4 THE FUNDAMENTAL INTERACTIONS

There are four kinds of interactions between elementary particles for all known processes in the physical universe on all scales of size. They are strong interaction, weak interaction, electromagnetic interaction and gravitational interaction.

Strong interaction A familiar example of strong interaction is the nuclear forces which binds the nucleons in the nucleus. The strong nuclear interaction is effective within the nucleus of radius 10^{-15} m and the Coulomb repulsive force becomes predominant outside the nucleus. The interaction is charge independent and it is not electric in nature. This interaction is stronger than other known electrostatic and gravitational interactions. The time interval of such interaction is roughly 10^{-23} sec.

Electromagnetic interaction Electromagnetic interaction operates on all charged particles. The interaction between like charges is attractive and repulsive between unlike charges.

Thus electromagnetic interactions are charge-dependent. The range of electromagnetic interaction is infinite. The formation of electron-positron pair production from a gamma ray photon is an example of electromagnetic interaction.

Gravitational interaction Gravitational interaction is the weakest of the four types of interactions. The range of gravitational interaction is infinite. Although the gravitational force has a measurable influence on macroscopic bodies, its interaction with subnuclear particles is very small. The interaction of a particle known as graviton with matter makes the gravitational interaction. The mass of graviton must be zero and therefore its velocity must be that of light. As the gravitational field is extremely weak, the graviton cannot be detected in the laboratory.

Weak interaction The beta decay of radioactive nuclei and decays of strange particles are typical examples of weak interactions. The weak interaction involved in leptons and hadrons takes place in a time 10^{-8} to 10^{-10} sec. It is a very short range force and is mediated through bosons. The intrinsic strength of weak interaction is 10^{-10} times smaller than that of electromagnetic interaction. In weak interaction, the strangeness quantum number and charge conjugation are not conserved. The parity may be violated in some cases as in beta decay.

Table 12.2 gives the summary of four fundamental interactions.

The number of charge states of a multiplet can be found by the formula $2I + 1$ where, I is called the isospin quantum number and is assigned to have a particular value. Thus, the nucleon multiplet to have its isospin $I = \frac{1}{2}$ and has $2 \times \frac{1}{2} + 1 = 2$ states which are proton and neutron charge states. The pion multiplet has $I = 1$ and it has $2 \times 1 + 1 = 3$ states which are π^-, π^-, and π^o charge states.

12.6 CONSERVATION LAWS

The behaviour of elementary particles is restricted by a number of conservation laws or invariance principles. That is, certain properties of physical quantities must remain unchanged in any process. The most familiar quantities in large-scale experiments that are conserved in all interactions (strong, weak, and electromagnetic and graviational) are conservation of linear momentum, angular momentum, energy, charge, baryon number and lepton number.

Conservation of linear momentum The total linear momentum is conserved in all the interaction. It is related to the invariance of the physical laws under translation in space. Thus, the laws of interaction do not depend on the place of measurement so that space is homogeneous.

Conservation of angular momentum The conservation of angular momentum includes both types of orbital and spin angular momentum. The orbital angular momentum is given by the motion of the object as a whole about any chosen external axis of rotation. The second is the intrinsic angular momentum of each object about an axis through its own centre of mass.

Strongly interacting fermions have a half integer spin $s = \frac{1}{2}$ for $\Xi, \Sigma, \Lambda,$ n and p, $s = \frac{3}{2}$ for Ω, strongly interacting bosons have spin $s = 0$ for η, K and π, weakly interacting fermions have spin $s = \frac{1}{2}$ for leptons μ, e, ν_e, ν_μ, mass-less bosons have $s = 1$ and gravitons have $s = 2$.

Conservation of energy In conservation of energy, a large fraction of total energy is often interchanged between rest energy associated with mass and kinetic energy or potential energy. The sum of these three, the total energy is always conserved in any reaction.

Conservation of charge The most familiar of the conservation laws is the conservation of electric charge. The charge is conserved in all processes and no exception is known. We should note that the elementary charges are 1, 0 or –1 and multiple charges are not found.

Conservation of baryon number In the case of baryons, the number of baryons minus the number of antibaryons must be conserved. In other words, the net baryon number in any process remains unchanged. All normal baryons such as $p^+, n^o, \Lambda^o, \Sigma^+, \Sigma^-, \Sigma^o, \Xi^-, \Xi^o$ and Ω^- have a baryon number of +1 and antiparticles have a baryon number of –1. All mesons have a baryon number zero.

Conservation of lepton number In the case of leptons, the number of leptons minus the number of antileptons must be conserved. In other words the net leptons number in any process remains unchanged. The electron, negative muon and neutrino have a lepton number +1 and the corresponding antiparticles known as antileptons have a lepton number of –1. The reaction $n \rightarrow p + e^- + \bar{\nu}$ is allowed because both baryon number and lepton number are conserved in this reaction.

Conservations in one or two interactions There are some other properties which are not conserved for all the three interactions (strong, weak and electromagnetic) but are conserved in one or two interactions only. These are conservation of isospin, hypercharge, strangeness, charge conjugation (C), space inversion invariance-parity (P) and time reversal (T).

Conservation of isospin Isospin numbers are associated with hadrons, the particles that can exhibit strong interaction but not leptons. The isospin component is conserved in both strong and electromagnetic interactions but not in weak interaction.

In the case of nucleons, the isospin value is $\frac{1}{2}$ and so there are two ($2I + 1 = 2$) charge states. The possible value of isospin I_s are $+\frac{1}{2}$ for the proton state and $-\frac{1}{2}$ for the neutron state. For pions, the isospin value is 1 and so there are three ($2I + 1 = 3$) charge states. The triplets consists of π^+, π^0 and π^- particles and the corresponding isospin I values are $+1, 0, -1$.

The use of I for the isospin is not likely to cause confusion with the same symbol employed for the so called spin of a nucleus. Some physicists represent the isospin by T, but the obvious symbol I is more widely used.

Conservation of hypercharge A quantity called hypercharge is also conserved in strong and electromagnetic interactions. The hypercharge is equal to the sum of strangeness and baryon number of the particle families ($Y = S + B$). For example, for the triplet π^+, π^o and π^-, the average charge is zero and hence all these three mesons have a hypercharge of zero.

The hypercharge of the pair of the particles K^+ and K^o is $+1$ and that of the pair of antiparticles K^- and $\bar{K}^0$ is -1. The alternate definition for the hypercharge is twice the difference between the actual charge Q and the isospin component I of a particle. Thus hypercharge $Y = 2(Q - I_s)$.

Conservation of strangeness Strangeness is an additional quantum number which describes the interaction of elementary particles. Strange particles possess the quantum number strangeness number (S). The strangeness quantum number (S) is conserved in the strong interactions in the cases of kaons and hyperons. The strangeness number $S = 0$ for nucleons and non-zero for hyperons ($S = 1$ for $K^+, K^o, \overline{\Lambda}^o, \overline{\Sigma}^+, \overline{\Sigma}^o, \overline{\Sigma}^-$, $S = 2$ for particles $\overline{\Xi}^o, \overline{\Xi}^+$, $S = -1$ for particles $K^-, \overline{K}^o, \Lambda^o, \Sigma^+, \Sigma^o, \Sigma^-$, $S = -2$ for particles Ξ^o, Ξ^- and $S = 0$ for other hadrons).

Invariance principles and symmetries It is probable that every conservation law is related to a corresponding invariance or symmetry principle. That is, a system or quantity remains unchanged as the result of a particular operation or operations although the nature of the operation or symmetry is not always apparent. The conservation of charge, baryon number, lepton number, isospin and hypercharge are associated with abstract rather than physical, symmetries or operations that have no relation to actual space and time. There are three conservative principles namely the conservation of parity, charge conjugation symmetry and time reversal in which the operations are expressed in physical terms.

Conservation of parity (P) It is known that the parity relates to the symmetry of the wave function that represents the system. If the sign of the wave function is unchanged, when the coordinates (x, y, z) are replaced by (−x, −y, −z), then the system has a positive parity of +1. If the sign of the wave function is changed, when the coordinates (x, y, z) are replaced by (−x, −y, −z), then the system has a negative parity of −1.

If the wave function is written as $\psi(x, y, z) = P\,\psi(-x, -y, -z)$, then the value of P can be assigned to have +1 or −1 for positive or negative parity. In a reaction, the total parity number should not change or the parity should be conserved. Indeed, the parity conservation is found to be true only in strong and electromagnetic interactions.

Charge conjugation symmetry (C) Charge conjugation is the act of symmetry operation in which every particle in a system is replaced by its antiparticle. If the antisystem or antimatter exhibits the same physical phenomena, then the charge parity (C) is conserved. For example, if in a hydrogen atom, the proton is replaced by antiproton and the electron is replaced by positron, then the antimatter hydrogen atom also behaves exactly like an ordinary atom. However, the charge parity (C) is not conserved in weak interaction.

Conservation of time reversal (T) The time parity or time reversal *T* describes the behaviour o a wave function, when *t* is replaced by −*t*, in all equations of motion. The symmetry operation tha corresponds to the conservation of time parity is time reversal. If symmetry under time reversa holds, it is impossible to establish by viewing it whether a motion picture of an event is being rur forward or backward.

Prior to 1964, time parity *T* was considered to be conserved in every interaction. It was discovere in 1964 that one form of the K° kaon can decay into $\pi^+ + \pi^-$ which violates the conservation of *T* The strong and electromagnetic interactions are invariant under time reversal transformation.

Example 12.1 Name the conservation law violated in the following reaction $v_e + p \rightarrow n + e^+$

Solution

Charge: $0+e \rightarrow 0+e$ $\qquad \Delta Q = 0$

Baryon number: $0+1 \rightarrow 1+0$ $\qquad \Delta B = 0$

Strangeness number: $0+0 \rightarrow 0+0$ $\qquad \Delta S = 0$

Lepton number: $1+0 \rightarrow 0+(-1)$ $\qquad \Delta L = 2$

In the reaction $v_e + p \rightarrow n + e^+$, the lepton number is not conserved.

Example 12.2 Answer whether the following reaction is allowed on the basis of conservati laws $p + \bar{p} \rightarrow 2\pi^+ + 2\pi^- + 2\pi''$

Solution

Charge: $+1e - 1e \rightarrow 2e - 2e + 0$ $\qquad \Delta Q = 0$

Baryon number: $1 - 1 \rightarrow 0 + 0 + 0$ $\qquad \Delta B = 0$

Strangeness number: $0 + 0 \rightarrow 0 + 0 + 0$ $\qquad \Delta S = 0$

Hypercharge: $1-1 \to 0+0+0$ $\qquad \Delta Y = 0$

The reaction $p + \bar{p} \to 2\pi^+ + 2\pi^- + 2\pi^0$ is allowed.

12.7 THE QUARK MODEL

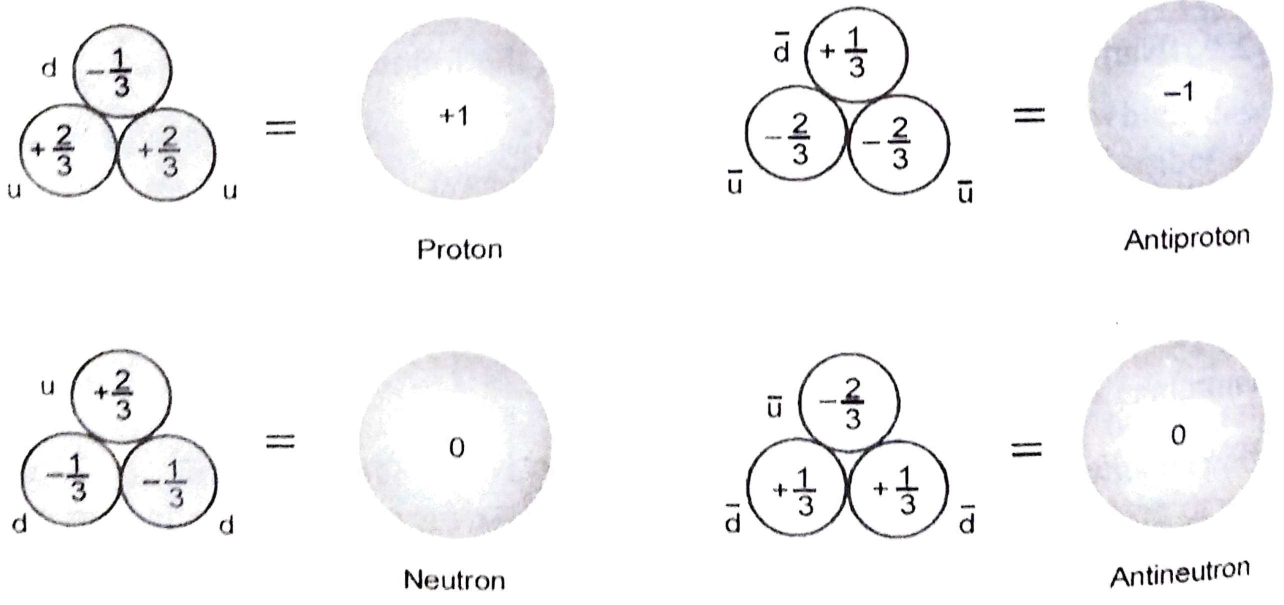
In 1964, Murray Gell-Mann and G. Zweig proposed the quark model. This theory is based on the idea that the hadrons are built up from a limited number of fundamental units which have acquired the name quarks. The original three quarks are labelled as u for up, d for down and s for strange.

u quark has electric charge $+\dfrac{2}{3}$ e and strangeness 0.

d quark has electric charge $-\dfrac{1}{3}$ e and strangeness 0.

s quark has electric charge $-\dfrac{1}{3}$ e and strangeness -1.

Each quark has a baryon number of $B = \dfrac{1}{3}$ and has an antiquark associated with it $(\bar{u}, \bar{d}, \bar{s})$. The magnitude of each quantum number associated with antiquarks has the same magnitude as that for the quarks, but the sign is changed.



Proton

Antiproton

Neutron

Antineutron

Figure 12.2 Quark models of proton, antiproton, neutron and antineutron

Hadrons may be baryons or mesons. A baryon is made up of three quarks. For example, the proton is made up of two up quark and down quark (uud). The electric charges for these quarks are

$+\frac{2}{3}$, $+\frac{2}{3}$ and $-\frac{1}{3}$ for a total value of +1. The baryon numbers are $+\frac{1}{3}$, $+\frac{1}{3}$ and $+\frac{1}{3}$ for a total of +1. The strangeness numbers are 0, 0 and 0 for a total strangeness of 0. All are in agreement with the quantum numbers for the proton.

Similarly, the neutron is made up of one up quark and two down quarks (*udd*). The electric charges for these quarks are $+\frac{2}{3}$, $-\frac{1}{3}$ and $-\frac{1}{3}$ for a total value of 0.

Figure 12.2 shows quark models of the proton, antiproton, neutron, antineutron. Electric charges are given in units of charge e.

A π^+ meson is made up of one quark and one antiquark. For example, meson is the combination of an up quark and a down antiquark ($(u\bar{d})$. Electric charges of these quarks are $+\frac{2}{3}$ and $+\frac{1}{3}$ for a total of +1. The baryon numbers are $+\frac{1}{3}$ and $-\frac{1}{3}$ for a total of 0. All are in agreement with the quantum numbers for the pi-meson. Quarks have the spins of $\frac{1}{2}$ which accounts for the observed half-integral spins of baryons and the 0 or 1 spins of mesons.

Table 12.4 shows the quark contents of five hadrons and how they account for the observed charges, spins and strangeness numbers of these particles.

Table 12.4 The composition of some hadrons according to quark model

Hadron	Quark content	Baryon number	Charge,e	Spin	Strangeness
π^+	$u\bar{d}$	$\frac{1}{3}-\frac{1}{3}=0$	$+\frac{2}{3}+\frac{1}{3}=+1$	$\uparrow\downarrow=0$	$0+0=0$
K^+	$u\bar{s}$	$\frac{1}{3}-\frac{1}{3}=0$	$+\frac{2}{3}+\frac{1}{3}=+1$	$\uparrow\downarrow=0$	$0+1=+1$
p^+	uud	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$	$\uparrow\uparrow\downarrow=\frac{1}{2}$	$0+0+0=0$
n^0	ddu	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$-\frac{1}{3}-\frac{1}{3}+\frac{2}{3}=0$	$\downarrow\downarrow\uparrow=\frac{1}{2}$	$0+0+0=0$
Ω^-	sss	$\frac{1}{3}+\frac{1}{3}+\frac{1}{3}=+1$	$-\frac{1}{3}-\frac{1}{3}-\frac{1}{3}=-1$	$\uparrow\uparrow\uparrow=\frac{3}{2}$	$-1-1-1=-3$