SEMESTER–II (Period–V)

TOPIC 6

Nuclear Chemistry

C11CH6

Learning Objectives

Upon completion of this topic, learners will:

- Describe radioactivity, including its historical development
- Explain how nuclear reactions differ from chemical reactions
- Describe the types and nature of radiations
- Explain the role of half-life in the stability of the nucleus
- Distinguish between fusion and fission and
- Explain the effects and applications of radioactivity.

6.1. HISTORY OF RADIOACTIVITY

Discovery of radioactivity in uranium by French physicist **Henri Becquerel** in 1896 forced scientist to radically changed their ideas about atomic structure. Discovery of cathode rays and anode rays showed that is neither indivisible nor immutable. Instead of serving merely as an inner matrix for electrons the atoms could change form and emit an enormous amount of energy. Radioactivity became an instrument for revealing the interior of atom. It was almost an accidental discovery when French physicist Henri Bequerel opened a drawer and discovered spontaneous radioactivity in March 1986. After the discovery of X ray which have ability to penetrate through black paper. X rays also penetrated the soft body tissues. This usefulness of X rays was seen as a good scope in the field of imaging. After learning about Rontgen finding of X rays, Baccqured thought that the phosphorescent uranium salts he had been studying might absorb sunlight and unit is as X rays. He in order to test wrapped photographic plates in black paper so that sunlight could not reach them. He then placed crystals of uranium salts on the top of wrapped plates and put the whose setup outside the sun. When plates were developed he saw an outline of the crystals. He also put coins and cut out metal shapes between the crystals and photographic plates and he found that outlines of those shapes appeared on photographic plates. He then concluded that uranium salts absorbed sunlight and emitted a penetrating radiation similar to X rays. He planned for further experiments but whether in Paris was not sunny. In order to wait in Feb. 1896 for sunny days he kept the uranium crystals and photographic plates away in the drawer. On March 1 1896 he opened the drawer and developed the plates. He was astonished to see very clear images of crystals on the photographic plates. He first thought that the effect was due to long lasting phosphorescence but soon he discovered that uranium salts emitted some new radiations of their own. He again did experiments on non phosphorescent uranium compounds and found that they also show the same effect.

He was firstly of the opinion that his rays were similar to X rays which were neutral but his rays, as he found, could be deflected by electric or magnetic field. It means those rays have some charged particles.

In 1898 Marie and Pierre curie in Paris began to study the storage uranium rays. During the course of they soon found other radioactive elements polonium, thorium and radium. Marie curie conived the term "radioactivity" to describe the new phenomenon. Soon Earnst Rutherford and Fredrick Soddy explained radioactivity as spontaneous transmutations of elements. For their discoveries Becquerel and the Curie shared the 1903 Nobel Prize for their work on radioactivity.

Definition: The spontaneous emission of active radiations by certain elements like uranium is called radioactivity and the elements are called radioactive elements.

The radioactive rays emitted when passed through strong electric on magnetic fields, are resolved into

(*a*) α **rays:** The rays which deflected slightly towards negative plate were named as α rays.

(*b*) β **rays:** The rays which deflected towards a positive plate were named as β rays.

(*c*) γ **rays:** The rays which remained undeflected were named as γ rays.

α rays consist of positively charged He^{2+} particles. The charge on α ray particles is 3.20×10^{-19} coulombs and its mass is 6.6×10^{-24} g. β rays are made up of electrons while γ rays are high energy electromagnetic radiations having no charge and negligible mass.

Table 6.1. Characteristics of α, β and γ-rays

Property	*α-rays*	*β-rays*	*γ-rays*
1. Mass	6.67×10^{-27} kg or 4 amu	9.11×10^{-31} kg	Negligible
2. Charge	+ 2 units	–1 unit	0
3. Identity	Helium nuclei (He^{++})	Electrons	High energy radiations
4. Velocity	Nearly 1/10th that of light	Nearly same as that of light (3.0×10^8 m/s)	Same as that of light
5. Effect of electric fields	Deflected towards negative plate	Deflected towards positive plate	Not deflected
6. Penetrating power	Small	Large, 100 times that of α-rays	Very large, 10000 times that of α-rays

Why atoms become radioactive?

There may be two possibilities with the atoms. Atoms may either be stable or unstable. If forces among constituent particles in the nucleus are balanced then atom is balanced. If forces among constituent particles are unbalanced then atoms are unstable. This unstability of atoms is the cause of radioactive decay of atoms. Unstability of nucleus of an atom because of excess of either neutrons or protons is the cause of radioactivity. A radioactive atom tries to attain stability by ejecting nucleons (protons or neutrons), as well as other particles or by releasing energy in other forms.

The nuclear stability bond shows various combinations of neutrons/ protons combinations that give rise to different types of observable nuclei with measurable half lives. Bond of nuclear stability shows that various types of radioactive processes undergone by various nuclides in the region from $z = 66$ (dysprosium) through $z = 79$ (Gold). Nuclides with lower neutron) proton ratio shows positron emission, electron capture, or alpha emission, while nuclei with higher neutron/proton ratio show beta emission.

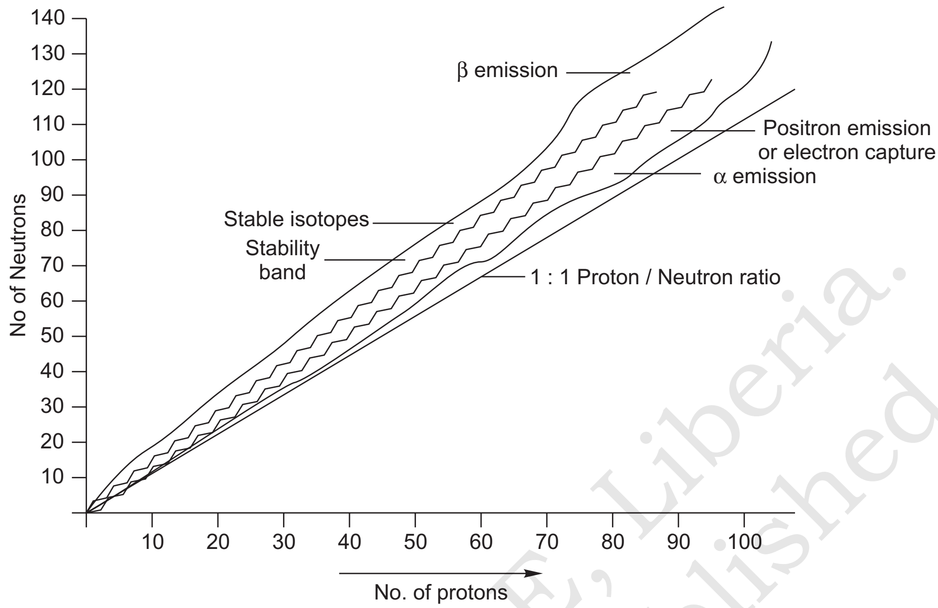

Fig. 6.1. Bond of nuclear stability

Second measure of stability is binding energy, which is the amount of energy required to overcome the strong nuclear force and pull apart a nucleon. When binding energy is more stability is also more.

Result of Emission of Radiations on Atoms

When a nucleus emits radiation or disintegrates, the radioactive atom (radionuclide) transforms to a different nuclide. This process of radioactive decay continues till the forces in the nucleus are balanced. When a radio nuclide decays, it will become a different isotope of the same element if it gives of neutrons. If it gives off protons, then a different element is formed.

Radiations in Everyday Life

Radioactivity is existed all along the globle. Natural radioactive materials are present in earth's crust in our homes, school offices and in the food we eat and drink. There are some radioactive gases in the air which we breath. In our body also, muscles, bones and tissues contain naturally occurring radio active elements. We are exposed to natural radiations emitted on the earth as well as coming from outside the earth. Such radiations which we receive from outer space is called cosmic radiations or cosmic rays. We also receive exposure from man made radiations such as X rays radiations used to diagnose diseases and for cancer therapy. Fall outs from nuclear explosive testing and small quantities of radioactive materials released to the environment from coal and nuclear power plants are also the source of radiation exposure to man.

Nuclear Reactions

As we know that nuclear chemistry is the study of reaction that involve changes in nuclear structure. Nuclear reactions are the reactions with are related with the nucleus and its constituents. Nuclear reaction is a process that occurs as a result of interaction between atomic nuclei when the interacting particles approach each other to within in distances of order of nuclear dimensions (-10^{-12} cm). While nuclear reactions occur in nature understanding of them and use of them as tools have taken place primarily in the controlled laboratory environment. In the usual experimental situation nuclear reaction are initiated by bombarding one of the interacting particles, the stationary target nucleus, with nuclear projectiles of some type, and the reaction product and their behaviour are studied.

How Nuclear Reactions Differ from Chemical Reactions

(*i*) Chemical reaction take place outside the nucleus while nuclear reactions occur only inside the nucleus. During chemical reactions atoms do not change their identity and nuclei of the atoms also remain unchanged. Nuclear reactions take place inside the nucleus as a result of which nuclei of atoms change completely and new elements are formed. In a chemical reaction reactants reacts chemical to form products by the way of chemical change. During a chemical reaction identity of elements remain same, and it does not change their identity. Elements and atoms on reactant side and product side in a chemical reaction remain same. No new atom or element is formed. But during nuclear reaction atoms and elements do not remain same and loose their identity to form new elements for example. In the following chemical reaction.

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

The number of carbon, hydrogen and oxygen atoms remain same on reactant side as well as product side of a chemical reaction identity (atomic mass or atomic number) are not changed and no new atom or element is formed.

Now take an example of a nuclear reaction.

$$^{14}C \xrightarrow{\text{Radio active decay}} {}^{14}N + \beta^- \text{ (beta particles)}$$

Here identity of carbon is changed and a new element ^{14}N is formed. There is a change in the nuclear composition of 14c.

(*ii*) Rate of chemical reactions are influenced by external effects like temperature, pressure and catalyst while. Rates of nuclear reaction are spontaneous and are unaffected by such factors.

(*iii*) Nuclear reactions do not depend upon the chemical form of the element. Same amount of radioactive element shows similar radio-activity whether it is in elemental or in compound state.

(*iv*) Chemical reaction follow law of conservation of mass. Nuclear reaction to don't follow law of conservation of mass. In nuclear reactions a huge amount of energy is released due to destruction of mass as in atom bomb or in nuclear reactors. As per $E = mc^2$

(*v*) In a chemical reaction the reactivity of elements depend upon their oxidation states; but nuclear reaction the reactivity of an element in a nuclear reaction is independent of its oxidations state.

(*vi*) Chemical reactivity of different isotopes is almost same in chemical reactions while nuclear reactivity of an isotope of an element differ drastically. e.g. ^{238}U is less reactive than ^{235}U.

(*vii*) Chemical reaction are almost reversible, while nuclear reactions are almost irreversible.

(*viii*) In a chemical reaction generally in electrons present in outer orbits participate while neutrons and protons do not participate in chemical reaction. Neutrons and Protons participate in nuclear reactions.

(*ix*) During chemical reactions new bonds form and old bonds break between the reacting atoms. During nuclear reactions nuclear fission and nuclear fusion take place.

Soddy's Displacement Law of Radioactive Transformations

1. When a nucleus ejects an α-particle, the mass becomes less by 4 units and charge decreases by 2 units. Thus, the nucleus $^{A}_{Z}Y$ on emission of α-particle gets transformed into a new nucleus $^{A-4}_{Z-2}Y$.

$$\therefore \qquad ^{A}_{Z}Y \xrightarrow{\alpha} {}^{A-4}_{Z-2}Y$$

Thus, the substance shifts or is displaced from its original position in the periodic table, two steps backwards.

2. When a nucleus ejects a β-particle, the mass remains unchanged and the charge increases by 1 unit. So a material ${}^{A}_{Z}Y$ on emission of β-particle gets transformed into a new nucleus as ${}^{A}_{Z+1}Y$.

Thus, the original substance shifts or is displaced one step higher in the periodic table.

Thus, $${}^{A}_{Z}Y \xrightarrow{\beta} {}^{A}_{Z+1}Y$$

3. When a nucleus emits γ-rays, the mass or the charge or the position of the nucleus in the periodic table are not affected. Only some energy is radiated and the original nucleus shifts from higher energy level to lower energy level.

Rutherford and Soddy's Laws of Radioactive Decay

1. The disintegration of radioactive material is purely a random process and it is merely a matter of chance, which nucleus will suffer disintegration, or decay first.

2. The rate of decay is completely independent of the physical composition and chemical condition of the material.

3. The rate of decay is directly proportional to the quantity of material actually present at that instant. Thus, as the decay goes on, the original material goes on decreasing in quantity and the rate of decay consequently goes on decreasing.

Thus from the third law, if N is the number of radioactive atoms present at any instant, then the rate of decay,

$$-\frac{dN}{dt} \propto N \quad \text{or} \quad -\frac{dN}{dt} = \lambda N,$$

where λ is the decay constant or the disintegration constant.

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

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

On integration $\log_e N = -\lambda t + C$

where C is the integration constant.

If at $t = 0$, we had N_0 atoms, $\log_e N_0 = 0 + C$

Thus, we get, $\log_e N - \log_e N_0 = -\lambda t$

or $$\log_e \frac{N}{N_0} = -\lambda t$$

or $$\frac{N}{N_0} = e^{-\lambda t} \quad \text{or} \quad N = N_0\, e^{-\lambda t}.$$

This equation represents the radioactive decay law. It gives the number of active nuclei left after time *t*.

Radioactive Disintegration Constant λ

According to the laws of radioactive decay, we have

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

If $dt = 1$ second, then $$\frac{dN}{N} = -\lambda$$

Thus, λ may be defined as the *relative number of atoms decaying per second.*

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

and if $t = \frac{1}{\lambda}$, we get $N = N_0\, e^{-1} = \frac{N_0}{e}$

Thus, λ is also defined as *the reciprocal of the time when* $\frac{N}{N_0}$ *falls to* $\frac{1}{e}$.

6.2. HALF LIFE OF RADIO ACTIVE ELEMENTS

Some isotopes of radioactive elements is an indefinitely stable while others are radioactive. Such radioactive and unstable isotopes are emit radiation during the process of decay using their mass into energy as a result of which with the passage of time the mass and number of atoms starts decreasing and a time comes whom its mass becomes just half in comparison of initial mass. Such time required to reduce the mass of a radioactive element to half is half life of that element. The decaying process continues, mass goes on decreasing but half life time is always same for that element.

Half life of a radioactive isotope is the amount of time it takes for one half of the radioactive isotope to decay. Half life of a specific radio active isotope is constant, and it is independent of the initial amount of that isotope.

The radio active isotope cobalt 60, which is used for radiotherapy, has a half life of 5.26 years. After passage of 5.26 years of time a sample of 12 g of Cobalt 60 will become 4 g and would emit only half amount of radiations. After another 5.26 years the sample would contain only 3 gms of Cobalt 60.

Visibly mass and volume of cobalt-60 seems to remain same inspite of radioactive decay. This is because the unstable cobalt-60 nuclei decay into stable nickel-60 nuclei remains with still undecayed cobalt.

Half lives are significant properties of unstable atomic nuclei of radioactive element. Alpha, beta, decay are slower process than gama decay. Half life of beta decay upwards from $\frac{1}{100}$th of a second, for alpha decay this period upwards from one millionth of a second. Half life for gamma rays may be around 10^{-14} second.

Half-Life Period

Consider the situation when the decaying material is reduced to exactly $\frac{1}{2}$ of its original quantity. The time taken for this decay $\left(\frac{N}{N_0} = \frac{1}{2}\right)$ is called the half-life period of the material. *It is defined as the time required for the disappearance of half of the amount of the radioactive substance originally present.*

If T represents the half-life period, then

$$\frac{N}{N_0} = \frac{1}{2} = e^{-\lambda T} \text{ or } e^{\lambda T} = 2$$

$$\therefore \quad \lambda T = \log_e 2 = 0.6931$$

$$\therefore \quad T = \frac{0.6931}{\lambda} \quad \text{or} \quad \lambda = \frac{0.6931}{T}$$

Combining these relations, we obtain

$$\frac{N}{N_0} = e^{-\lambda t} \quad \text{or} \quad \frac{N_0}{N} = e^{\lambda t}$$

$$\therefore \quad \log_e \frac{N_0}{N} = \lambda t \quad \text{or} \quad 2.303 \log_{10} \frac{N_0}{N} = \frac{0.6931}{T} t$$

or
$$t = \frac{2.303}{0.6931} T \log_{10} \frac{N_0}{N}$$

or
$$t = 3.323 \, T \log_{10} \frac{N_0}{N}$$

This relation shows that a material with a half-life period T changes in quantity from N_0 to N in time t.

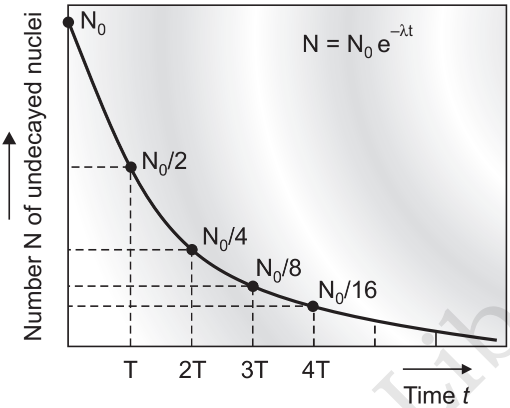

Fig. 6.2. Exponential decay of a radioactive species. After a lapse of T, population of the given species drops by a factor of 2.

Plutonium and tritium are not found in observable quantities in nature because their half life is very less.

Formula for Number of Atoms Left Behind after *n* Half-Lives

Let N_0 be the number of atoms of a radioactive substance in the beginning. After time T, the number of atoms left will be $\frac{N_0}{2}$. After a time 2T, the number of atoms left will be $\frac{1}{2} \times \frac{N_0}{2}$ *i.e.*, $N_0 \left(\frac{1}{2}\right)^2$. After a time 3T, the number of atoms left will be $\frac{1}{2} \times N_0 \left(\frac{1}{2}\right)^2$ *i.e.*, $N_0 \left(\frac{1}{2}\right)^3$. Proceeding in the same way, the number of atoms left behind after n half-lives will be $N_0 \left(\frac{1}{2}\right)^n$.

$$\therefore \qquad N = N_0 \left(\frac{1}{2}\right)^n$$

If t is the time corresponding to n half-lives, then $t = n\,T$

or $\qquad n = \frac{t}{T} \qquad \therefore \qquad N = N_0 \left(\frac{1}{2}\right)^{t/T}$

Activity of a Radioactive Substance

The activity or rate of decay of a sample is defined as the number of radioactive disintegrations taking place per second in the sample.

If a radioactive sample contains N radioactive nuclei at any time t, then its activity or decay rate R at time t will be

$$R = \frac{dN}{dt}.$$

The negative sign indicates that the activity of the sample decreases with the passage of time.

According to the radioactive decay law,

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

$$\therefore \qquad R = \lambda N$$

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

$$\therefore \qquad R = \lambda N_0 e^{-\lambda t}$$

$$\text{or} \qquad R = R_0 e^{-\lambda t}$$

This is another form of radioactive decay law. Here $R_0 = \lambda N_0$, is the decay rate at time $t = 0$. R is the decay rate at time t. Clearly, R decreases exponentially with time.

Units of Radioactivity

The activity of a radioactive sample is generally expressed in terms of its rate of decay. In other words, the activity of a radioactive sample is expressed in terms of the number of disintegrations per unit time. The radioactivity is measured in the following three units.

The definition of curie says nothing about the nature of decays. **This unit is not appropriate to describe the ionising effects of** X-rays from, say, a medical X-ray machine. The radiation must be emitted only from a radionuclide.

(*i*) The curie (Ci). This was originally defined as the activity of 1 g of radium in equilibrium with its by-products. But it is now defined as under :

The activity of a radioactive substance is said to be one curie if it undergoes 3.7×10^{10} disintegrations per second.

$$1 \text{ curie} = 3.7 \times 10^{10} \text{ disintegrations/s}$$

Smaller units are millicurie and microcurie.

$$1 \text{ millicurie} = 3.7 \times 10^7 \text{ disintegrations/s}$$
$$1 \text{ microcurie} = 3.7 \times 10^4 \text{ disintegrations/s}$$

(*ii*) The rutherford (Rd). *The activity of a radioactive substance is said to be one rutherford if it undergoes 10^6 disintegrations per second.*

$$1 \text{ rutherford} = 10^6 \text{ disintegrations s}^{-1}$$

Smaller units are millirutherford and microrutherford.

$$1 \text{ millirutherford} = 10^3 \text{ disintegrations s}^{-1}$$
$$1 \text{ microrutherford} = 1 \text{ disintegration s}^{-1}$$

(*iii*) The becquerel (Bq). *It is the SI unit for activity. The activity of a radioactive substance is said to be one becquerel if it undergoes 1 disintegration per second.*

$$1 \text{ becquerel} = 1 \text{ disintegration s}^{-1}$$

Relation between different units

$$1 \text{ curie} = 3.7 \times 10^4 \text{ rutherford}$$
$$= 3.7 \times 10^{10} \text{ becquerel.}$$

6.3. TYPES AND NATURE OF RADIATIONS

Alpha Decay

The phenomenon of emission of an α-particle from a radioactive nucleus is called **alpha decay**. When a nucleus undergoes alpha decay, it transforms to a different nucleus by emitting an alpha particle (a helium nucleus, ${}^4_2\text{He}$). Since an alpha particle consists of two protons and two neutrons, an alpha decay reduces the Z, N and A of the original nucleus by two, two and four respectively.

Transformation of ${}^A_Z\text{X}$ nucleus into ${}^{A-4}_{Z-2}\text{Y}$ nucleus by an alpha decay is expressed by the following equation :

$${}^A_Z\text{X} \longrightarrow {}^{A-4}_{Z-2}\text{Y} + {}^4_2\text{He}$$

The energy Q released in the process can be obtained from Einstein's mass-energy relation. It is given by

$$Q = (m_X - m_Y - m_{He})\, c^2$$

This energy is shared both by the daughter nucleus ${}^{A-4}_{Z-2}\text{Y}$ and the alpha particle ${}^4_2\text{He}$.

Some **examples** of emission of α-particle are :

$$^{210}_{84}\text{Po} \longrightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\text{He}$$

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

$$^{232}_{90}\text{Th} \longrightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He}$$

$$^{238}_{92}\text{U} \longrightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

Speed of α-particles

Transformation of the $^{A}_{Z}X$ nucleus into the $^{A-4}_{Z-2}Y$ nucleus by an alpha-decay can be expressed by the equation

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\text{He} + Q$$

$$Q = (m_X - m_Y - m_{He})\, c^2$$

As the parent nucleus $^{A}_{Z}X$ is at rest before it undergoes alpha decay, alpha particles are emitted with fixed energy, which can be calculated by applying the principles of conservation of energy and momentum. Let v_{He} and v_Y be the velocities of the alpha particle and the daughter nucleus, $^{A-4}_{Z-2}Y$. The principle of conservation of momentum gives

$$m_Y\, v_Y = m_{He}\, v_{He} \qquad \text{...(1)}$$

By equating the sum of kinetic energies of the nucleus Y and the alpha particle to the energy released in the alpha decay, we have another equation

$$\frac{1}{2}\, m_{He}\, v_{He}^2 + \frac{1}{2}\, m_Y\, v_Y^2 = Q$$

Substituting the value of v_y from eq. (1), we get

$$\frac{1}{2}\, m_{He}\, v_{He}^2 + \frac{1}{2}\, m_Y\, \frac{m_{He}^2\, v_{He}^2}{m_Y^2} = Q$$

or $$\frac{1}{2}\, m_{He}\, m_Y v_{He}^2 + \frac{1}{2}\, m_{He}^2\, v_{He}^2 = m_Y Q$$

or $$\frac{1}{2}(m_Y + m_{He}) = m_{He}\, v_{He}^2 = m_Y Q$$

or $$\frac{1}{2}\, m_{He}\, v_{He}^2 = \frac{m_Y}{m_Y + m_{He}}\, Q \qquad \text{...(2)}$$

If we substitute $m_Y \simeq A - 4$ amu and $m_{He} \simeq 4$ amu in eq. (2), the kinetic energy carried by the alpha particle can be approximated by the relation

$$KE_{He} = \frac{1}{2} m_{He} v_{He}^2 \simeq \frac{(A-4)}{A} Q$$

In the decay of $^{222}_{86}Rn$, Q = 5.587 MeV and KE_{He} = 5.486 MeV. The velocity of the alpha particle emitted by $^{222}_{86}Rn$ can be easily estimated from its kinetic energy.

$$v_{He} = \sqrt{\frac{2 \times 5.486 \times 1.6 \times 10^{-13}}{4.00 \times 1.66 \times 10^{-27}}} \text{ m s}^{-1} = 1.63 \times 10^7 \text{ m s}^{-1}.$$

Beta Decay

(*i*) Definition. Beta decay is a process in which a nucleus decays spontaneously by emitting an electron or a positron.

Like alpha decay, it is a spontaneous process with a definite disintegration energy and half-life.

In beta-minus (β^-) decay, an electron is emitted by the nucleus. In beta- plus (β^+) decay, a positron is emitted by the nucleus.

(*ii*) Difficulties in explanation of beta decay.

(*a*) *Presence of electron in the nucleus.* It is difficult to understand this process because there are strong arguments against the presence of electron in the nucleus. However, this difficulty is solved if we assume that (*i*) a neutron inside the nucleus breaks up into a proton and an electron (*ii*) the electron is ejected from the nucleus immediately after its creation. In other words, we have assumed that the neutron within the beta-emitting nucleus is radioactive just like a free neutron.

(*b*) *Apparent violation of law of conservation of energy.* If we study the energy distribution of electrons emitted in the β-decay of $^{210}_{83}Bi$, it is observed that the energy varies between zero and 1.17 MeV (Fig. 6.3). It is of course very rare that the emitted electron has an energy of 1.17 MeV. Most of the electrons have an energy of 0.15 MeV. This presents another serious difficulty in the proper understanding of the process of beta decay. For every $^{210}_{83}Bi$-decay, the same mass vanishes but very few emitted electrons possess an energy of 1.17 MeV. This creates doubts about the validity of the law of conservation of energy itself. We cannot even say that the 'energy difference' is taken away by γ-rays because there is no emission of γ-radiation in the example under consideration.

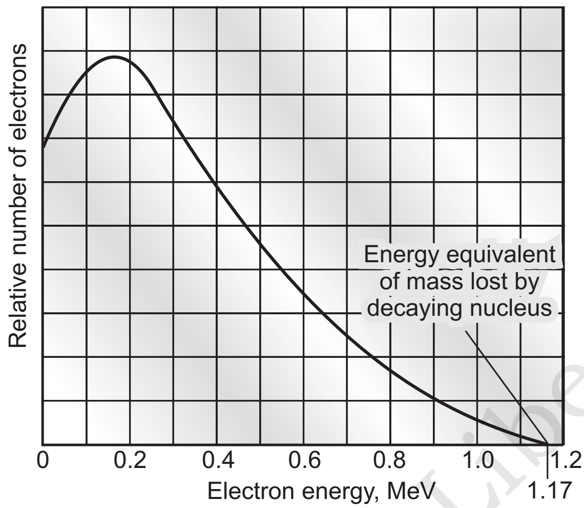

Fig. 6.3. Energy spectrum of electrons from the beta decay of $^{210}_{83}Bi$.

(*c*) ***Apparent violation of law of conservation of momentum.*** When the directions of the emitted electrons and of the recoiling nuclei are observed, they are almost never exactly opposite as required for linear momentum to be conserved.

(*d*) ***Apparent violation of law of conservation of angular momentum.*** The spins of the neutron, proton and electron are all $\frac{1}{2}$. If beta decay involves just a neutron becoming a proton and an electron, spin (and hence angular momentum) is not conserved.

(***iii***) **Emission of neutrino/antineutrino.** All the difficulties were overcome in 1933 by Wolfgang Pauli who proposed that a second particle is also emitted and assigned theoretically the following properties to this particle:

(*i*) zero rest mass (*ii*) zero charge (*iii*) a spin equal to $\frac{1}{2}$.

Enrico Fermi developed the theory of this new particle and called it neutrino. It was later on found that two kinds of neutrinos are involved in beta decay, the neutrino and the antineutrino. In the beta-minus decay, a neutron (inside the nucleus) transforms into a proton. An electron and anti-neutrino are emitted.

$$n \rightarrow p + e^{-} + \bar{\nu} \quad ...(1)$$

In the beta-plus decay, a proton (inside the nucleus) transforms into a neutron. A positron and neutrino are emitted.

$$p \rightarrow n + e^{+} + \nu \qquad ...(2)$$

These processes show why the mass number A of a nuclide undergoing beta decay does not change.

(*iv*) Sharing of disintegration energy. The disintegration energy is shared by the daughter nucleus, electron or positron and neutrino or antineutrino. So, kinetic energy of electron or positron in β-decay is not unique. The energy of electron or positron may range from zero to some maximum value. The maximum energy is called end-point energy.

(*v*) A free neutron can decay. In beta-minus decay, $n \rightarrow p + e^{-} + \bar{\nu}$

Since the mass of the neutron is greater than the combined mass of a proton and electron therefore the Q value is positive. The process is energetically allowed. So, a neutron outside the nucleus can decay as suggested by the above equation.

(*vi*) A free proton cannot decay. In beta-plus decay, $p \rightarrow n + e^{+} + \nu$

The Q value of this reaction is negative. So, a proton outside the nucleus cannot decay unless it gets additional energy in some collision. *Note that the behaviour of a free proton is different from the behaviour of a bound proton.* In-fact, a free proton is stable. The life time of a free proton is greater than the life of our universe.

(*vii*) Electron-capture (third type of beta decay). The third type of beta decay is electron capture. In electron capture, an orbital electron (usually in the K shell) combines with a proton in the nucleus to form a neutron and a neutrino. The neutron remains in the nucleus and the neutrino is emitted.

$$p + e^{-} \rightarrow n + \nu$$

A remains constant, N increases by one and Z decreases by one.

When one of the atom's outer electrons falls into the resulting vacant state, an X-ray photon is emitted.

Electron capture is competitive with positron emission. Both the processes lead to the same nuclear transformation. Electron capture occurs more often than positron emission in heavy nuclides. This is because the electrons in such nuclides are relatively close to the nucleus.

Gamma Decay

Just like an excited atom, an excited nucleus can make a transition to a state of lower energy by emitting a photon. The energies of the atomic states of hydrogen are of the order of electron volts. So, the wavelength of light emitted in atomic transitions correspond to photons having energy of the order of electron volts. On the other hand, the energies of the nuclear states are of the order of million electron volts. So, the photons emitted by nuclei can have energy of the order of several million electron volts. The wavelength of photons of such energy is a fraction of an angstrom. The short wavelength electromagnetic waves emitted by nuclei are called the gamma rays. Most radioisotopes, after an alpha decay or a beta decay, leave the daughter nucleus in an excited state. An excited nucleus is denoted by an asterisk after its usual symbol. Thus, ${}^{87}_{38}Sr^{*}$ refers to ${}^{87}_{38}Sr$ in an excited state.

Excited nuclei return to their ground states by emitting photons whose energies correspond to the energy differences between the various initial and final states in the transitions involved. The photons emitted by nuclei range in energy upto several MeV. These are traditionally called gamma rays.

Fig. 6.4 shows the beta decay of ${}^{27}_{12}Mg$ to ${}^{27}_{13}Al$. The half-life of the decay is 9.5 min and it may take place to either of the two excited states of ${}^{27}_{13}Al$. The resulting ${}^{27}_{13}Al^{*}$ nucleus then undergoes one or two gamma decays to reach the ground state.

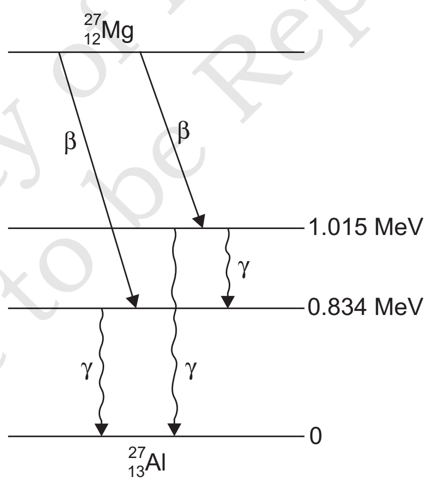

Fig. 6.4

Let us now consider another example. It is the decay of ${}^{60}_{27}Co$. By beta emission, the ${}^{60}_{27}Co$ nucleus is first transformed into an excited ${}^{60}_{28}Ni$ nucleus which in turn reaches the ground state by emitting photons of energies 1.17 MeV and 1.33 MeV. Fig. 6.5 shows the process through an energy level diagram.

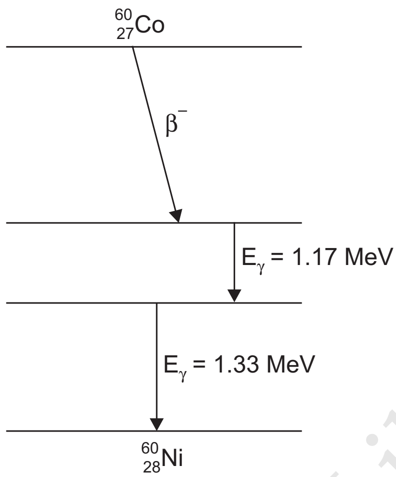

Fig. 6.5

As an alternative to gamma decay, an excited nucleus in some cases may return to its ground state by giving up its excitation energy to one of the orbital electrons around it. This process is known as internal conversion. It can be regarded as a kind of photoelectric effect in which a nuclear photon is absorbed by an atomic electron. The internal conversion in-fact represents a direct transfer of excitation energy from a nucleus to an electron. The emitted electron has a kinetic energy equal to the lost nuclear excitation energy minus the binding energy of the electron in the atom.

Most excited nuclei have very short half-lives against gamma decay. But a few remain excited for as long as several hours. A long-lived excited nucleus is called an isomer of the same nucleus in its ground state. The excited nucleus $^{87}_{38}Sr^*$ has a half-life of 2.8 hour and is accordingly an isomer of $^{87}_{38}Sr$.

6.4. NUCLEAR REACTIONS

When a nucleus is bombarded with nucleons or other sub-atomic particles, it undergoes a change in composition. A nuclear reaction indicates that change. *A nuclear reaction may be defined as the transformation in nuclei brought about by their interaction with elementary particles or with different nuclei themselves.*

Most nuclear reactions involve a nucleus A and a particle '*a*', This pair is known as *parent pair*. After a collision between these two, a new nucleus B is formed and another particle '*b*' is ejected. This pair is called the *final pair*. The nuclear reaction may be expressed as under :

$$A + a \longrightarrow B + b$$

In some reactions, energy Q is evolved. Such a reaction is known as **exothermic or exoergic reaction**. In a reaction in which energy is absorbed, the reaction is known as **endothermic or endoergic reaction**. So, in the final analysis, a nuclear reaction may be written as under :

$$A + a \longrightarrow B + b + Q$$

Here, in the usual expression, *a* is the bullet fired on a target A. This results in the recoil nucleus B and giving the product particle *b* with a release or absorption of reaction energy Q. Q is known as the reaction energy or Q-value of nuclear reaction. *The absorption or evolution of energy in a nuclear reaction takes place in accordance with Einstein's mass-energy equivalence relation.*

Important Nuclear Reactions

1. γ-ray photon as projectile. A nuclear reaction in which γ-ray photon is the projectile is known as *photo-nuclear reaction* or *photo disintegration reaction.*

(*i*) (γ-*n*) reaction. $^{2}_{1}H + \gamma \rightarrow {}^{1}_{1}H + {}^{1}_{0}n$

$$^{9}_{4}Be + \gamma \rightarrow {}^{9}_{4}Be \rightarrow {}^{8}_{4}Be + {}^{1}_{0}n$$

(*ii*) (γ-*p*) reaction. $^{9}_{4}Be + \gamma \rightarrow {}^{8}_{3}Li + {}^{1}_{1}H$

2. Neutron as projectile:

(*i*) (*n*-γ) reactions

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

$$^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U \longrightarrow {}^{239}_{92}U + \gamma$$

(*ii*) (*n*-*p*) reactions

$$^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{15}_{7}N \longrightarrow {}^{14}_{6}C + {}^{1}_{1}H$$

$$^{27}_{13}Al + {}^{1}_{0}n \longrightarrow {}^{28}_{13}Al \longrightarrow {}^{27}_{12}Mg + {}^{1}_{1}H$$

(*iii*) $$^{27}_{13}Al + {}^{1}_{0}n \longrightarrow {}^{28}_{13}Al \longrightarrow {}^{26}_{13}Al + 2\,{}^{1}_{0}n$$

(*iv*) (*n*-α) reactions

$$^{6}_{3}Li + {}^{1}_{0}n \longrightarrow {}^{7}_{3}Li \longrightarrow {}^{3}_{1}H + {}^{4}_{2}He$$

$$^{10}_{5}B + {}^{1}_{0}n \longrightarrow {}^{11}_{5}Li \longrightarrow {}^{7}_{3}Li + {}^{4}_{2}He$$

3. Proton as projectile:

(*i*) (*p*-α) reactions

$$ {}^{7}_{3}\text{Li} + {}^{1}_{1}\text{H} \longrightarrow {}^{8}_{4}\text{Be} \longrightarrow {}^{4}_{2}\text{He} + {}^{4}_{2}\text{He} $$

$$ {}^{9}_{4}\text{Be} + {}^{1}_{1}\text{H} \longrightarrow {}^{10}_{5}\text{B} \longrightarrow {}^{6}_{3}\text{Li} + {}^{4}_{2}\text{He} $$

(*ii*) (*p*-*n*) reactions

$$ {}^{7}_{3}\text{Li} + {}^{1}_{1}\text{H} \longrightarrow {}^{7}_{4}\text{Be} + {}^{1}_{0}n $$

$$ {}^{18}_{8}\text{O} + {}^{1}_{1}\text{H} \longrightarrow {}^{18}_{9}\text{F} + {}^{1}_{0}n $$

(*iii*) (*p*-*d*) reactions

$$ {}^{7}_{3}\text{Li} + {}^{1}_{1}\text{H} \longrightarrow {}^{6}_{3}\text{Li} + {}^{2}_{1}\text{H} $$

$$ {}^{9}_{4}\text{Be} + {}^{1}_{1}\text{H} \longrightarrow {}^{8}_{4}\text{Be} + {}^{2}_{1}\text{H} $$

(*iv*) (*p*-γ) reactions

$$ {}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \longrightarrow {}^{13}_{7}\text{N} + \gamma $$

$$ {}^{27}_{13}\text{Al} + {}^{1}_{1}\text{H} \longrightarrow {}^{28}_{14}\text{Si} + \gamma $$

4. Deuteron as projectile:

(*i*) (*d*-α) reactions

$$ {}^{6}_{3}\text{Li} + {}^{2}_{1}\text{H} \longrightarrow {}^{8}_{4}\text{Be} \longrightarrow {}^{4}_{2}\text{He} + {}^{4}_{2}\text{He} $$

$$ {}^{16}_{8}\text{O} + {}^{2}_{1}\text{H} \longrightarrow {}^{18}_{9}\text{F} \longrightarrow {}^{14}_{7}\text{N} + {}^{4}_{2}\text{He} $$

(*ii*) (*d*-*p*) reactions

$$ {}^{12}_{6}\text{C} + {}^{2}_{1}\text{H} \longrightarrow {}^{14}_{7}\text{N} \longrightarrow {}^{13}_{6}\text{C} + {}^{1}_{1}\text{H} $$

$$ {}^{31}_{15}\text{P} + {}^{2}_{1}\text{H} \longrightarrow {}^{33}_{16}\text{S} \longrightarrow {}^{32}_{15}\text{P} + {}^{1}_{1}\text{H} $$

(*iii*) (*d*-*n*) reactions

$$ {}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \longrightarrow {}^{3}_{2}\text{H} + {}^{1}_{0}n $$

$$ {}^{12}_{6}\text{C} + {}^{2}_{1}\text{H} \longrightarrow {}^{14}_{7}\text{N} \longrightarrow {}^{13}_{7}\text{N} + {}^{1}_{0}n $$

5. α-particle as projectile:

(*i*) (α-*p*) reactions

$$ {}^{10}_{5}\text{B} + {}^{4}_{2}\text{He} \longrightarrow {}^{14}_{7}\text{N} \longrightarrow {}^{13}_{6}\text{C} + {}^{1}_{1}\text{H} $$

$$ {}^{23}_{11}\text{Na} + {}^{4}_{2}\text{He} \longrightarrow {}^{27}_{13}\text{Al} \longrightarrow {}^{26}_{12}\text{Mg} + {}^{1}_{1}\text{H} $$

(*ii*) (α-*n*) reactions

In general, α-*n* reaction is represented as:

$$ {}^{A}_{Z}\text{X} + {}^{4}_{2}\text{He} \longrightarrow {}^{A+4}_{Z+2}\text{Cn} \longrightarrow {}^{A+3}_{Z+2}\text{Y} + {}^{1}_{0}n $$

Examples :

$${}^{7}_{3}\text{Li} + {}^{4}_{2}\text{He} \longrightarrow {}^{11}_{5}\text{B} \longrightarrow {}^{10}_{5}\text{B} + {}^{1}_{0}n$$

$${}^{9}_{4}\text{Be} + {}^{4}_{2}\text{He} \longrightarrow {}^{13}_{6}\text{C} \longrightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}n$$

In many cases, in addition to the emission of neutrons, γ-rays are also emitted by the excited nuclei. Moreover, neutrons also possess very high energy.

6.5. CONSERVATION LAWS IN NUCLEAR REACTIONS

Broadly, the following conservation laws are obeyed in nuclear reactions.

(*i*) **Conservation of number of nucleons.**

(*ii*) **Conservation of charge.** In a reaction, the total electric charge is conserved. This ultimately means that the total Z number, the atomic number is conserved.

(*iii*) **Conservation of linear momentum.** Like all physical processes involving collisions, the total momentum along any direction, before and after the event, is always conserved.

(*iv*) **Conservation of angular momentum.**

(*v*) **Conservation of mass-energy.** According to mass-energy equivalence in the theory of relativity, mass and energy are equivalent. So the principle of conservation of energy in mechanics has to be extended to the conservation of mass-energy in nuclear reactions. The mass-energy equation for the nuclear reaction may be written as :

$$m_1c^2 + E_{k_1} + m_2c^2 + E_{k_2} = m_3c^2 + E_{k_3} + m_4c^2 + E_{k_4}$$

where m_1, m_2, m_3 and m_4 are the rest masses and E_{k_1}, E_{k_2}, E_{k_3} and E_{k_4} are their respective kinetic energies.

Nuclear Fission

In 1939, German Scientists Otto Hahn and Strassmann while studying nuclear reactions, discovered that when a uranium nucleus is bombarded with a neutron, it explodes into two nearly equal fragments, Barium and Krypton. Since this process somewhat resembles fission of cells in biology, therefore this phenomenon of nuclear disintegration was also called fission.

Nuclear fission *is defined as a type of nuclear disintegration in which a heavy nucleus splits up into two nuclei of nearly comparable masses with liberation of energy.*

The fission is accompanied by the release of three neutrons and radiation energy in the form of γ-rays. The reaction is represented as :

$$^{1}_{0}n + ^{235}_{92}U \longrightarrow [^{236}_{92}U] \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + \gamma$$

The diagrammatic sketch is given in Fig. 6.6. A neutron strikes the ^{235}U nucleus and in the process two nuclides ^{141}Ba and ^{92}Kr are formed with the release of 3 neutrons as shown. The wavy lines indicate the energy released in the form of γ-radiations. An important point to note here is that a *slow* neutron is used to cause fission. Further whereas one neutron is lost in the process to produce fission, three neutrons are produced as a product of the fission. This fact has a tremendous significance in the construction of nuclear bomb.

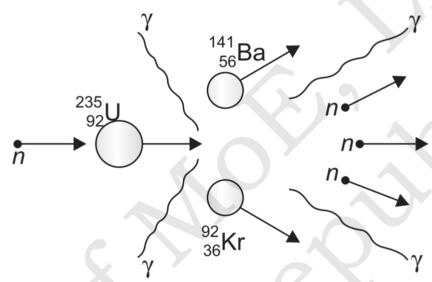

Fig. 6.6. Nuclear fission

Energy released in fission. The fission fragments Barium, Krypton and neutrons are released with high velocities. Also energy is released in the form of γ-rays. An estimate can be made as in the example given below :

Before the reaction:

Mass of $^{235}_{92}U$ = 235.0439 amu ; Mass of $^{1}_{0}n$ = 1.0087 amu

Total mass = 236.0526 amu ...(*i*)

After the reaction:

Mass of $^{141}_{56}Ba$ = 140.9129 amu ; Mass of $^{92}_{36}Kr$ = 91.8973 amu

Mass of three $^{1}_{0}n$ = 3.0261 amu

Total mass = 235.8363 amu ...(*ii*)

Mass defect = 0.2163 amu [(*i*) – (*ii*)]

Since 1 amu = 931 MeV,

∴ The energy released = 931 × 0.2163 = 201.37 MeV ≈ 200 MeV

This is a huge figure. Calculations reveal that 235 g of Uranium, on complete fission, releases energy equivalent to the burning of about

600 tonnes of coal. However, this 200 MeV consists of K.E. of fission fragments, of released neutrons and of the γ-rays. Eventually, it is transferred to the surrounding matter appearing as heat.

Nuclear Fission Explained on the Basis of Liquid-drop Model

Nuclear fission can be understood on the basis of the liquid-drop model of the nucleus. When a liquid-drop is suitably excited, it may oscillate in a variety of ways. A simple one is shown in Fig. 6.7. The drop in turn becomes a prolate spheroid, a sphere, an oblate spheroid, a sphere, a prolate spheroid again, and so on. The restoring force of its surface tension always returns the drop to spherical shape, but the inertia of the moving liquid molecules causes the drop to overshoot sphericity and go to the opposite extreme of distortion.

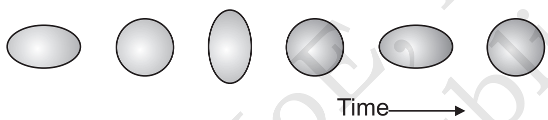

Fig. 6.7. The oscillation of a liquid-drop.

Nuclei exhibit surface tension, and so can vibrate like a liquid-drop when in an excited state. They also are subject to disruptive forces due to the mutual repulsion of their protons. When a nucleus is distorted from a spherical shape, the short-range restoring force of surface tension must cope with the long-range repulsive force as well as with the inertia of the nuclear matter. If the degree of distortion is small, the surface tension can do this, and the nucleus vibrates back and forth until it eventually loses its excitation energy by gamma decay. If the degree of distortion is too great, however, the surface tension is unable to bring back together the now widely separated groups of protons and the nucleus splits into two parts. This picture of fission is illustrated in Fig. 6.8.

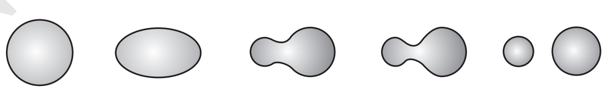

Fig. 6.8. Nuclear fission according to the liquid-drop model

Chain Reaction

If the energy available per reaction is large and one reaction can trigger reaction in other nuclei, then the nuclear reaction will act as a real source of energy.

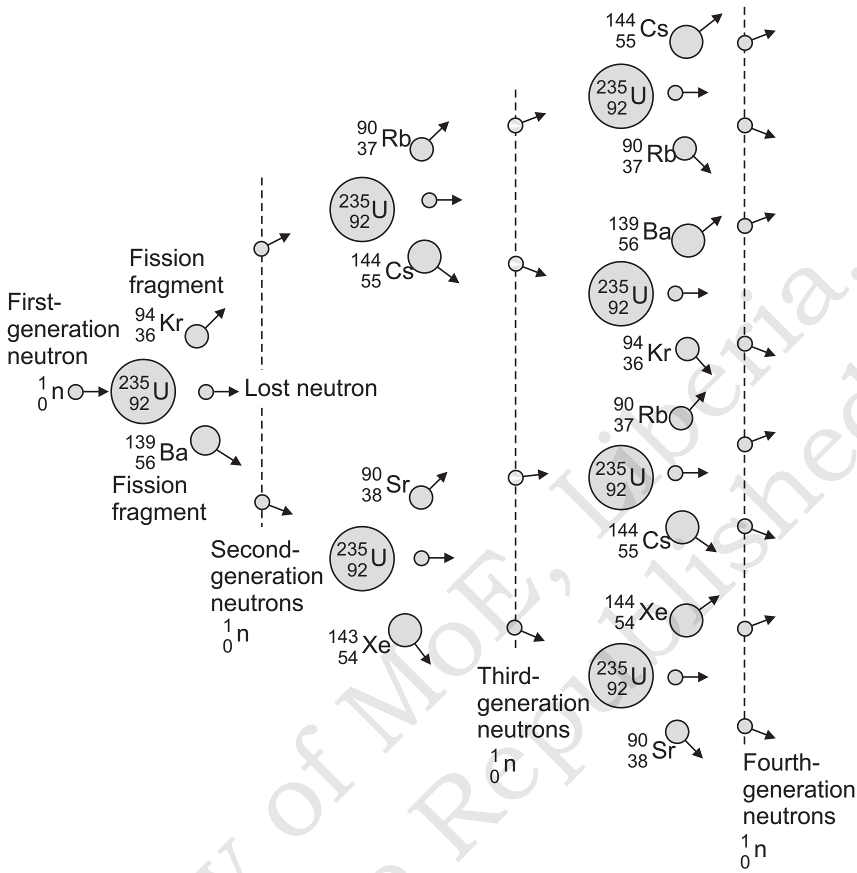

Fig. 6.9. Chain reaction.

When a single Uranium nucleus undergoes fission, it releases a number of neutrons. Some of them are absorbed in the body of the material and some in air. At least, two may be capable of having the right speed to cause further fission. The number of neutrons produced and available for further fission divided by the number of neutrons present initially before the reaction is called the *reproduction factor.* This reproduction factor k should be at least equal to one so that the nuclear reaction may be sustained. It may be > 1. A case when $k = 2$ is shown as a sketch in Fig. 6.9. Here one single neutron is absorbed to cause a nuclear reaction. And in so doing, it releases two neutrons which take over this job further. Under suitable circumstances, these secondary neutrons cause the fission of more nuclei and yield more secondary neutrons. Thus, the whole process takes place in a *geometric progression* and the reaction once started continues to gather momentum rapidly. This is known as a *chain reaction.* Every time a ^{235}U splits, 200 MeV energy is released. Partly it goes to give the K.E. to the fragments but quite a sizeable portion of this is released in the form of γ-rays. It has been calculated that a neutron takes about 10^{-8} second from its release from a nucleus to cause the splitting of another nucleus. Thus, 200 MeV energy is released in just 10^{-8} s. Thus, in about a μs (10^{-6} s), the total energy released in a chain reaction would be about 2×10^{13} J. This is really a large quantity of energy and if left uncontrolled, it would cause a violent explosion. This uncontrolled chain reaction is utilised in the nuclear bomb-popularly known as atom bomb.

Critical size. For chain reaction to occur, the size of the material must be within certain limits. The neutrons produced as a result of one fission may (*i*) be straying out due to leakage from the surface ; or (*ii*) be absorbed in the non-fissionable part in the system ; or (*iii*) be absorbed in the system itself if the size of the system is so large that the velocity of the neutron becomes very small ; and is of too low energy to cause further fission. It has been estimated that a released neutron must travel about 10 cm so that it is now properly slowed down to cause further fission. If the size of the material is less than 10 cm in any direction, the neutron simply crosses it and goes out without doing any further fission. So *if the material is too small, no fission is possible.* Thus, there has to be an optimum size of the material such that the neutrons once released would be slowed down in the material to the right speed and further chain reaction may get going. This optimum size of the material is called the **critical size.** The corresponding mass is called the **critical mass.** If the size of ^{235}U piece is equal to the critical size, then number of neutrons lost is just equal to the number of neutrons produced.

It is thus to be noted that if the size of the fissionable material is less than the critical size, a chain reaction is simply not possible and the material is quite safe to handle. But if the material is of a size greater than the critical size, it may capture a stray neutron and start an uncontrolled chain reaction, resulting in a violent spontaneous explosion, and consequent release of energy.

Nuclear Fusion

We know 'fission' to be a process in which a heavy nucleus breaks up into two lighter nuclei. Fusion, on other hand, is the reverse of fission. Thus, fusion *is a process in which lighter nuclei merge into one another to form a heavier nucleus.* As in fission, fusion also is accompanied by a release of energy.

The binding energy per nucleus thus formed is greater than the binding energy per nucleon of the lighter elements, which fuse to form the single nucleus. Taking an example, let us consider the fusion of the deuterium nuclei to form a single helium nucleus :

We know that mass of a deuteron = 2.01471 amu

∴ Mass of two deuterons = 4.02942 amu

Mass of α-particle (*i.e.*, a Helium nucleus) = 4.00388 amu

∴ Δm, mass defect = 0.02554 amu

Since 1 amu = 931 MeV,

∴ The energy liberated = 0.02554 × 931 MeV

= 23.78 MeV ≈ 24 MeV

Thus, a single helium nucleus formed out of fusion of two deuterons (*i.e.*, deuterium nuclei) releases 24 MeV energy. In case a large number of helium nuclei are fused, we readily see that a tremendous amount of energy is released.

Since both the deuterons are similarly charged (+ 1), therefore, we require a large amount of energy to bring the two together for fusion against Coulomb repulsion. Though theoretically this energy may be given to them by accelerating them through strong electric field, practically it is not easy or convenient. The other alternative is to give them high thermal energies. In the Sun and the stars, such high temperatures (≈ 10 Million K) are available which impart enough energy to the fusing particles which are protons or deuterons. Thus, such a fusion process is called a *thermonuclear fusion.*

Energy Source of Stars and Sun

(*i*) Proton-Proton Cycle. The interior of Sun is at about 27 million K. The thermonuclear reactions taking place are as follows :

$$^{1}_{1}H + ^{1}_{1}H \longrightarrow ^{2}_{1}H + ^{0}_{1}e + 0.4 \text{ MeV} \qquad ...(i)$$

$$^{1}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{2}He + 5.5 \text{ MeV} \qquad ...(ii)$$

$$^{3}_{2}He + ^{3}_{2}He \longrightarrow ^{4}_{2}He + 2^{1}_{1}H + 12.9 \text{ MeV} \qquad ...(iii)$$

The reactions (*i*) and (*ii*) occur twice. So, the net reaction is :

$$4^{1}_{1}H \longrightarrow ^{4}_{2}He + 2^{0}_{1}e + 24.7 \text{ MeV}$$

Thus at that high temperature available in the core of the Sun, four protons fuse into a Helium nucleus with the release of two positrons and 24.7 MeV of energy.

(*ii*) Carbon-Nitrogen Cycle. It is understood that for stars whose interior temperatures are greater than that of Sun, a Carbon-Nitrogen cycle takes place to produce the desired thermonuclear fusion reactions. It takes place as indicated below:

$$^{12}_{6}C + ^{1}_{1}H \longrightarrow ^{13}_{7}N + h\nu \text{ (energy)}; \quad ^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{1}e \text{ (positron)}$$

$$^{13}_{6}C + ^{1}_{1}H \longrightarrow ^{14}_{7}N + h\nu \text{ (energy)}; \quad ^{14}_{7}N + ^{1}_{1}H \longrightarrow ^{15}_{8}O + h\nu \text{ (energy)}$$

$$^{15}_{8}O \longrightarrow ^{15}_{7}N + ^{0}_{1}e \text{ (positron) + energy}; \quad ^{1}_{1}H + ^{15}_{7}N \longrightarrow ^{12}_{6}C + ^{4}_{2}He$$

The net result of this complete cycle of reactions is that four protons fuse into one helium nucleus with the emission of positrons and release of energy.

Hydrogen Bomb

We know that a thermonuclear fusion reaction involving the fusion of four protons into a helium nucleus or two deuterons into a helium nucleus releases tremendous energy. This energy is produced by the Sun for peaceful purposes to sustain our life. But man has made use of this very energy to create a weapon of destruction—the hydrogen bomb.

Fusion cannot take place at ordinary temperatures. So, initially in the hydrogen bomb, we have a small fission bomb, which on explosion, causes the temperature to rise very high to about 10^7 K. At this temperature, a fusion of lighter nuclei takes place and helium nuclei are formed with the release of tremendous energy in an uncontrolled manner. Since proton is a hydrogen nucleus, we in a layman's language call this instrument of destruction as a hydrogen bomb. It is obvious that its explosive power is greater than that for a fission bomb ; because in reality the hydrogen bomb is a combination of both the processes-fission to produce the desired initial high temperature and fusion to produce the extra energy for devastation.

Radiation Hazards

After the invention of the nuclear reactions as a pure scientific study, man developed the atomic and hydrogen bombs in an attempt to gain supremacy over other men. But in this process, the large amount of radiated energy to which mankind as a whole is exposed is really posing a problem even for human existence. These radiations are causing great dangers to human organism.

For instance, let us see how γ-ray acts on a human system. When γ-ray or any high energy nuclear particle passes through any material, it knocks out electrons from its atoms and ionises them. With the atom thus broken and ionised, the complex molecular structure of the organism becomes weak and may break up. This breaking up of the molecules disrupts the entire normal functioning of the biological system. This leads to a permanent damage of the tissues, and ultimately leads to death.

The extent to which a human organism is damaged depends upon (*i*) the dose and the rate at which the radiation is being given, (*ii*) the part of the body exposed to it. Our hands and feet, not being vital organs, can receive much greater dose than other parts of the body. The damage itself can be either (*i*) **pathological** or (*ii*) **genetic.**

In the **pathological damage,** the organism exposed to the radiation may ultimately die. This happens when the body is exposed to about 600 *r*. Smaller dose of 100 *r* approximately may cause a start of leukemia (death of red blood corpuscles in the blood) or cancer, which on spreading causes death ultimately.

The **genetic damage** is still worse. The radiations cause injury to genes in the reproductive cells. This gives rise to mutations which pass on from generation to generation. Mutations are always harmful and are irreversible. There is no way to escape from the results of this damage. In a simple language, it may mean that a person exposed to such damage may have a certain disorder; and all his subsequent generations will continue having the same disorder in their systems. The only hope and prayer is that when one is exposed to these radiations, the exposure is too small to cause any serious damage.

When an atom bomb explodes nearby, the radiations are extremely intense and sudden. This causes immediate death and destruction of life, pathologically, and damage to the heredity, by genetic damage.

Nuclear holocast: Large scale destruction and devastation caused by nuclear weapons is known as nuclear holocast.

Types and Nature of Radiations

In natural radioactive decay, three common emissions are observed. As scientists were unable to identify them as some already known particles hence name them alpha particles (α), beta particles (β) and gama rays (γ) using first three letters of Greek alphabet. Later alpha particles were identified as H^{-4} nuclei, Beta particles as electrons and gama rays as electromagnetic radiations.

Alpha Particles: Alpha particles are identical to helium nucleus. Alpha particles are positively charged particled made up of two protons and two neutrons from an atom's nucleus. Heaviest radioactive elements like uranium, radium and polonium. Because of two protons and two neutrons, alpha particles are heavy particles so they move only up to short distances even if they are very energetic. They are unable to travel very far from the atom.

Alpha particles are unable to penetrate even the outer layer of the skin. Hence exposure to alpha particles is not problem, but alpha particles can damage soft tissues inside our body if swallowed, inhaled or enter into our body through a cut. They are more dangerous as they cause more severe damage to cells and DNA. They are able to release all their energy in few cells. For example uranium$^{238}_{92}$decays to form thorium$^{234}_{90}$

$^{238}_{92}U \longrightarrow Th + ^{4}_{2}He$ equation for alpha decay is $^{A}_{Z}X \longrightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He$

Alpha decay occurs in heaviest elements and have energy level upto 5 MeV and speed of amount 5% of light.

Beta Particles β: Beta particles are small, fast moving, negatively charged electrical particles emitted from an atoms nucleus during radioactive decay. β-particles are emitted by certain unstable atoms such as hydrogen–3 (tritium), carbon-14 and strontium-90 and sulphur-35. β particles are more penetrating but less damaging to living tissues than alpha particles because they produced widely spaced ionizations. They move farther in air than alpha particles but can be stopped by a layer of clothings or by a thin layer of aluminium. Some β particles are capable of penetrating the skin and causing damage such as skin burns. β emitters are more harmful and dangerous than alpha emitter if they are inhaled or swallowed. Beta particles is 1/7000th the size of an alpha particle.

Gama Rays γ: Gama rays are weightless particles of energy. Unlike alpha and beta particles which have both mass and energy, gama rays are pure energy. Gama rays are emitted immediately after the ejection of alpha or beta particles during radio active decay. Gama rays are like visible light but have much energy.

Gama rays are hazardous for our entire body. They are more penetrating than alpha and beta particles. They can penetrate clothes as well as skin. Gama rays pass through several inches thick dense material like lead and 1–2 feet of concrete even. Gama rays can pass through complete human body and cause ionisation as a result of which tissues and DMA can be damaged.

X-rays: X rays are just like gama rays as they are photons of pure energy. X rays and gama rays have same basic properties but originate from different parts of atoms. Gama rays are emitted from inside of the nucleus while X rays are emitted from outside the nucleus. X rays have less energy and are less penetrating than gama rays. X rays can be produced both naturally and by machines using electricity.

X rays are publically known because of their use in medicines. X ray machines are used world wide in medical field. Computerised tomography (CT or CT scan) use specialised X ray machine to make high resolution images of bones and soft tissues in the body. X-rays are also in use for inspection and control processes in industries.

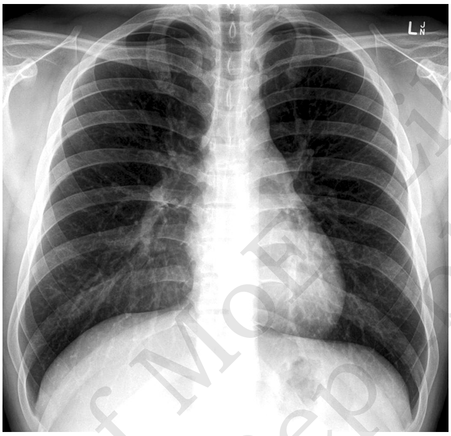

Fig. 6.10. Picture of X ray

Natural Radiations: Radiations are present naturally all around us. We have been adapted to these natural radiations as we have evolved in a world containing significant level of ionizing radiations.

The United Nations Scientific Committee on the effect of Atomic Radiation (UNSCER) identifies four major sources of public exposure to natural radiation.

(*a*) Cosmic radiation
(*b*) Terrestrial radiation
(*c*) Inhalation
(*d*) Ingestion

(*a*) **Exposure from cosmic radiations:** Our planet's atmosphere is continuously bombarded by cosmic radiations coming from sun, and other celestial bodies and events in the space. Cosmic radiations consist of fast moving particles, protons, or wave energy. Such ionising radiations which enter earth's environment are absorbed by human beings which results in natural radiation exposure. High altitudes receive more radiations.

(*b*) **Exposure from Terrestrial Radiations:** Deposits of uranium, thorium and potassium found as natural deposits in earths crust, release small amount of ionizing radiations which become the cause of exposure to natural radiations.

(*c*) **Exposure through inhalations:** Gases like radon and thoron are produced by uranium 238 and thorium found in the soil and bedrock. These gases when released in air get accumulated in houses in the mining areas and cause exposure to human beings through inhalation.

(*d*) **Exposure through ingestion:** Traces of radioactive mineral are found in vegetables, grains and ground water. Once ingested these minerals result in internal exposure to natural radiation. Naturally occurring radioisotopes like K^{40} and carbon 14 are such radioactive minerals.

Table 6.2. Radioactive isotropes in Body (70 kg adult)

Isotope	*Amount of radio activity in Bq.*
Uranium	2.3
Thorium	0.21
Potassium 40	4000
Radium 266	1.1
Carbon 14	3700
Polonium 210	40

Artificial Sources of Radiation: Radiation are also emitted by the way of following:

(*a*) **Atmospheric testing:** We receive smaller doses of fall out of radioactive material because of testing of atomic weapons by different countries. Radioactive material having short half life do not exist for longer time but those with more half life decay slowly and exist for longer time.

(*b*) **Medical sources:** X ray, CT scanners, MRI machines release radiations. Nuclear medicines containing radioactive isotopes used in the treatment of diseases like cancer are also the source of radiations.

(*c*) **Industrial sources:** Radioactive materials used in nuclear gauges (used to build roads), density gauges (used to measure flow of material through pipes), spread radiation in the environment, smoke detectors glow signs and some of the sterilizers spread radiations.

(*d*) **Nuclear power plants:** Nuclear power plants use uranium which being radioactive elements spreads radiations around nuclear power plant inspite of best checks and controls.

Ionizing Power of Radiations

When radiation particles attack the atoms, the impact causes atoms to loose electrons to form ions. Alpha particles have highest ionizing power and greatest ability to damage tissue.

The process in which electron is given enough energy to break away from atoms is called ionisation which results in the formation of two charged ions, the molecule with net positive charge and a free electron with negative charge.

Gama radiations have least ionizing power, beta radiations have 100 times the ionising strength of game radiations and alpha radiations have 1000 times the ionizing power of gama radiations.

Penetrating Power: Penetrating power is defined as the power of the radiation to pass through the matter. The more material the radiation can pass through, the greater the penetrating power and the more dangerous they are. The greater the mass of radiation particles, greater the ionizing power and lower the penetrating power.

6.6. EFFECTS AND APPLICATIONS OF RADIOACTIVITY

Radiations interact with matter to produce exitation and ionization of atoms and molecules and cause physical and biological effects. Radiations have effects on human life also. Radiation have some uses and applications also. Radiations also have played a significant role in improving the quality of human life. Radio isotopes are useful in the field of, tracing, radiography, food preservations, sterilization, eradication of insects and pests, medical diagnosis and therapy, and new variety of crops in agricultural field.

Effects of Radioactivity

Radiations emitted by radioactive isotopes release much energy and produce physical chemical and biological changes. Damage is caused by interaction of this energy with nuclei or orbiting electrons resulting in change of material structure and properties.

(*a*) **Effect on Metals:** Radiations effect on metals was first recognised by Wigner in 1946. Effect of radiation depend on type and duration of radiations. Ionising radiations have two types of effects on metals

(*i*) By displacing the atoms from original position in lattice structure causing displacement damage production.

(*ii*) Chemical composition of the target can be changed by ion implantation or transmutation.

Neutrons released by radioactive elements cause increase in electrical and thermal resistance, hardness and tensile strength and decrease in ductibility. Thermal neutrons (the neutrons at high temperature have very less significant effect on mechanical properties of metals.

(*b*) **Effect on non metals:** Radiations increase the viscosity of oils and greese and make them gummy, tar like polymers. Rubber may be come harder or softer. Concavate heats up under radiation exposure resulting in swelling, cracking and spalling.

(*c*) **Effect on polymers:** When polymers are exposed to radiations, their ionised and excited species are formed due to bond rearrangement, chain scission radical formation etc. As a result chemical, electrical, mechanical, properties of polymers are changed leading to their applications in different scientific and technology fields.

(*d*) **Cross linking:** Due to radiation polymerisation two free radical monomers combine to form three dimensional network of cross linked high molecular polymer which possess high thermal resistance and strong mechanical strength.

(*e*) **Radiation grafting:** Radiations cause, grafting changes the surface of polymeric materials. Radiation induced grafting is used in a variety of applications biomedical environmental and industrial.

(*f*) **Degradation:** Radiation induced degradation is used to develop viscose, pulp, paper, food preservation, pharmaceutical production, and natural bio-active agent industries.

(*g*) **Biological effects of radiations:** Radiation may cause harmful health effects in human beings. Radiation cause damage to DNA of the tissues of human beings.

Applications of Radioactivity

1. **In medical field**

(*i*) Radio isotope Iodine 131 is used for determining. Cardiac output, plasma volume, fat metabolism and to measure the activity of thyroid gland.

(*ii*) Phophorus 32 is used for identifying malignant tumours cancer cells accumulate phosphorus more than normal cells.

(*iii*) Technetium 99 is used with radiographic scanning devices and for examining the anatomic structure of organs.

(*iv*) Radio isotopes cobalt-60 and cesium-137 are used to treat cancer.

2. **Industrial uses**

(*i*) Fission energy of uranium is used in nuclear power stations.

(*ii*) Radio isotopes are used to density of metals and plastic sheets.

(*iii*) Radio active substances are used to stimulate cross linking of polymers.

(*iv*) Radioactive substances are used to induce mutations in plants to develop harder seeds.

(*v*) Used to kill microbes that cause spoilage of tools.

(*vi*) Radio isotopes are used in tracer applications.

(*vii*) Radio isotypes are used in motor oils which increase the life of piston and ring alloys.

(*viii*) Radiometric dating is used to find out the age of rocks and rock formation.

3. **Carbon dating:** Carbon 14 dating is used to find out the age of fossils, old structures, rocks etc.

4. Radio isotopes are used to measure deep water currents and snow water content in water sheds.

5. Radioactive substances are used to sterlize mass reared insects so that they are not able to increase their progeny as a result life of crop is preserved and production is increased.

6. Radiation ^{60}Co and ^{137}Cs, X rays and electrobeams are used for food irradication and saved from attack of pests, insects, bacteria and fungi.

SUMMARY

- Discovery of radioactivity in uranium by French physicist **Henri Becquerel** in 1896 forced scientist to radically changed their ideas about atomic structure.
- The nuclear stability bond shows various combinations of neutrons/ protons combinations that give rise to different types of observable nuclei with measurable half lives.

- **Half life** of a radioactive isotope is the amount of time it takes for one half of the radioactive isotope to decay. Half life of a specific radio active isotope is constant, and it is independent of the initial amount of that isotope.
- The activity or rate of decay of a sample is defined as the number of radioactive disintegrations taking place per second in the sample.
- In 1939, German Scientists Otto Hahn and Strassmann while studying nuclear reactions, discovered that when a uranium nucleus is bombarded with a neutron, it explodes into two nearly equal fragments, Barium and Krypton.
- **Nuclear fission** *is* defined as a type of nuclear disintegration in which a heavy nucleus splits up into two nuclei of nearly comparable masses with liberation of energy.

EVALUATION

I. Multiple Choice Questions

1. The half-life of a certain radioactive element is such that 7/8 of a given quantity decays in 12 days. What fraction remains undecayed after 24 days?

(a) 0 (b) $\frac{1}{128}$

(c) $\frac{1}{64}$ (d) $\frac{1}{32}$

2. β-decay means emission of electron from

(a) innermost electron orbit. (b) a stable nucleus.

(c) outermost electron orbit. (d) radioactive nucleus.

3. A radioactive isotope has a half-life to T years. How long will it take the activity to reduce to 1% of its original value?

(a) 3.2T years (b) 4.6T years

(c) 6.6T years (d) 9.2T years

4. Fusion reaction takes place at high temperature because

(a) nuclei break up at high temperature.

(b) atoms get ionised at high temperature.

(c) kinetic energy is high enough to overcome the coulomb repulsion between nuclei.

(d) molecules break up at high temperature.

5. The half-life of an old rock element is 5800 years. In how many years its sample of 25 gm is reduced to 6.25 gm.
   (a) 2900 years (b) 5800 years
   (c) 11600 years (d) 23200 years
6. The fusion reaction in the sun is a multi-step process in which the
   (a) helium is burned into deuterons.
   (b) helium is burned into hydrogen.
   (c) deutron is burned into hydrogen.
   (d) hydrogen is burned into helium.
   (e) helium is burned into neutrons.
7. A nuclear fission is said to be critical when multiplication factor or K
   (a) $K = 1$ (b) $K > 1$
   (c) $K < 1$ (d) $K = 0$
8. What amount of original radioactive materials is left after 3 half-lines?
   (a) 6.5% (b) 12.5%
   (c) 25.5% (d) 33.3%
9. Nuclear fusion is not found in
   (a) thermonuclear reactor (b) hydrogen bomb
   (c) energy production in sun (d) atom bomb
   (e) energy production in stars.
10. During β-emission
   (a) a neutron in the nucleus decays emitting an electron.
   (b) an atomic electron is ejected.
   (c) an electron already present within the nucleus is ejected.
   (d) a part of the binding energy of the nucleus is converted into an electron.
   (e) a proton in the nucleus decays emitting an electron.

II. Descriptive Questions

1. Write one equation representing nuclear fusion reaction.
2. Name two radioactive elements which are not found in observable quantities in nature. Why is it so?
3. Write down the radioactive rays in the order of increasing penetrating power.
4. Very high temperature as those obtained in the interior of the sun are required for fusion reaction to take place.
5. The half-lives of radioactive nuclides that emit α-rays vary from microsecond to billion year. What is the reason for this large variation in the half-life of α-emitters?

6. An element emits in succession 2 α-particles and 1 β-particle. What is the change in mass number?
7. Why α-particles have a high ionising power?
8. What is the mass in g of a radioactive element whose activity is equal to 1 curie?

III. Numerical Questions

1. Explain with the help of a nuclear reaction in each of the following cases. How the neutron to proton ratio changes during (*i*) alpha decay (*ii*) beta decay.
2. A radioactive material is reduced to 1/10th of original amount in 4 days. How much material should one begin with so that 4×10^{-3} kg of the material is left over?

   (Ans. Original amount = $4 \times 10^{-3} \times 64$ kg = 0.256 kg)
3. A radioactive isotope has a half life of 10 years. How long will it take for the activity to reduce to 3.125%? (**Ans.** Required Time = 50 years)
4. A radioactive isotope has a half life of T year. How long will it take the activity to reduce to 3.125%. (**Ans.** t = 5T years)
5. Half life of $^{90}_{38}Sr$ is 28 years. What is the disintegration rate of 15 mg of this isotope? (**Ans.** 2.129 Ci, 7.878×10^{10} Bq)