$$\therefore\ 16 = 9 \times 10^9 \frac{(2\times10^7)(t)(1.6\times10^{-19})}{10^2}$$

$$\therefore\ t = \frac{16\times10^2}{9\times2\times1.6\times10^{-3}} = 55578 \text{ s} = 15.438 \text{ hr.}$$

6.13 α-decay

In the process of radioactivity, the unstable nucleus of a radioactive element disintegrates and forms a new nucleus. The disintegrating nucleus is called the parent nucleus and the newly formed nucleus is called the daughter nucleus.

Most of the nuclei with Z > 83 emit α-particles. As an illustration ${}_{92}U^{238}$ nucleus, emits α-particle and converts into ${}_{90}Th^{234}$.

This process can be written as :

$$ {}_{92}U^{238} \rightarrow {}_{90}Th^{234} + {}_{2}He^{4} \quad (6.13.1)$$

Thus, in the process of α-decay, as compared to parent element the value of atomic number of daughter element is 2 unit less and the atomic mass number is 4 unit less.

All nuclei in the substance emitting α-particles, do not together emit α-particle at the same time. This process is related to probability. Hence no α-particle after its formation in the nucleus is emitted immediately or all α-particles are not together emitted. Moreover spontaneous emission of α-particle is possible only if mass of ${}_{92}U^{238}$ nucleus is greater than the sum of the masses of ${}_{90}Th^{234}$ nucleus and the α-particle. If it is not so this process cannot occur spontaneously (but can occur by giving energy from outside). We can verify this fact by obtaining masses of nuclei with the help of standard table.

It is clear that in this case the energy emitted is equal to $[M_U - (M_{Th} + M_\alpha)]c^2$, where M is the mass of the respective nuclide.

6.14 β-decay

In the process of β-decay, a nucleus spontaneously emits electron or the positron. Positron has the same charge as that of electron but it is positive, and its other properties are exactly identical to those of electron. Thus positron is the anti-particle of electron. Positron and electron are respectively written as β^+ and β^- or ${}^{0}_{+1}e$ and ${}^{0}_{-1}e$ or e^+ and e^-. Known illustrations of β-decay are

$$ {}_{15}P^{32} \rightarrow {}_{16}S^{32} + {}^{0}_{-1}e + \bar{\upsilon} \quad (6.14.1)$$

(electron) (antineutrino)

$$ {}_{11}Na^{22} \rightarrow {}_{10}Ne^{22} + {}^{0}_{+1}e + \upsilon \quad (6.14.2)$$

(positron) (neutrino)

Compared to the parent element, the atomic number of the daughter element is one unit more in β^--decay and one unit less in β^+-decay. In both cases the atomic mass number of the daughter element is the same as that of the parent element. Along with the emission of e^+, a particle called neutrino and with emission of e^-, a particle called anti neutrino are emitted. Neutrino and anti neutrino are the anti particles of each other. They are electrically neutral and their mass is extremely small as compared to even that of electron. Their interaction with other particles is negligible and hence it is extremely difficult to detect them. They can pass without interaction even through very large matter (even through the entire earth). They have $\frac{\hbar}{2}$ spin $\left(\hbar = \frac{h}{2\pi}\right)$.

In β-decay the electron is emitted from the nucleus (and not from the extra nuclear electronic orbits). Electrons do not reside in a nucleus, then how can they be emitted from nucleus ? In fact, a neutron in a nucleus disintegrates into a proton and an electron and this newly born electron (it can born in a nucleus but cannot stay there) is immediately expelled out which we call β^{-}particle. In a nucleus which contains more neutrons than that required for stability, a neutron disintegrates and a β^{-} is emitted.

$$n \rightarrow p + e^{-} + \bar{\upsilon}$$

If the proton is converted into neutron, e^{+} is emitted.

$$p \rightarrow n + e^{+} + \upsilon$$

6.15 γ-decay

There are energy levels of nuclei similar to the energy levels of the atoms. Also like the atom, when a nucleus makes a transition form a higher energy level to the lower energy level, a photon with energy equal to their difference is emitted. The energy levels of the nuclei are of the order of M*e*V. Even when the energy difference between such levels is 1 M*e*V, the wavelength of the emitted photon is obtained in the region of γ-rays. The following calculation will clarify this.

From $hf = 1$ M*e*V, $\frac{hc}{\lambda} = (1 \times 10^{6})\ (1.6 \times 10^{-19}\ \text{J})$

$$\therefore\ \lambda = \frac{hc}{(1\times10^{6})(1.6\times10^{-19})}$$

$$\therefore\ \lambda = \frac{(6.6\times10^{-34})(3.0\times10^{8})}{1\times10^{6}\times1.6\times10^{-19}} = 12.37 \times 10^{-13}\text{m} = 0.0012\ \text{nm}$$

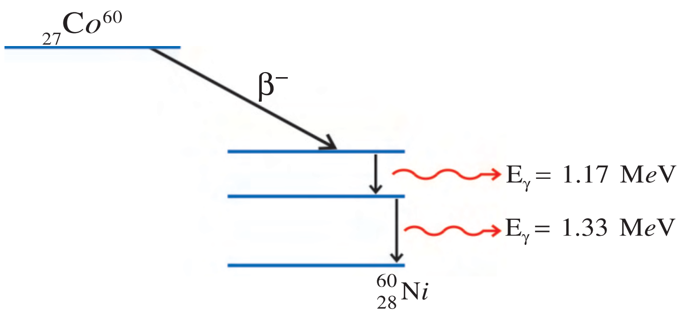


Figure 6.7 γ-decay

This value of λ falls in the region of γ-rays. Thus this radiation is γ-ray. When a nucleus emits α or β-particle, the daughter nucleus is mostly in an excited state. Such a daughter nucleus emits γ-photon by making one or more transitions.

As an illustration, when $^{60}_{27}Co$ by emitting β^{-}-particle converts into $^{60}_{28}Ni$, the $^{60}_{28}Ni$ nucleus is in the excited state and by successive transitions it emits γ-ray photons of energies 1.17 M*e*V and 1.33 M*e*V.

Illustration 10 : If by successive disintegration of $^{238}_{92}U$, the final product obtained is $^{206}_{82}Pb$, how many α and β particles are emitted ?

Solution : Suppose in this process x, α-particles and y, β-particles are emitted.

$$\therefore \quad {}^{238}_{92}U \rightarrow {}^{206}_{82}Pb + x\left({}^{4}_{2}He\right) + y\left({}^{0}_{-1}e\right)$$

Comparing atomic mass numbers on both the sides,

$$238 = 206 + x(4) + y(0)$$

$$\therefore \; x = 8$$

Now comparing atomic numbers on both the sides,

$$92 = 82 + 2x + y(-1)$$

$$= 82 + 16 - y$$

$$\therefore \; y = 6$$

Thus, in this process 8 α-particles and 6 β-particles are emitted.

6.16 Nuclear Reactions

In 1919, Rutherford showed that by bombarding suitable particles of suitable energy on a stable element; that element can be transformed into another element. Such a reaction is called artificial nuclear transmutation. When he bombarded α-particles on nitrogen, he found that nitrogen was converted into oxygen. This process can be written as under :

$${}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H + Q \qquad (6.16.1)$$

Such processes, in which change in the nucleus takes place, are called nuclear reactions. Here Q is called the Q-value of the nuclear reaction and it shows the energy produced (released) in the process. Such reactions are also shown symbolically as $A + a \rightarrow B + b + Q$ or A (a, b) B.

Here, A is called the target nucleus,

a is called the projectile particle,

B is called the product nucleus,

and b is called the emitted particle.

The energy Q, liberated in the process is equal to the energy equivalent to the decrease in mass in the process.

$$Q = [m_A + m_a - m_B - m_b]c^2 \qquad (6.16.2)$$

where m is the mass of the respective particle.

The energy so produced appears as the increase of kinetic energy in the reaction. If $Q > 0$, the reaction is called exoergic reaction. If $Q < 0$, the reaction is called endoergic. It is self evident that endoergic reaction cannot occur spontaneously but can occur only if sufficient energy is supplied.

In nuclear reactions, it is necessary that the momentum, the electric charge and the energy each one is conserved.

The conservation of charge can be seen from the atomic numbers. Moreover, the sums of the atomic mass numbers before and after the reaction are equal, but the mass can change. In short, we will note that the Q value of the reaction = energy equivalent to decrease in mass in the reaction = increase in the kinetic energy.

Illustration 11 : Usually in laboratory, neutrons are obtained by bombarding α-particles, emitted from ${}^{226}Ra$, on ${}^{9}_{4}Be$ through the reaction ${}^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$. The energy of these α-particles is 4.78 MeV. Find the maximum kinetic energy of neutron.

[Take M_α = 4.002603 u, M_{Be} = 9.012183 u, M_c = 12.000000 u, m_n = 1.0086 u, 1 u = 931.494 MeV]

Solution : ${}^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$

Applying law of conservation of energy,

$(M_{Be} + M_\alpha)c^2 + K_\alpha = (M_c + m_n)c^2 + K_n + K_c$

Here as neutron is getting maximum kinetic energy, the kinetic energy of carbon K_c must be zero. (Since Be is the target $K_{Be} = 0$ is taken)

$\therefore$ (9.012183 + 4.002603)(931.494) + 4.78 = [12.000000 + 1.0086] × 931.494 + K_n

$\therefore$ K_n = 10.54 MeV

Illustration 12 : ${}^{241}Am$ in a steady state emits α-particle and the reaction ${}^{241}Am \rightarrow \alpha + {}^{237}Np$ takes place. Using following data, find the kinetic energy of α-particle.

M_{Am} = 241.05682 u, M_α = 4.002603 u, M_{Np} = 237.04817 u, 1 u = 931.474 MeV

Solution : According to law of conservation of energy

we get, $(M_{Am})c^2 = (M_\alpha - M_{Np})c^2 + K_f$

where K_f = Total kinetic energy of final products (α and Np)

$\therefore$ $K_f = (M_{Am} - M_\alpha - M_{Np})c^2$

= energy equivalent to mass difference

= [241.05682 − 4.002603 − 237.04817] × 931.474 MeV

= 5.6326 MeV

According to the conservation of momentum,

$0 = \vec{P}_\alpha + \vec{P}_{Np}$ ($\because$ momentum of Am = 0)

$\therefore$ $P_{Np} = P_\alpha$ (in magnitude)

$\therefore$ Total kinetic energy $K_f = \frac{p_\alpha^2}{2M_\alpha} + \frac{p_{Np}^2}{2M_{Np}}$ (Kinetic Energy = $\frac{p^2}{2m}$)

$= \frac{p_\alpha^2}{2M_\alpha} + \frac{p_\alpha^2}{2M_{Np}}$ ($p_{N_p} = P_\alpha$)

$= \frac{p_\alpha^2}{2}\left[\frac{1}{M_\alpha} + \frac{1}{M_{Np}}\right] = \frac{p_\alpha^2}{2}\left[\frac{M_{Np} + M_\alpha}{M_\alpha M_{Np}}\right]$

$\therefore$ Kinetic energy of α-particle $= \frac{p_\alpha^2}{2M_\alpha} = \frac{K_f . M_{Np}}{M_{Np} + M_\alpha} = \frac{(5.6326)(237.04817)}{237.04817 + 4.002603}$

= 5.539 MeV

Illustration 13 : In the reaction ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + Q$ of the nucleus X at rest, taking the ratio of mass of α-particle M_α and mass of Y-nucleus M_Y as $\frac{M_\alpha}{M_Y} = \frac{4}{A-4}$, show that the Q-value of the reaction is given by $Q = K_\alpha\left(\frac{A}{A-4}\right)$, where K_α = kinetic energy of α-particle.

Solution : Q-value of reaction = energy equivalent to mass-difference.

$$= (M_X - M_Y - M_\alpha)c^2$$

= increase in kinetic energy

$$= (K_\alpha + K_Y) - 0 \ (\because \ X \text{ was steady})$$

$$= \frac{1}{2}M_\alpha v_\alpha^2 + \frac{1}{2}M_Y v_Y^2 \qquad (1)$$

From conservation of momentum,

$$M_Y \vec{v}_Y + M_\alpha \vec{v}_\alpha = 0$$

$$\therefore \ M_Y v_Y = M_\alpha v_\alpha \ \text{(in magnitude)} \qquad (2)$$

$$\therefore \ v_Y = \left(\frac{M_\alpha}{M_Y}\right)v_\alpha$$

Substituting this value in equation (1),

$$Q = \frac{1}{2}M_\alpha v_\alpha^2 + \frac{1}{2}M_Y\left(\frac{M_\alpha}{M_Y}\right)^2 v_\alpha^2$$

$$= \frac{1}{2}M_\alpha v_\alpha^2\left[\frac{M_\alpha}{M_Y}+1\right] = K_\alpha\left(\frac{4}{A-4}+1\right)$$

$$= K_\alpha\left(\frac{A}{A-4}\right)$$

6.17 Nuclear Fission

In 1932, Chadwick discovered neutron. Thereafter, Fermi suggested that as the neutron is electrically neutral it does not have to face the coulomb repulsive forces and hence by bombarding neutron on the nucleus it can go deep into the nucleus. Thus, it is a good projectile.

When Hann and Strassman, bombarded thermal neutron (of energy $\approx 0.04eV$) on compounds of uranium, they found ${}_{56}Ba^{144}$ in the newly formed radioactive elements. They were surprised with this result. Meitner and Frisch found that when thermal neutron is bombarded on uranium nucleus, it disintegrates uranium nucleus in two almost equal parts and in this process enormous energy is produced (released). This process was named nuclear fission.

In the fission of uranium, many different product nuclei have been obtained.

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

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{133}_{51}Sb + ^{99}_{41}Nb + 4^{1}_{0}n + Q$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{140}_{54}Xe + {}_{38}Sr^{94} + 2^{1}_{0}n + Q$$

The product nuclei obtained by the fission are called the fission fragments, the neutrons are called the fission neutrons and the energy is called the fission energy. In the above reaction, 60 different nuclei are obtained as fission fragments, having Z values between 36 and 56. The probability is maximum for formation of nuclei with A = 95 and A = 140. The fission fragments are radioactive and by successive emission of β^{-}-particles result in stable nuclei.

The neutrons produced in this reaction are fast (almost 2 MeV energy).

The Q-value of this reaction, that is, the energy produced is very large like almost 200 MeV per fission. This energy is obtained due to conversion of mass difference, between the reactants and the products, into energy. Initially this energy is in the form of the kinetic energy of the fission fragments and the neutrons which eventually transforms into the heat energy in the surrounding material.

In a nuclear reactor which produces electric power such successive nuclear fission processes take place but in the controlled form, while in the nuclear bomb such successive processes occur in the uncontrolled manner and produces explosion.

The theoretical explanation of the nuclear fission reaction is given by "liquid drop model of the nucleus", in which a nucleus is compared with a drop of liquid.

6.18 Nuclear Chain Reaction and Nuclear Reactor

Nuclear Chain Reaction : In the previous article, we have seen that in the fission process of $^{235}_{92}U$ by a slow neutron, one or more neutrons are emitted. For every fission average $2\frac{1}{2}$ neutrons are obtained per fission. The reason for the fraction which appears here is that in certain fission processes, we get 4 or 3 or 2 neutrons emitted. In 1939 Fermi suggested that with the help of neutrons produced in this way if fission of other uranium nuclei is accomplished then, we get still more energy and still more neutrons. A series of such processes is called nuclear chain reaction. If such a process is properly controlled, then energy can be obtained continuously at steady rate. Nuclear reactor is the illustration of this. If such a process occurs in uncontrolled manner, then the energy produced causes explosion. Nuclear bomb is the illustration of this.

Now, we shall see about the difficulties encountered in the success of such nuclear chain reaction and their removal.

(1) Fission neutrons are fast (average energy is 2 MeV). They should be stopped from escaping from the fission material. Moreover, they should be slowed down and converted into thermal neutron (energy almost 0.04 MeV), to become suitable for fission.

To stop neutrons from escaping, neutron reflecting surfaces are used and in the arrangement of fission material the surface/volume ratio is kept low, because the leakage process of neutrons is a surface process. To slow down the neutrons, materials known as moderator are kept along with the fission material. Normal water (H_2O), heavy water (D_2O), Graphite, Beryllium etc. are good moderators. They slow down the neutrons but do not absorb them.

In producing fission of $^{235}_{92}U$ slow neutrons are more effective as compared to fast neutrons.

(2) In such a chain reaction enormous heat energy is produced and the temperature is likely to become 10^6K. Hence the fission material, moderator etc. should be cooled and that heat energy should be converted into the useful form. For this coolants are used.

Water, molten sodium metal, gases etc are passed as coolants through the tubes in fission chamber.

(3) In a nuclear chain reaction the ratio of the number of neutrons produced at any stage to the number of neutrons incident at that stage is called the multiplication factor K. It is a measure of the growth of number of neutrons. When K = 1, the reactor is said to be critical. If K becomes grater than 1, the reactor is said to be in super critical state. In this state the rate of reaction and the energy abruptly increase and explosion takes place. If K becomes less than 1 (sub critical state), the process slows down and eventually stops and we cannot get energy continuously with uniform rate. Hence in order to control the value of K, rods of materials which can absorb neutrons like Cadmium and Boron are kept in the fission material. These rods are controlled automatically.

If the value of K tends to be more than 1, the rods go deeper in fission material to absorb more neutrons. If the value of K tends to be less than 1, these rods automatically rush outside to decrease absorption of neutrons. These rods are called control rods.

When all these requirements are together fulfilled, energy is obtained continuously at a steady rate from the reactor.

Nuclear Reactor : It works on the principle of controlled nuclear chain reaction. A schematic diagram of a typical nuclear reactor power plant is shown in the figure 6.8. In order that fission can be accomplished with a thermal neutron, $^{235}_{92}U$ is taken as a fuel. But in natural Uranium its proportion is only 0.7% and that of $^{238}_{92}U$ is 99.3%. By specific processes, the proportion of $^{235}_{92}U$ is made nearly 3%. Such uranium is called enriched uranium. When $^{238}_{92}U$ absorbs a neutron, $^{239}_{94}Pu$ is formed by the following processes.

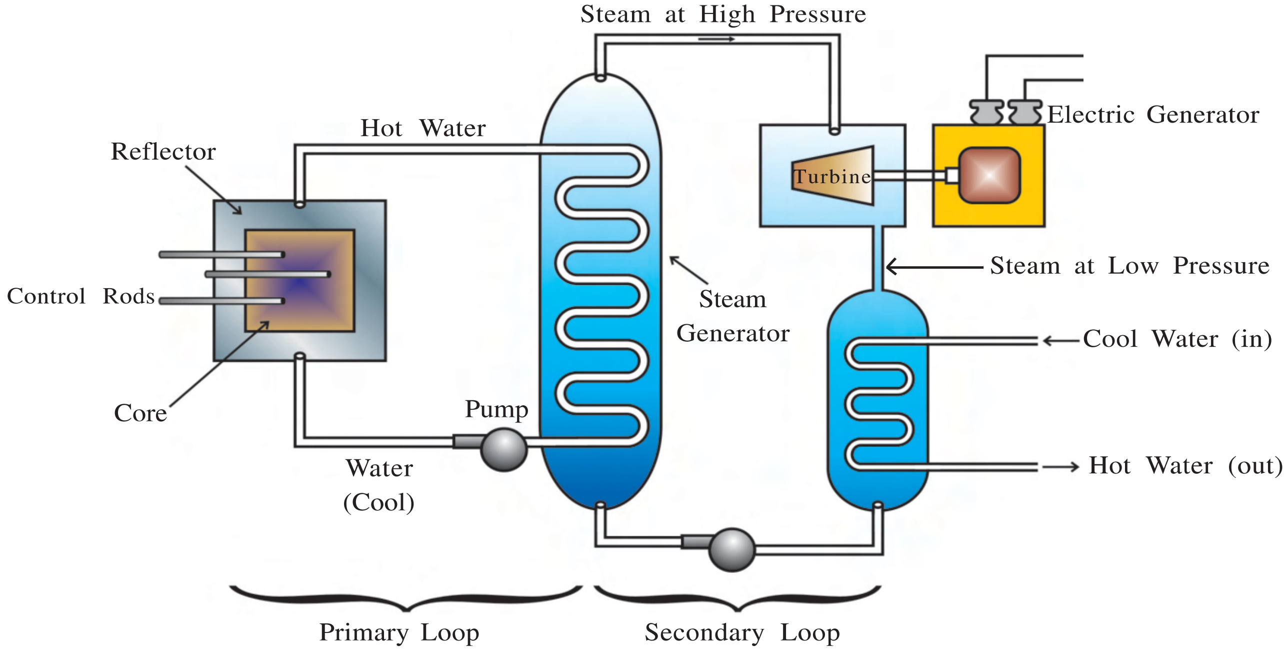


Figure 6.8 Nuclear Reactor

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

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

This plutonium is intense radioactive and is fissionable by slow neutron.

Materials used as fuel and moderator are kept in the core part of the reactor. Fission occurs in the fuel material. Here normal water is used as moderator and also as coolent. This is called pressurised water reactor. Water is pushed into the core of the reactor using a pump. When it comes out of the core, its temperature becomes 600 K at 150 atm pressure. It is then passed into the steam generator. The steam of very high pressure produced in it, operates the turbine, which produces electric power.

After moving the turbine the pressure of the steam decreases. This steam is then cooled and converted into water and it is again pushed into the reactor with the pump. In order to control the multiplication factor K, control rods are kept.

6.19 Thermonuclear Fusion in Sun and other Stars

The Sun has been emitting energy at a tremendous rate of 3.8×10^{26} J/s since almost 500 crore years. The origin of such enormous energy remained unknown to scientists for many years. But from the study of nuclear physics, explanation of this has been obtained.

Energy is obtained by the fission of a heavy nucleus. But conversely, when two proper light nuclei are fused at a very high temperature to form a heavy nucleus, then also enormous amount of energy is produced. Such a process is called thermonuclear fusion. For example when Helium nucleus is made from protons or deuterons, much energy is produced. In the Sun and other stars the energy is produced by thermonuclear fusion.

In the Sun, energy is produced by a process called proton – proton cycle which occurs according to the following stages.

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + _{+1}e^{0} + \nu + 0.42 \text{ MeV} \quad (6.19.1)$$

$$_{+1}e^{0} + _{-1}e^{0} \rightarrow 2\gamma + 1.02 \text{ MeV} \quad (6.19.2)$$

$$^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He + \gamma + 5.49 \text{ MeV} \quad (6.19.3)$$

$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H + 12.86 \text{ MeV} \quad (6.19.4)$$

When first three reactions occur twice, two $^{3}_{2}He$ nuclei are produced and between them the fourth reaction takes place. As a result of all reactions $4\,^{1}_{1}H$ and $2\,_{-1}e^{0}$ produce one α-particle, 2ν and 6γ-photons. Here energy equal to $2 \times 0.42 + 2 \times 1.02 + 2 \times 5.49 + 12.86 = 26.7$ MeV is liberated. Moreover, another process called carbon-nitrogen cycle is also suggested for the energy produced in the stars. We shall not go into the details of it at present.

It will take further 500 crore years for all of hydrogen in the core of the Sun to burn out and become helium. Thereafter, since the combustion of hydrogen is stopped, sun will start colling down and will collapse (contract) due to its own gravitation. This will again raise the temperature of its core and the outer envelope will expand, and thus the Sun will turn into a red giant. If the temperature will again rise to 10^{8} K, then the combustion of He will take place to form C. By further evolution of such a star, still higher temperature will be reached and by other fusion processes other heavy elements will be formed. But even with the fusion processes progressing further elements heavier than those near the peak of the binding energy curve will not be formed.

Attempts are in progress to produce energy (electric power) constantly and continuously in many countries of the world by a controlled chain reaction of nuclear fusion. They have not reached to the stage of great success. In India, such a research is going on in the Institute for Plasma Research (IPR) at, Bhat near Ahmedabad.

Illustration 14 : Assume the Sun to be completely made up of protons. When four protons fuse to form ${}_2^4He$ nucleus in a proton-proton cycle occurring in the Sun, 6.7 MeV energy is released per proton. The total output power of the Sun is 3.9×10^{26}W. Consider this power to be constant and mass of the sun equal to 2.0×10^{30} kg. How long will the Sun take to be fully converted into ${}_2^4He$ particles ?

[Take Mass of a proton = 1.67×10^{-27} kg, 1 yr = 3.16×10^{7} s]

Solution : Total mass of the Sun = 2.0×10^{30} kg

$$\therefore \text{ The number of protons in the Sun} = \frac{2.0 \times 10^{30}}{1.67 \times 10^{-27}} = 1.2 \times 10^{57}$$

Total output power of the Sun = 3.9×10^{26} J s^{-1}

Energy obtained per proton = 6.7 MeV = $6.7 \times 10^{6} \times 1.6 \times 10^{-19}$ J

If N is the number of protons destroying per sec, the total energy per second will be,

$(N)\ (6.7 \times 10^{6} \times 1.6 \times 10^{-19}) = 3.9 \times 10^{26}$

$$\therefore N = \frac{3.9 \times 10^{26}}{6.7 \times 10^{6} \times 1.6 \times 10^{-19}} = 3.6 \times 10^{38} \text{ protons destroy per s.}$$

Thus, 3.6×10^{38} protons take -1 s to destroy

then 1.2×10^{57} proton take $-t$ s to destroy

$$\text{where } t = \frac{1.2 \times 10^{57}}{3.6 \times 10^{38}} = 0.33 \times 10^{19} \text{ s} = \frac{0.33 \times 10^{19}}{3.16 \times 10^{7}} \text{ yr} = 1.044 \times 10^{11} \text{ yr}$$

= 104.4 Billion Year

6.20 Nuclear hazards

The energy produced by nuclear fission and nuclear fusion is found to be useful in many ways. But devastating calamities can also occur due to them. The distructive effects of atom bomb have already been experienced by the mankind.

Although getting power from a nuclear reactor is beneficial; the waste products from it are intense radioactive and hence are harmful to the living bodies. No satisfactory solution is still found to store them or to dispose off. Moreover, accidents occurring in such a reactor can cause distruction in the surrounding. The large scale devastation in the surrounding of a reactor at Chernobyl in Ukraine in April 1986, due to an explosion in it is the illustration of it.

At present a huge amount of nuclear weapons are present on earth. They are capable of destroying all forms of life on earth for several times over. Not only that but its products will make this earth unfit for life for ever.

Theoretical calculations reveal that due to extravagant use of nuclear energy the radioactive waste will hang in the earth's atmosphere like the clouds and will absorb the solar radiation and a "nuclear winter" will be produced on the earth.

SUMMARY

1. The entire positive charge and almost entire mass of the atom is concentrated in the nucleus.

2. In ${}^{A}_{Z}X$ or ${}_{Z}X^{A}$, Z shows the atomic number and A shows the atomic mass number of the element. A − Z = N shows the number of neutron in the nucleus. The masses of the atom and the nuclei are expressed in the unit called the atomic mass unit (symbol : amu or u). The twelfth part of the mass of unexcited ${}^{12}_{6}C$ atom is called 1 u mass.

1 u (mass) = 1.66×10^{-27} kg. Nuclei having equal Z values but different A values are called isotopes. Nuclei having same number of neutrons (N = A − Z) are called isotones of each other.

Nuclei having same values of atomic mass number (A = N + Z) are called isobars of each other. Nuclei having equal Z and also equal A, but having different radioactive properties are called isomers of each other.

3. A strong attractive force acts which after balancing the repulsive force between protons, can tightly hold all nucleons together in a nucleus. Since such a nuclear force is short range, every nucleon can interact only with a few neighbouring nuclei (saturation property).

Basically the forces between quark–quark ultimately result into nuclear forces. Nuclear forces depend on the 'spin' of nucleons.

4. The characteristic average radius of the nucleus is given by $R = R_0 A^{\frac{1}{3}}$, where A = atomic mass number. $R_0 = 1.1 f_m$ = constant. The density of nucleus is = 2.3×10^{17} kg m^{-3}.

5. In stable nuclei of light elements, the number of protons (Z) and the number of neutrons (N) are equal or almost equal, while in heavy stable nuclei, the number of neutron is greater than the number of proton.

6. According to Einstein's special theory of relativity, mass and energy can be transformed into each other. Mass m is equivalent to mc^2 energy. $E = mc^2$, where c = velocity of light in vacuum.

"The change in the kinetic energy of an electron while passing through a potential difference of 1 Volt is called 1 eV (electron volt) energy."

1 keV = $10^3 e$V, 1 MeV = $10^6 e$V

1 u (mass) = 931.48 MeV (energy).

The mass of the nucleus is always slightly less than the total mass of its constituents in the free state. This mass difference is called the mass defect Δm. The energy equivalent to it is $E_b = (\Delta m)c^2$ and it is called the binding energy of the nucleus. By dividing the binding energy with the total number of nucleons, we get the average binding energy per nucleon; $E_{bn}\left(=\frac{E_b}{A}\right)$. It is the measure of the stability of the nucleus. The maximum value of E_{bn} is found for nucleus of Fe and it is 8.8 MeV/nucleon. For nuclei of intermediate masses the value of E_{bn} is almost constant. For nuclei heavier or lighter than them, E_{bn} has smaller values. The nuclear structure is shell type. By the fission of heavy nuclei like U, energy is produced. It is called nuclear fission. Energy is also produced by the fusion of light nuclei. It is called nuclear fusion.

7. Becquerel found that Uranium spontaneously and continuously emits from itself radiations of specific properties. This phenomenon is called natural radioactivity. Madam Curie obtained other radioactive elements-Radium and Polonium–from the ore of uranium. Radioactivity is a nuclear phenomenon.

8. α rays are the nuclei of ${}_2^4He$ atoms. β-rays are electrons only. γ rays are not material particles but are electromagnetic waves. They all, produce fluorescence, affect photographic plate, can produce ionization and can penetrate.

9. In a given sample the number of nuclei disintegrating per unit time at an instant is called the rate of disintegration (or activity I) of that element at that instant and it is proportional to the number of undisintegrated nuclei at that instant. $\frac{dN}{dt} = -\lambda N$.

λ is called the decay constant or radioactive constant. It depends on the type of the radioactive element. It remains constant throughout the life of that element. The SI unit of activity is Becquerel (Bq). "The activity of a substance in which 1 disintegration occurs per second is called 1 Becquerel." "The activity of a substance in which 3.7×10^{10} disintegrations occur per sec is called 1 curie (Ci)."

$1\ mCi = 10^{-3}\ Ci,\ 1\ \mu Ci = 10^{-6}\ Ci$

10. From rate of disintegration $\frac{dN}{dt} = -\lambda n$, the number of undisintegrated nuclei at time t is obtained as $N = N_0\ e^{-\lambda t}$. It is called the exponential law of radioactive disintegration. The graph of $N \rightarrow t$ is called the decay curve.

11. The time-interval during which the number of nuclei of a radioactive element (N) reduces to half its value at the beginning of the interval N_0, is called half-life $\tau_{\frac{1}{2}}$, of that element.

$$\tau_{\frac{1}{2}} = \frac{0.693}{\lambda}.\ \text{If}\ \frac{\text{given time}(t)}{\text{half life}(\tau_{\frac{1}{2}})} = n,$$

the number of nuclei at time t is given by

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

12. "The time interval during which the number of nuclei of a radioactive element reduces to e^{th} part of the initial value is called the average life (τ) of that element. (e = 2.718)

$$\tau = \frac{1}{\lambda},\ \tau_{\frac{1}{2}} = (0.693)(\tau)$$

$$\tau = \frac{\tau_{\frac{1}{2}}}{0.693} = 1.44\,\tau_{\frac{1}{2}}$$

13. In α dacay, the atomic number and the atomic mass number of the daughter element are respectively 2 units and 4 units less than those of the parent element.

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

The energy produced in this process is equal to $(M_X - M_Y - M_{He})c^2$.

14. The atomic number of the daughter element is one unit more in β^--decay and one unit less in β^+-decay than that of the parent element. In both the cases, there is no change in the atomic mass number.

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \bar{\nu} \qquad (\beta^- \text{-decay})$$

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \nu \qquad (\beta^+ \text{-decay})$$

ν and $\bar{\nu}$ are respectively neutrino and anti-neutrino. As their interaction with matter is negligible, their detection is very difficult. They are electrically neutral and have extremely small mass and $\frac{\hbar}{2}$ spin.

In β^--decay, a neutron in a nucleus disintegrates into proton and electron and this newly born electron gets emitted instantaneously.

15. The energy levels of the nucleus are of the order of MeV. When the nucleus makes a transition between these levels, electromagnetic waves of energy of the order of MeV are emitted. They are γ–rays.

16. Rutherford found that if suitable particles of suitable energy are bombarded on a stable element, that element gets transformed into another.

$${}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H + Q \quad (\alpha\text{-particle})$$

Q is called the Q value of this reaction. It shows the energy emitted in this process. It is equivalent to the mass difference occurring in the reaction. A reaction with $Q > 0$ is called exoergic reaction and the one with $Q < 0$ is called endoergic reaction. In these reactions momentum, electric charge and energy are conserved.

17. From the experiments of Hann and Stranssman as well as Meitner and Frisch, it was found that when uranium is bombarded by a thermal neutron, it breaks the uranium nucleus into two almost equal parts and enormous amount of energy is produced in this process. This phenomenon was named as nuclear fission.

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

In such a process other elements are also produced. 60 such different nuclides can be formed, which have Z values between 36 to 56. These fission fragments are intense radioactive. The neutrons produced in this process are fast (energy almost 2 MeV). The energy produced in this process is tremendous (nearly 200 MeV).

18. In the fission of ${}_{92}U^{235}$ nucleus by slow neutron, more than one neutron are produced. By using them for fission of other uranium nuclei, we get still more energy and still more neutrons. A series of such processes is called nuclear chain reaction. By controlling this process, energy is obtained from nuclear reactor continuously at

uniform rate. For this, the neutrons produced in the reaction should be stopped from escaping and should be slowed down also. For this neutron reflecting surfaces and moderators respectively are used. Moderator slows down neutron but does not absorb them. H_2O, D_2O, graphite, berelium etc are good moderators. Since excessive heat is produced, the temperature is likely to rise to 10^6 K. Hence with the help of coolant materials the fuel and moderator are cooled. H_2O, molten sodium metal, gas are used as coolants. In a fission chain reaction the ratio of number of neutrons emitted to the number of neutrons incident at any stage is called the multiplication factor K. For K = 1 the reactor is said to be critical. If K > 1, the reactor is said to be in the supercritical state, and it causes explosion. If K tends to be less than 1, then reactor gradually stops. For controlling the value of K, rods of C*d* and B are kept in the fission material. They can absorb neutron and can move automatically.

19. In the Sun and other stars energy is produced by the process of nuclear fusion. When light nucliei (e.g. proton) are coaleased to form a heavier nucleus (e.g. He) at a very high temperature, enormous energy is produced. Such a reaction is called thermonuclear fusion.

Such energy is produced in the Sun by a process called proton–proton cycle. Attempts are made throughout the world to get energy by a controlled chain reaction of nuclear fusion.

20. The waste-products from nuclear reactor are intense radioactive and hence dangerous to the living world. Moreover accidents are also likely to occur in the reactor.

EXERCISE

For the following statements choose the correct option from the given options :

1. How many protons, neutrons and nucleons respectively is the ${}^{206}_{82}Pb$ nucleus made up of ?

(A) 82, 206, 288 (B) 206, 82, 288 (C) 82, 124, 206 (D) 124, 82, 206

2. Which are the isotope, isotone and isobar nuclei respectively of ${}^{12}_{6}C$ from among ${}^{14}_{6}C$, ${}^{12}_{5}B$, ${}^{13}_{7}N$?

(A) ${}^{14}_{6}C$, ${}^{13}_{7}N$ ${}^{12}_{5}B$ (B) ${}^{12}_{5}B$, ${}^{14}_{6}C$, ${}^{13}_{7}N$ (C) ${}^{13}_{7}N$, ${}^{12}_{5}B$, ${}^{14}_{6}C$ (D) ${}^{14}_{6}C$, ${}^{12}_{5}B$, ${}^{13}_{7}N$

3. If the radii of ${}^{27}_{13}Al$ and ${}^{64}_{30}Zn$ nuclei are R_1 and R_2 respectively, then $\frac{R_1}{R_2}$ = ...

(A) $\frac{27}{64}$ (B) $\frac{3}{4}$ (C) $\frac{9}{16}$ (D) $\frac{13}{30}$

4. The binding energy per nucleon for deuteron (${}^{2}_{1}H$) nucleus is 1.1 M*e*V and that for ${}^{4}_{2}He$ nucleus is 7 M*e*V. If two deuteron nuclei fuse to form ${}^{4}_{2}He$ nucleus, how much energy will be produced ?

(A) 11.8 M*e*V (B) 23.6 M*e*V (C) 26.9 M*e*V (D) 32.4M*e*V

5. Which is the necessary and sufficient condition for an element to be naturally radioactive?

(A) Z > 50 (B) Z > 60 (C) Z > 70 (D) Z > 83

6. Which one of the following is true for the relative ionizing power of α, β and γ ?

(A) It is maximum for α particle (B) It is maximum for β Particle.

(C) It is maximum for γ radiation (D) It is equal for α, β and γ

7. During the life time of a radioactive element as time passes the number of its nuclei decreases and along with that ....

(A) activity and λ go on decreasing (B) activity and λ go on increasing

(C) activity decreases but λ remains constant

(D) activity decreases but λ increases.

8. Half-life of a radioactive element is 5 min. At the end of 20 min. its .... % quantity will remain undisintegrated.

(A) 93.73 (B) 75 (C) 25 (D) 6.25

9. After a time interval equal to 3 half-lives; how many times would (*a*) the activity of a radioactive element be, of its initial activity ? Or (*b*) mass of a radioactive element be, of its initial mass or (*c*) number of nuclei of a radioactive element be of its initial number ?

(A) 2^3 (B) 3^2 (C) $\frac{1}{3^2}$ (D) $\frac{1}{2^3}$

10. By the disintegration of ${}_{94}Pu^{241}$, the element which is produced is also radioactive and disintegrates. In such a series total 8 α-particles and 5 β-particles are emitted and then the process stops. Which is the final element produced?

(A) ${}_{83}Bi^{209}$ (B) ${}_{82}Pb^{209}$ (C) ${}_{83}Bi^{214}$ (D) ${}_{82}Pb^{214}$

11. 1 g radioactive element reduces to $\frac{1}{3}$ g after 2 days. After total 6 days how much mass will remain ?

(A) $\frac{1}{27}$ g (B) $\frac{1}{6}$ g (C) $\frac{1}{9}$ g (D) $\frac{1}{12}$ g

12. Binding energy per nucleon for ${}^{n}_{z}P$ and ${}^{2n}_{z'}Q$ are x and y respectively. How much energy would be absorbed in the process ${}^{n}_{z}P + {}^{n}_{z}P = {}^{2n}_{z'}Q$?

(A) $2nxy$ (B) $2ny + 2nx$ (C) $2nx - 2ny$ (D) $\frac{2nx}{2ny}$

13. If the number of undisintegrated nuclei at time t is given by $N = N_0 e^{-\lambda t}$, what is the number of nuclei disintegrated between the time t_1 and t_2 ?

(A) $N_0(e^{-\lambda t_2} - e^{-\lambda t_1})$ (B) $N_0(e^{-\lambda t_1} - e^{-\lambda t_2})$

(C) $N_0(e^{\lambda t_2} - e^{\lambda t_1})$ (D) $N_0(e^{\lambda t_1} - e^{\lambda t_2})$

14. If the half-lives of a radioactive element for α-decay and β-decay are 4 yr and 12 yr respectively, what percent would its total activity be of its initial activity after 12 yrs ?

(A) 50 (B) 25 (C) 12.5 (D) 6.25

15. Out of Cd, molten Na-metal and graphite which can be used respectively as moderator, coolant and the material for control rods in a reactor?

(A) Molten Na-metal, graphite, Cd (B) graphite, molten Na-metal, Cd

(C) Cd, molten Na-metal, graphite (D) graphite, Cd, molten Na-metal

16. If $^{27}_{13}Al$ is a stable nucleus, what could be emitted from $^{32}_{13}Al$ nucleus ?

(A) α-particle (B) β^--particle (C) proton (D) β^+-particle

17. The half-life of a radioactive element is 2 hr and that of the other is 4 hr. Their initial activities are equal. After 4 hr what will be the ratio of their activities ?

(A) 1 : 4 (B) 1 : 3 (C) 1 : 2 (D) 1 : 1

18. 1 mole of an element emitting α-particles is placed in a vessel which stores them. Half-life of that element is 5 hr. How long would it take for 4.515×10^{23} α-Particles to be stored in that vessel?

(A) 4.515 hr (B) 9.030 hr (C) 10 hr (D) 20 hr

19. In the radioactive transformation $^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X_1 \rightarrow {}^{A-4}_{Z-1}X_2 \rightarrow {}^{A-4}_{Z}X_3$, which are the successively emitted radioactive radiations?

(A) α, β^-, β^- (B) β^-, α, β^- (C) β^-, β^-, α (D) α, α, β^-

20. In the radioactive transformation $X \xrightarrow{\alpha} X_1 \xrightarrow{\beta^-} X_2 \xrightarrow{\beta^-} X_3$ which two are the isotopes ?

(A) X and X_1 (B) X and X_3 (C) X_1 and X_2 (D) X_2 and X_3

21. Half life of a radioactive element X is 3 hr. It transforms to form a stable element Y. After the birth of X; at time t, the ratio of the nuclei of X and Y is 1 : 15, what is the value of t ?

(A) 12 hr (B) 6 hr (C) 24 hr (D) 45 hr

22. In the process of forming helium from hydrogen, the mass defect is 0.5%. What is the energy produced when helium is formed from 1 kg hydrogen ? [1 kWH = 36×10^5 J]

(A) 1.25 kWH (B) 1.25×10^6 kWH (C) 1.25×10^8 kWH (D) 1.25×10^4 kWH

23. A radioactive element X disintegrates successively as under :

$$X \xrightarrow{\alpha} X_1 \xrightarrow{\beta^-} X_2 \xrightarrow{\alpha} X_3 \xrightarrow{\gamma} X_4.$$

If the atomic number and the atomic mass number of X are respectively 72 and 180, what are the corresponding values for X_4 ?

(A) 69, 176 (B) 69, 172 (C) 71, 176 (D) 71, 172

24. The half life of a radioactive element X is equal to the average life of other element Y. Initially number of atoms in both of them is same. Then,

(A) initially rates of disintegration of X and Y would be equal

(B) X and Y both disintegrate at the same rate, always.

(C) initially rate of disintegration of Y would be greater than that of X

(D) initially rate of disintegration of X would be greater than that of Y.

25. The elements X_1 and X_2 have decay constants 10λ and λ respectively. If initially they have equal number of nuclei, then after what time would the ratio of numbers of nuclei of X_1 and X_2 be $\frac{1}{e}$.

(A) $\frac{1}{10\lambda}$ (B) $\frac{1}{11\lambda}$ (C) $\frac{11}{10\lambda}$ (D) $\frac{1}{9\lambda}$

ANSWERS

1.	(C)	**2.**	(A)	**3.**	(B)	**4.**	(B)	**5.**	(D)	**6.**	(A)
7.	(C)	**8.**	(D)	**9.**	(D)	**10.**	(A)	**11.**	(A)	**12.**	(C)
13.	(B)	**14.**	(D)	**15.**	(B)	**16.**	(B)	**17.**	(C)	**18.**	(C)
19.	(B)	**20.**	(B)	**21.**	(A)	**22.**	(C)	**23.**	(B)	**24.**	(C)
25.	(D)										

Answer the following questions in brief :

1. What is mass defect ?

2. How can we say that radioactivity is a nuclear phenomenon ?

3. What is the meaning of rate of disintegration ?

4. 5 mCi = ...Bq. (fill in the blank)

5. What is the slope of the ln I $-$ t graph? (I = activity)

6. In a specimen the number of nuclei of a radioactive element at t = 0 time is 2048. If its half life is 5 hr, how many nuclei would have been disintegrated in 25 hr ?

7. "The half life of a radioactive element shows the half of its total life-time."
Is this true ?

8. What is artificial nuclear disintegration ?

9. What is meant by Q-value of a nuclear reaction ?

10. What is nuclear fission ?

11. "Neutron is a good projectile." Why ?

12. How much energy is produced by the fission of U^{235} nucleus ?

13. What is nuclear chain reaction ?

14. What is the function of moderator ?

15. What is meant by multiplication factor (K) in a nuclear chain reaction ?

16. What is the function of the control rods in a nuclear reactor ?

17. What is nuclear fusion ?

18. Define the SI unit of radioactivity.

19. Define the unit 'curie' for the activity.

20. Electrons do not stay in a nucleus, then how do electrons come from the nucleus in the process of β^--decay ?

Answer the following questions :

1. Give a brief account of nuclear forces.

2. Explain the stability of a nucleus.

3. Explain the binding energy of the nucleus.

4. Show the nature of the graph of average binding energy per nucleon against atomic mass number and explain its notable points.
5. Explain natural radioactivity.
6. Which are the radioactive radiations ? Mention their properties.
7. Explain the rate of disintegration of a radioactive element and the decay constant.
8. Obtain the exponential law of radioactive disintegration.
9. Define half–life of a radioactive element and obtain its formula.
10. What is meant by the average life of a radioactive element? Obtain its formula.
11. Explain the phenomenon of β–decay.
12. Explain the Q-value of a nuclear reaction.
13. Explain the process of nuclear fission in detail.
14. What is a nuclear chain reaction ? Explain the difficulties and their removal in its success.
15. Explain nuclear reactor with its working.
16. Explain the thermonuclear fusion in the Sun and other stars.
17. Discuss nuclear hazards.

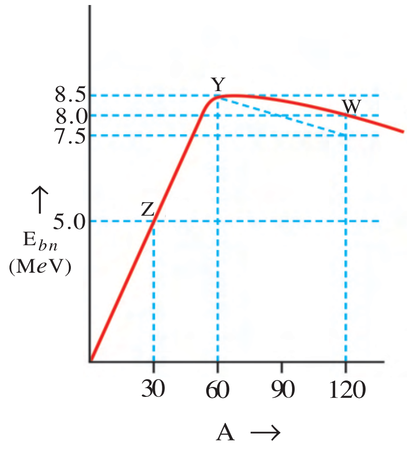
Solve the following examples :

1. In the figure, a graph of average binding energy per nucleon against atomic mass number is shown. In which one of the following reactions will energy be produced ?

   (*a*) Y $\rightarrow$ 2Z

   (*b*) W $\rightarrow$ 2Y

   [**Ans. :** Reaction (*b*)]



2. A radioactive element emits both α and β particles. The average life corresponding to α-emission is 1600 yr and that corresponding to β-emission is 400 yr. If both these emissions simultaneously take place, find the time for 75% of the specimen to decay.

   [**Ans. :** 443.52 yr]

3. Two protons in a star are involved in a head on collision. If the kinetic energy of each of these protons is 18 *ke*V, what would be the distance of closest approach between them ? (k = 9 $\times$ 10^9 Nm^2C^{-2}) [**Ans. :** 4 $\times$ 10^{-14} m]

4. When a counter is brought near a patient injected with a radioactive dose, it records 16000 counts per minute. In equal circumstances, after 4 hours it records 500 counts per minute. Find the half life of the radioactive element in the given dose .

   [**Ans. :** 48 min]

5. Half life of Ra^{226} is 4.98 $\times$ 10^{10} s. Find the activity of its 1 g specimen. Take Avogadro number as 6.02 $\times$ 10^{23} mol^{-1}. [**Ans. :** 1 C*i*]

6. Mass of $^{35}_{17}\text{Cl}$ nucleus is 34.9800 u. Taking the mass of proton as 1.00783 u and that of neutron as 1.00866 u, find the binding energy per nucleon for $^{35}_{17}\text{Cl}$ nucleus.

[**Ans. :** $8.219 \frac{\text{MeV}}{\text{nucleon}}$]

7. The average radius of a nucleus is 6.6 fermi. If the average mass of the nucleon is 1.0088 u, find the average density of the nucleus. ($R_0 = 1.1$ *fermi*, $1\ u = 1.66 \times 10^{-27}$ kg)

[**Ans. :** 3×10^{17} kg m^{-3}]

8. In a given sample, at some instant, the rate of disintegration of radioactive element is 8000 disintegrations per second. At this instant, the number of undisintegrated nuclei of this element is 8×10^7. Find the decay constant and half life of this element.

[**Ans. :** $\lambda = 10^{-4}\ s^{-1}$, $\tau_{\frac{1}{2}} = 6930$ s]

9. By the fusion of 1 kg deuterium ($_1H^2$) according to the reaction, ($_1H^2 + {_1H^2} \rightarrow {^3_2He} + {_0n^1} + 3.27$ MeV) how long can a bulb of 100 W give light ?

($N_A = 6.02 \times 10^{23}$, 1 yr $= 3.16 \times 10^7$ s)

[**Ans. :** Nearly 24917 yr]

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7

Semiconductor Electronics : Materials, Devices and Simple Circuits

7.1 Introduction

Electronics is a very familiar name in this modern age. The electron was discovered in the electric discharge experiment carried out in gases. It was later known that the electron is a very important particle in the constitution of matter. A detailed study on the various electronic property of the matter like the electrical conduction etc. has been done.

The electrical conductivity in the metals is due to its free electrons. Ohm's law is normally obeyed in the case of good conductors. This means that electric current is directly proportional to the electric potential difference.

We can establish different relation between the electric current I and the electric potential difference V, if we somehow control the number of electric charges which are responsible for the electric current. As a result, different types of application can be achieved by applying the electric potential difference and the current resulting due to it. We can think of making newer devices in which we obtain a specific I – V relationship by controlling the production of electrons, their numbers as well as its conduction. Such a device can be specially made or could be available in a natural form which can be modified as per our requirement. The branch of electronics deals with the study of such devices and its various applications.

(**Note :** The word electronics is coined from the word electron mechanics.)

There are many substances found in nature in which the conduction of electricity is different from the metals. By properly adding impurities in such a substance appropriate I-V relation can be established. The branch of solid state electronics has progressed due to such a substance.

Solid state devices have a very small dimension and they are lighter in weight. The electronic products made from such devices are small in dimension and are very efficient, at the same time there has been drastic reduction in their cost.

We shall study semiconductor device like the P-N junction diode, transistor, LED (Light Emitting Diode) and solar cell in the following section. We shall also study about logic circuits which are the pillars of the digital electronics.

7.2 Conductors, Insulators and Semiconductors (A Bond Picture)

The elements in the first three groups of the periodic table like the alkali metals, noble metals, aluminium etc. are good conductors. The electrical conduction is easily possible in such elements due to the presence of free electrons. The electrical resistivity of such elements is comparatively quite less. Non-metals (insulators) are almost bad conductors of electricity. There are no free electrons in such elements. These elements have a larger electrical resistivity.

The elements in the fourth group of the periodic table like the Si and Ge have greater electrical resistivity than the good conductors but have a lower resistivity than the bad conductors. Such elements are known as semiconductors.

The mechanism of flow of electric current is different in conductors and semiconductors. Pure semiconductors behave as insulator at 0K temperature.

The resistivity of conductors increases with temperature, while the resistivity of the semi-conductors decreases with increase in temperature upto certain limit. The conductivity of the semiconductor is changed by incidenting radiation of suitable frequency.

Table 7.1

Resistivity of Conductors, Insulators and Semiconductor (At Room Temperature)
(Only for Information)

Substance	Resistivity (ρ) (Ω m)	Conductivity ($\sigma = \frac{1}{\rho}$) (S/m)	Classification
Silver	1.6×10^{-8}	6.25×10^{7}	Conductors
Copper	1.7×10^{-8}	5.88×10^{7}	
Aluminium	2.6×10^{-8}	3.85×10^{7}	
Germanium (pure)	6.5×10^{-1}	1.54	Semiconductors
Silicon (pure)	2×10^{8}	5×10^{-9}	
Glass	1.7×10^{11}	5.88×10^{-12}	Insulators
Hard rubber	1.0×10^{16}	1×10^{-16}	

Si and Ge are known as elemental semiconductors. PN junction diode, zener diode, transistor etc are fabricated from it.

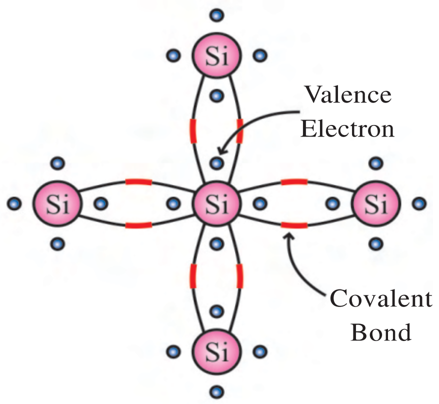
Many of the compounds apart from the elemental semiconductors also behave as semiconductors. Many of such compounds are carbonic, non-carbonic compounds as well as polymer carbonic substances. As for example CdS (Cadmium sulphide), GaAs (Gallium Arsenide), CdSe (Cadmium selenide) etc. are non-carbonic semiconductors. Solar cell, LED, LASER diode etc. are some of the devices which are made from such semiconductors.

After 1990, some of the electronic devices are made from carbonic and polymer carbonic substances. As result, branches of polymer electronics and molecular electronics have developed.

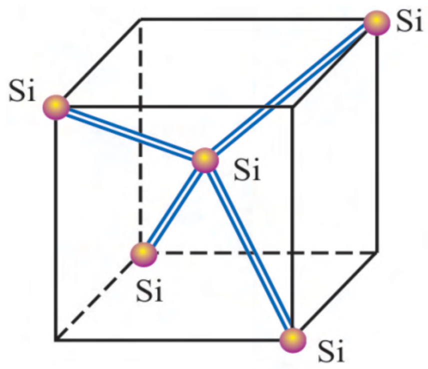
We will study only elemental semiconductors in this chapter. The Si is a very important semiconductor.

Atomic number of Si is 14. The electronic configuration of Si is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$. The electrons up to $1s^2\ 2s^2\ 2p^6$ completely occupy the K and L shells. $3s^2\ 3p^2$ electrons are the valence electrons. Hence Si (and Ge(z = 32)) is tetravalent. Here the two s orbital and two

p orbitals combine to form four (sp^3) complex orbitals. These orbitals combine with similar such orbitals of the neighbouring atoms and constitute covalent bond. There are two electrons for every covalent bond. In this way the four valance electrons of the Silicon makes a covalent bond with its four neighbouring atoms by sharing one-one electron. Figures 7.1 (*a*) and 7.1 (*b*) shows the above situation in two dimensions and three dimensions respectively. A crystal lattice of a diamond is obtained if one extends the above arrangement of atoms in three dimensional space. Thus Si and Ge have diamond structure.



(*a*)



(*b*)

Figure 7.1

Concept of Hole : At absolute zero temperature each of the valence electrons of Si (and Ge) is bound by the covalent bond. As a consequence Si (and Ge) behave as insulators at absolute zero temperature. The atoms of the crystal perform thermal oscillations at the room temperature. This results in the breaking of several covalent bonds and results in the electrons freeing from the covalent bond. These free electrons are responsible for electrical conduction.

Deficiency of electron is created at the place from where the electron became free. This deficiency has the ability of attracting the electrons. An electron which has become free from any other covalent bond can get trapped in this place. This deficiency of electron is known as hole. It behaves as if it has positive electric charge. (see figure 7.2) It has to be remembered that hole is not a real particle and it neither has any positive electric charge. The question then arises is that, what is the importance of hole.

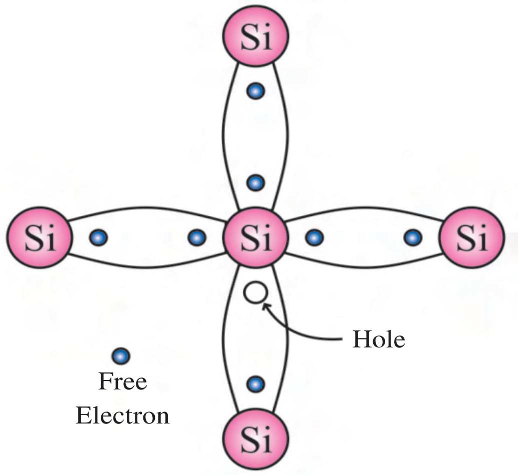


Figure 7.2

At room temperature in Si the required energy for electrons to escape from covalent bond is 1.1 eV and for Ge it is 0.72 eV.

Electrical Conduction in Semiconductors : We have seen how an electron leaves behind a hole on becoming free from the covalent bond. In this situation on applying a p.d. between two ends of a crystal, the free electrons move from negative end to positive end and constitute the electric current (see figure 7.3).

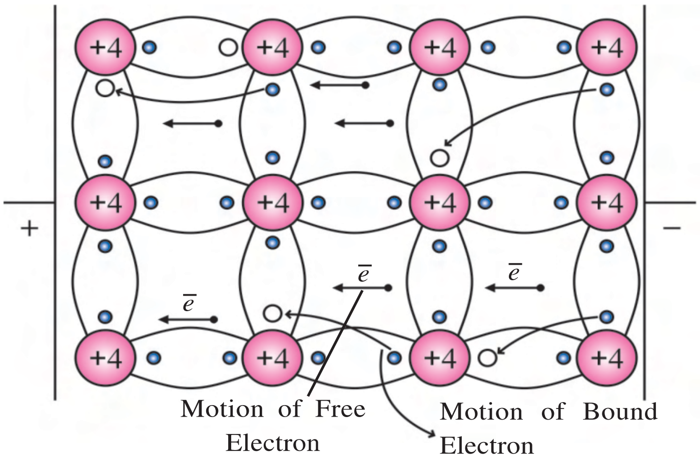


Figure 7.3 Electrical Conduction in Semiconductor

Apart from this, thermal oscillations and external electric field causes the bound electrons to be free from covalent bond and gets trapped in the nearest hole. And a new hole is created at the place where the electron escaped from the covalent bond. The motion of the bound electron is from the negative end towards the positive. Hence, it is understood that motion of hole is from positive end towards the negative end.

Thus, we get two types of currents in a semiconductor, (1) Due to motion of free electron (I_e) (2) Due to motion of bound electron or hole (I_h).

Such an electron becomes free from a bound state and again gets bound in the nearest hole. Such electrons cannot be considered as free electrons. To differentiate the motion of the bound and the free electron, one can consider the motion of the hole in a direction opposite to the direction of the motion of the bound electron.

The hole behaves as a particle having positive charge. Since its motion is in the opposite direction to that of the electron i.e. from the positive end towards the negative end. We will have to remember that the conduction of holes means that the conduction is due to bound electrons. In the case of a pure semiconductor like Si and Ge the electrical conduction is due to both electrons as well as holes.

The number density of free electron and hole in a intrinsic (pure) semiconductor n_e and n_h respectively are equal due to pair production. Here, electron and hole are also known as intrinsic electric charge carriers, hence it's number density is indicated as n_i. For an intrinsic semiconductor, $n_e = n_h = n_i$

In Si (or Ge) more number of bonds get broken with the increase in temperature. This results in increase in the number of electrons and hole. Due to increases in the number density of charge carriers the conductivity also increases.

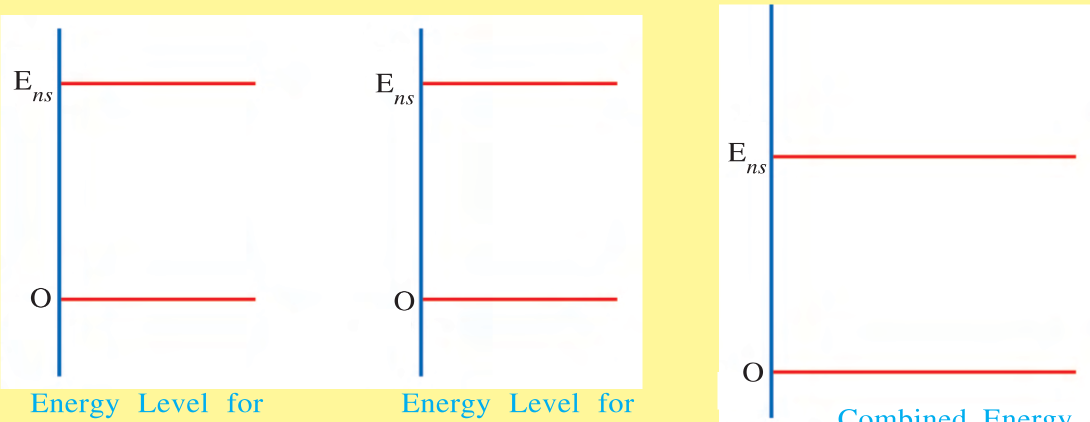
7.3 Conductor, Insulator and Semiconductors (A Band Picture)

Only for Information : The X-ray and other studies show that some solids have a crystalline structure. This shows that there is a systematic arrangement of atoms or molecules. In previous chapter, we have studied the energy level of an electron of a hydrogen atom, but it is not applicable to crystalline material. When atoms are arranged close to each other, the atom gets interact with neighbouring atoms and other atoms. As a result energy levels of electrons of atoms are changed. The energy level of inner shells electrons are not affected, hence they are strongly bound with the nucleus. But the energy levels of the outer shells electrons (valence electrons) are changed, since these electrons are shared, by more than one atom in the crystal. It is observed that electrons of the atoms in the crystal has closely spaced different energy levels instead of widely separated energy level of electrons of isolated atom. Such a band of close energy levels is called energy band. Now we shall learn, how energy bands are formed in solid materials.

We know that quantized energy levels of quantized system are drawn on the vertical axis with proper scale and with small horizontal line is called energy level diagram.

The study of quantum mechanics is inevitable in the understanding of the molecules containing more than one atom as well as the behaviour of the electron and their energy levels in solid substance.

The valence electrons of the constituent atoms are only considered to determine the configuration of the electron of a solid substance. Let us consider a simple example in order to understand the energy levels of the electrons of a solid substance. Consider a simple molecule containing only two atoms. Let each of the atom contain one valence electron represented as *ns* (Here n = principal quantum number and s means $l = 0$ orbital quantum number). The energy of the atom be represented as E_{ns}. When these atoms are at infinite distance from each other, then no interaction takes place between them. Hence the two atoms can be thought as independent. Each of them has an *ns* electron whose energy is equal in E_{ns}. figure 7.4 shows the energy level diagrams of each of these atoms respectively.



Energy Level for Atom (1)   Energy Level for Atom (2)   Combined Energy Level of Two Atoms

(*a*)   (*b*)

Figure 7.4 Energy Level of Atom

If the above two diagrams are represented on a single figure then we obtain a single line E_{ns} as shown in the figure 7.4 (*b*) indicating the energy of the two atoms.

When the two atoms are brought closer to each other then the constituent particles of the two atoms will interact with each other and as a result the energy of the valance electron will be different from the situation when they were separated by an infinite distance. A new wave function and as a consequence a different value of energy is obtained. The value of the energy E_{ns} will be now different for the two electrons which

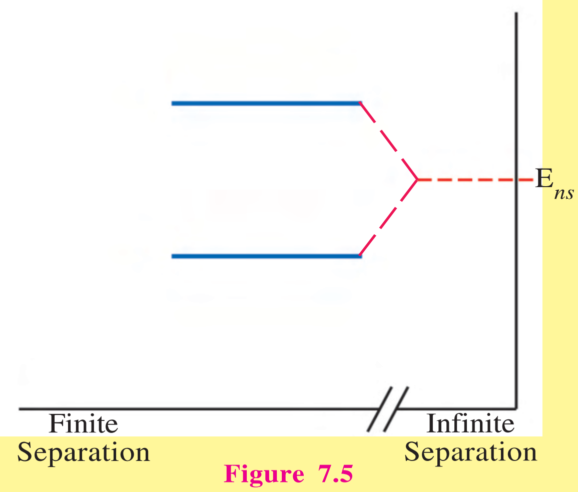


Figure 7.5

was earlier identical and represented as a single line. This results in the splitting of the energy E_{ns}. Such a representation of the splitting of the energy is given by an imaginary representation in the figure 7.5.

In the first case, we have two energy levels of energy E_{ns} and from which we obtained two energy levels having different energy.

In our imaginary example, if we had three atoms, E_{ns} then we would have obtained three different energy levels or in other words the original energy level will get split into three different energy levels.

If we extend our discussion to the energy E_{ns} of the N atoms, we shall obtain N energy levels. (It has to be noted that the total number of energy levels remain fixed.) For a two atom system the distance versus energy contains two graphs, while the N atom system will contain N graphs. For the sake of simplicity figure 7.6 shows the energy levels of the electron having the maximum and the minimum value, after the splitting has taken place. In between energy levels are merely indicated by horizontal lines.

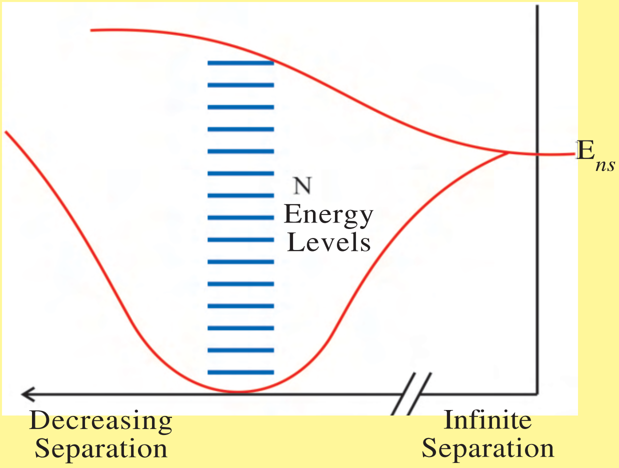


Figure 7.6 Energy Levels on N Atoms

The difference in the energy between two adjacent splitted energy levels is very less. One can say that the splitting of the N energy levels constitutes an energy band. In the example considered so far, we have been discussing the band structure due to the *ns* band. Since *ns* is considered as the state of valence electron, the band can also be referred to as valence band.

Let us try to understand the band structure obtained in case of silicon (Si).

The electronic configuration of silicon atom is given as $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$. Here the $n = 1$ (K-shell) and $n = 2$ (L-shell) are completely filled hence $3s^2\ 3p^2$ four electrons are valence electrons. Hence, we have a total of four valence electron. Let us consider that N number of atoms are present in solid silicon. If initially these atoms are separated by an infinite distance, we have 2 N electrons of the $3s$ type and 2N electrons of the $3p$ type. The total number of valence electrons would be equal to 4 N. Each atom has total number of 2 valency states in the 3s sub shell and 6 number of $3p$ valency states. Hence a total of 8 valence states are available for the $3s$ and $3p$ states. For a solid containing

N number of atoms, a total (2 N + 6 N) valence states are existing. All 2N states of E_{3s} as well as all the 2 N states of E_{3p} are identical when they are an infinite distance from each other. This is shown in the figure 7.7.

As the separation between the atoms is reduced, the splitting of the 3*s* state into 2N levels and the splitting of the 3*p* state into 6N levels takes place. For example, the splitting for distance R_1 of the 3s and 3*p* states into 2N and 6N levels respectively is shown in the figure. Here E_g is called the band gap.

Band gap is the difference between the maximum energy level of the E_{3s} state and the minimum energy level of the E_{3p} state for the given inter atomic separation.

On further reduction in the inter atomic separation, there is no gap between 3*s* and 3p types of bands. From this separation onwards, we get a combined wave function, by carrying out the integration of the 3*s* and 3*p* type wave function. On further reducing the separation the two bands containing 4N energy level each are obtained. The band gap between them is shown in figure 7.7. The two bands for the equilibrium position of silicon is shown in the figure. As per Pauli's exclusion principle, we can have one electron for each energy level. As a result, the lower band will be completely occupied by 4 N number electrons. (As per Pauli's exclusion principle, each level cannot accommodate more than one electrons.) Here lower band is called valence band.

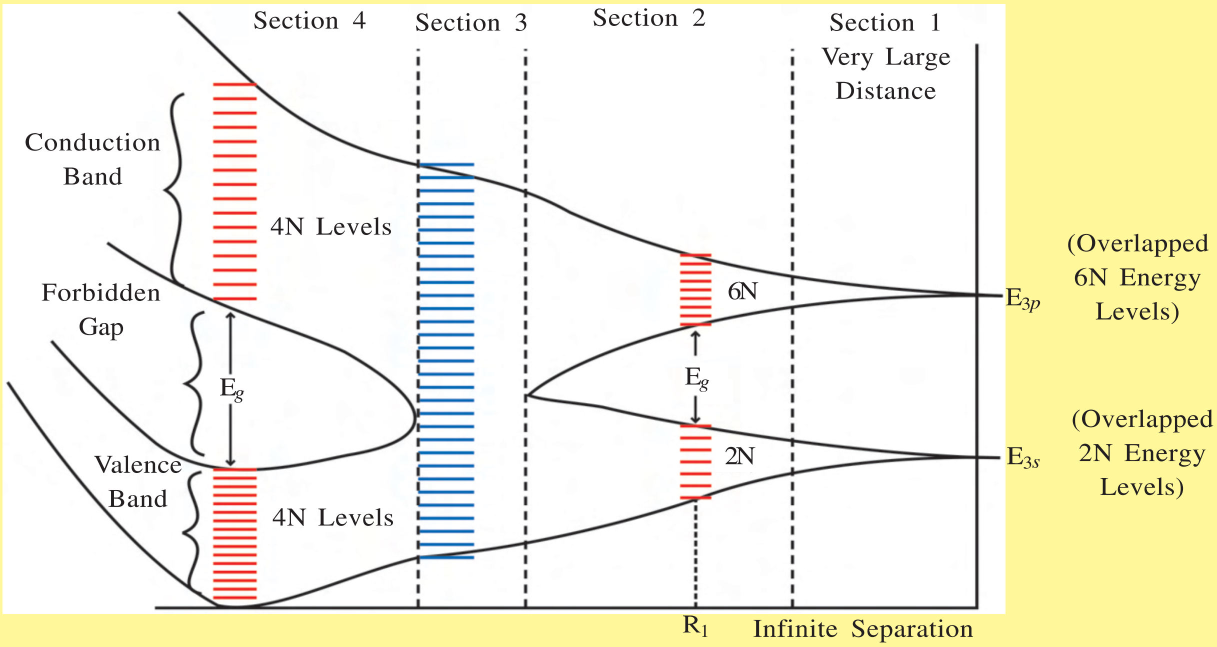


Figure 7.7 Band Diagram of Si

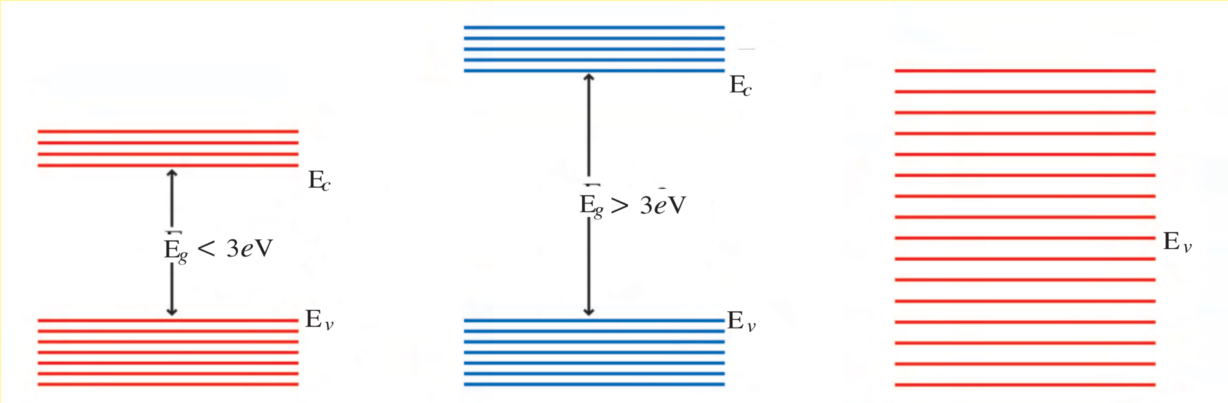
The upper band is completely empty. A minimum of E_g energy will have to be supplied to the electron to move from the valence band to the upper band. It can move in to any of the energy levels in the upper band, since it is completely empty. If it does so it becomes a free electron and is available for electrical conductions. It is for this reason the upper band is known as the conduction band.

The difference in the lowest energy of the conduction band and the maximum energy of the valence band is known as band gap (E_g). There are no available energy states in the band gap. It is for this reason that this gap is known as forbidden gap.

The situation of an insulator is similar to that of semiconductors in which the valence band is completely filled while the conduction band is completely empty. The only difference between the two is the value of the band gap. The value of the band gap is large in case of an insulator. It is more than 3*e*V while for a semiconductor it is less than 3*e*V.

Let us consider an example of the sodium metal in order to understand the energy levels of a conductor. The electronic configuration of N*a* is given as $1s^2\ 2s^2\ 2p^6\ 3s^1$. Thus there is one valence electron in Na atom. There are two quantum states if one considers the spin for the 3s state. If we consider the sodium atom to be made up of N atoms then there are total number of 2N available states or 2N number of energy levels. (Here we are discussing the energy levels arising from the 3 s state). If we start filling the electrons in the valence band, since there are N number of valence electrons, the valence band will be half filled according to the Pauli's exclusion principle. In such a situation, with very little energy, the electron can move into the available energy levels. These electrons behave as if they are free electrons and contribute towards electrical conduction. The study of the band structure of the metals containing more than one valence electrons suggests that the valence band and the conduction band overlap each other.

The insulators, semiconductors and the conductors have the valence band and the conduction band structure as shown in the symbolic diagram of figure 7.8.



Semiconductor | Insulator | Good Conductor (Overlaped Valence Band and Conduction Band)

Figure 7.8 Band Diagram for Conductor Insulator and Semiconductor

The explanation given in the box gives us an idea about of the band structure of the solid substance. Let us summarize the discussion as follows.

The atoms have energy levels similar to the energy states of all atoms. The classification of insulators, semiconductors and conductors is based on the basis of these energy levels.

Let us consider the example of silicon in order to understand the electrical conductivity of the insulators.

Semiconducter : Let there be N number of atoms in the diamond structured silicon crystal. There are two electrons in the $3s^2$ state and six electrons in $3p^2$ of the silicon atom which are the available valence states. Out of which four states are filled.

When the Si atom constitutes the crystal, we have a total of 8N valence state and the corresponding energy levels are indicated in the figure 7.9.

The closely spaced 4N levels constitute a band structure. As per the Pauli's exclusion principle, one electron occupies only one energy level. As a result with the 4N available electrons the lower band is completely filled.

This lower band is known as valence band. As the band is completely filled, the electrons cannot move to other energy levels. Hence, there is no electrical conductivity.

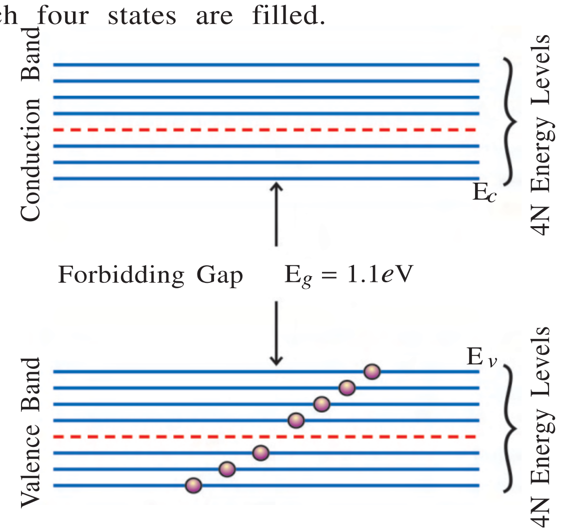


Figure 7.9 Band Diagram of S_i at (0 K Temperature)

Above the valence band, there is a region where there is no available energy levels. This region is known as the forbidden gap. The width of the forbidden gap is < 3 *e*V. The values of E_g for Si and Ge are 1.1 *e*V and 0.72 *e*V respectively.

The region of the energy above the forbidden gap is known as the conduction band. At 0 K temperature, the conduction band is completely empty. If the electron has enough energy to cross the forbidden gap then the electron can move from the valence band to the conduction band. These electrons will then contribute towards the electrical conduction.

A hole is created when an electron moves from valence band to the conduction band. The number of holes created is equal to the number of electrons present in the conduction band. Hence in an intrinsic semiconductor number of electrons and holes are same.

Insulator Substances : Such a substance has large forbidden gap (>3 *e*V). For diamond value of E_g is 5.4*e*V. As a result, the electrons are not able to move easily from the valence band to the conduction band and such a substances are bad conductors of electricity.

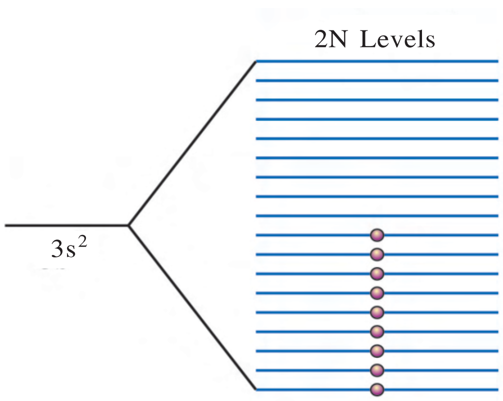


Figure 7.10 Band Diagram of Sodium

Conductors : Figure 7.10 shows the band structure of a sodium atom, which explains the reason why it is a good conductor of electricity. The electronic configuration of sodium atom is given as $1s^2\ 2s^2\ 2p^6\ 3s^1$. There are 2 N valence states for the 3s state. Out of which N states are filled due to the contribution of one electron from each of the sodium atom. The remaining N states are empty. As a result, the electrons can move easily into the empty available states and contribute towards electrical conductivity. In many of the metals, the conduction and the valence bands overlap each other. In such a situation too the electrons contribute in the electrical conduction.

7.4 N and P Types Semiconductors (Extrinsic Semiconductors)

The conductivity of the pure semiconductor can be drastically changed by adding impurities in the right proportion. This process of adding impurities in the semiconductor is known as doping. As for example pentavalent impurities like Antimony and Arsenic or trivalent impurities like aluminium, Gallium or Indium can be used for doping, the doped atoms arrange themselves in place of the original atom in the host crystal.

Two dimensional symbolic representation of silicon crystal lattice structure is shown in figure 7.11. Here the Arsenic atoms have been added as impurity atoms. The figure shows Arsenic atoms replacing one silicon atom.

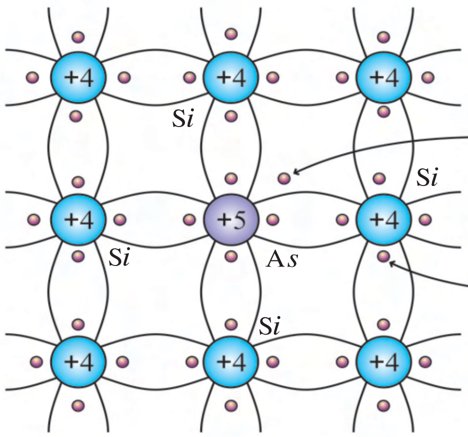


Figure 7.11 Si Crystal Lattice with as Impurity

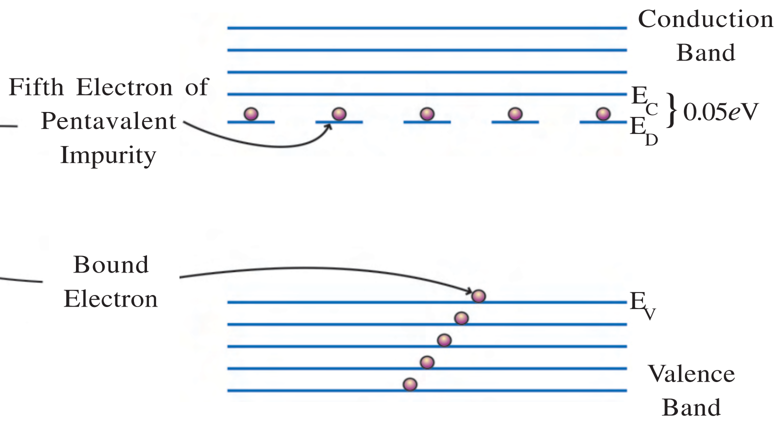


Figure 7.12 Band Diagram of N-type Semiconduction (At 0 K Temperature)

The four out of the five valence electrons of the Arsenic atom are involved in the formation of the covalent bonds with its four neighbouring silicon atoms. The fifth electron is available as an extra electron to the crystal. If 0.05 eV energy is available to this electron, it can act as a free electron. This energy is 0.01 eV in case of Germanium. This much energy is already available to the electron in the form of thermal energy at the room temperature. The impurity atoms donate electric charge carriers (electron) to the host crystal. Such an impurity atom is known as donor atom. Their proportion is kept as approximately as 1 in 10^6 pure atoms. Hence, 1 mole crystal contains approximately 10^{17} impure atoms. Each of these impurity atoms contribute one electron. 1 mole crystal contains approximately 10^{17} free electrons. A metal like copper which is a good conductor contains approximately 10^{23} free electron.

Apart from the number of free electrons mentioned above, some more free electrons are obtained due to the breaking of the bonds resulting in the formation of the holes. Their number is very small compared to the number of free electrons donated by the impurity atoms. We can thus say that the charge carriers available for electrical conduction is primarily obtained from the electrons donated by the impurity atoms. Thus electrons are known as majority charge carriers, in the case of the addition of pentavalent impurities. The electron carries negative charges and hence such a crystal is known as N-type semiconductor crystal, deriving it's name from the first letter of the word Negative. The electrical conduction due to holes in such a crystal is very less, so holes are known as minority charge carriers. It is very clear that $n_e > n_h$.

Figure 7.12 gives the energy levels in N-type semiconductors which helps in understanding the electrical conductivity in N-type semiconductor. The figure shows the completely filled valence band as well as the completely empty conduction band. Apart from these energy levels the valence energy levels of the impurity atoms is also indicated by the dashed lines. The above situation refers to 0 K temperature.

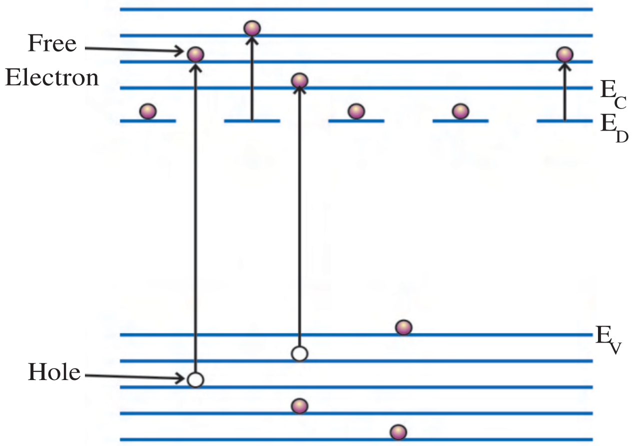


Figure 7.13 Band Diagram of N-type Semiconductor (At Room Temperature)

At 0 K temperature, one electron each of the impurity atoms occupies one of these energy levels. We are aware of the fact that the impurity atoms are scattered in the crystal structure of the semiconductor. The wave function of these valence states lie closer to the impurity atoms or in other words are not present in the entire crystal. Hence the symbolic representation is shown by dotted line.

The difference between (E_C) and (E_D) being very less, when the temperature increases, more and more electrons from the valence band of the semiconductor as well as the valence electrons of the impurity atoms would cross over to the conduction band and occupy empty energy levels in it. The number of charge carriers available for electrical conduction will be much more than the pure semiconductors. Hence, in N-type semiconductor $n_e > n_h$.

P-type semiconductors : If we add trivalent impurity like Aluminium in the Germanium or silicon then three free electrons of these impurity atoms form covalent bonds with its neighbouring three Germanium or Silicon atoms. As a result, there is a deficiency of one electron in the formation of the covalent bond in one of the four neighbouring Ge or Si atoms. This deficiency of electron can be considered as a hole. This hole is present in one of the bonds between the aluminium and silicon atoms. This hole attracts electron and hence in this sense the aluminium impurity is known as acceptor impurities. The electrical conduction in such a crystal is primarily due to holes. Holes behave as a positively charged particle. Hence, such a semiconductor is known as P-type semiconductor. Holes are the majority carriers while electrons are the minority charge carriers in a P-type semiconductor. In this case $n_h > n_e$.

Figure 7.14 shows symbolic representation of Aluminium impurity added to a Germanium crystal lattice.

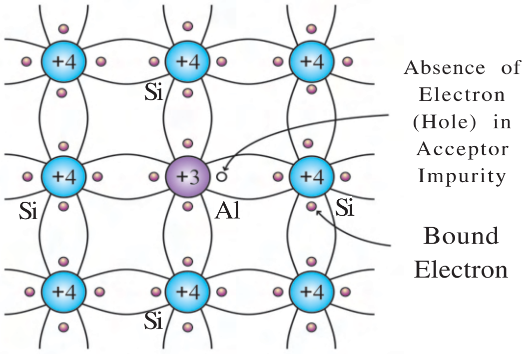


Figure 7.14 Si Crystal with Al Impurity

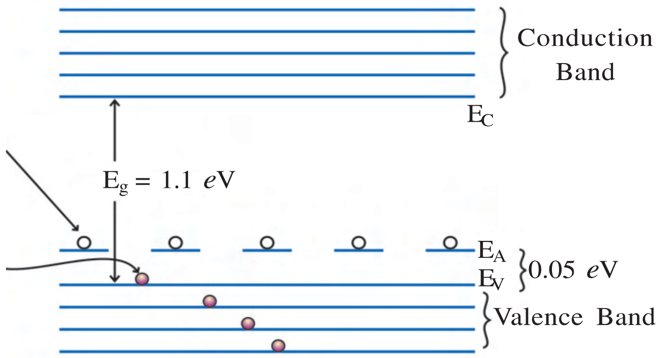


Figure 7.15 Band Diagram of P-type Semiconductor (At 0 K Temperature)

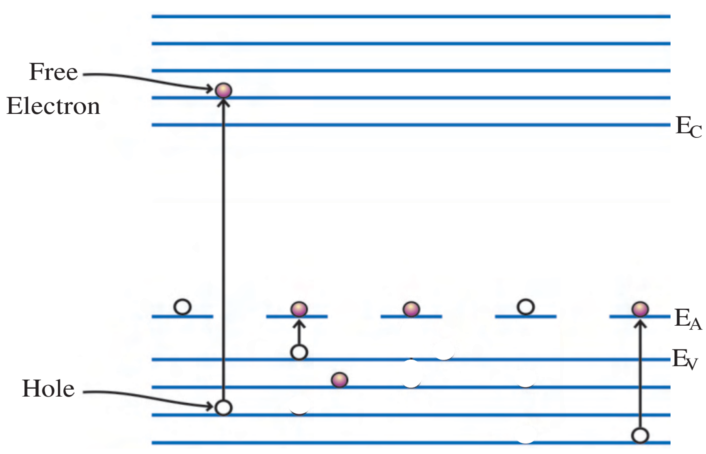


Figure 7.16 Band Diagram of P-type Semiconductor (At Room Temperature)

Figure 7.16 shows the energy levels of the semiconductor as well as the impurity atoms of a P-type semiconductor. Here the impurity atoms energy levels E_A lies very close to E_V. Since no electrons are present at these energy levels one can say that there is an existence of holes. The electrons present in the valence band of the semiconductors can easily occupy the empty energy levels of the impurity atoms on getting sufficient energy at the room temperature. Apart from these, some of the electrons occupy empty energy levels in the conduction band and as a result create holes in large numbers and the possibility of the motion of the electrons also increases. Hence in a P-type semiconductor the electrical conductivity is much more than the electrical conductivity of a pure semiconductor. Here $n_h > n_e$.

The next question arises in our mind as to why don't all the electrons from the valence band cross over to the conduction band. Actually the creation of electron hole pair due to the migration of the electron to the conduction band is not a very stable situation. The electrons and holes collide with each other as per the laws of thermodynamics and the temperature. The electrons once again occupy the hole. The creation of the electron hole pair and it's recombination process takes place at the same time. In the equilibrium position the rate of electron hole pair formation and their recombination is equal.

The recombination rate $\propto n_h n_e$

Recombination rate $= R\ n_h n_e$ (7.4.1)

Here R is known as the recombination coefficient.

For an intrinsic (or pure) semiconductor, $n_e = n_h = n_i$

Hence the recombination rate $= Rn_hn_e = Rn_i^2$ (7.4.2)

The recombination rate for an intrinsic semiconductor and it's extrinsic semiconductor as per the laws of thermodynamics are equal.

$\therefore\ Rn_en_h = Rn_i^2$

$\therefore\ n_i^2 = n_en_h$ (7.4.3)

7.5 P-N Junction Diode

When Si or Ge wafer is doped with donor impurity (As) at one end and accepter impurity (A*l*) at the other end, the silicon wafer contains N-type semiconductor region, P-type semiconductor region and junction between them. Figure 7.17 shows the situation of P region and N region before PN Junction is formed.

There are excess holes in the P-section. The holes are represented as a small circle (O). These holes exist in the site of the covalent bond between the impurity atoms Al and Si atoms. In the N section there are excess electrons and it is represented as small line (–). These electrons are obtained from the impurity atoms (As). To illustrate the impurity atoms three As atoms and three Al atoms are shown in figure 7.17.

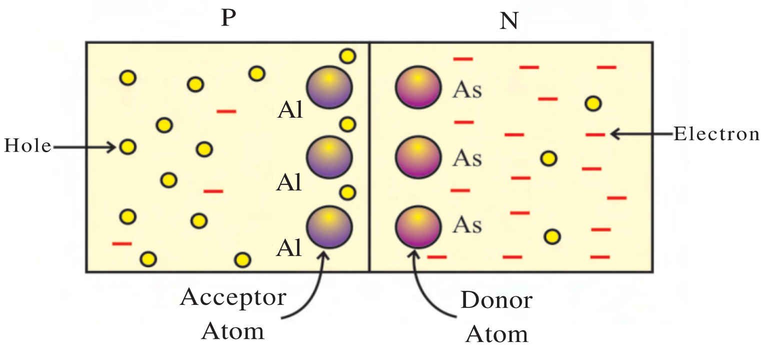


Figure 7.17 A Situation before Formation of PN Junction

In this situation both N and P are electrically neutral. In N section, Arsenic atom donates one electrons but its nucleus carries one excess positive charge. In a similar way in the P section, there is a deficiency of one electron due to aluminium atom but its nucleus also has one positive charge less.

N–section has excess of free electrons compared to the P section. Hence, the diffusion of electron takes place from the N-section towards the P-section. As a result, the electrons diffuse in the hole existing in the P section of the junction. Similarly, the holes also diffuse from P-section towards N-section in a small amount. i.e. near the junction small amount of valence electrons of N-section diffuse in the holes of P-section.

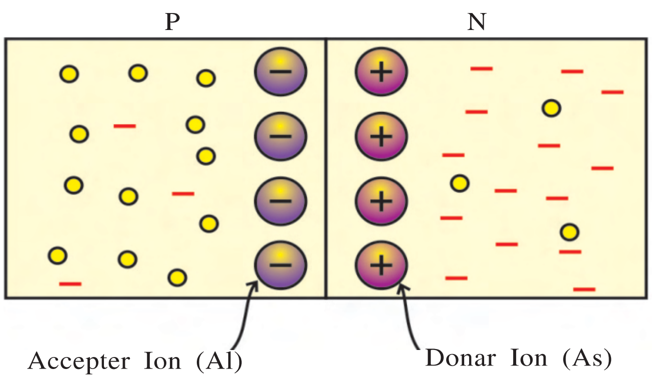


Figure 7.18 Situation of PN Junction After the Diffusion

Figure 7.18 shows the situation after some diffusion has taken place. As the electron from Arsenic atom of the N-section diffuses into the hole of Al atom in P-section. Arsenic atom becomes positive ion and Al atom becomes negative ion near the junction. As the diffusion process continues the number of the positive ion increases on the N side of the junction and negative ion increases on the P side of the junction. Thus the negative charges and positive charges are accumulated near the junction in the P-section and N-section respectively. These charges are steady since they are charges of the ions. Due to these charges, electric field is established at the junction from N region towards the P region. In other words, positive potential on the N side and negative potential on the P side is established. Now the electrons have to overcome the electric field in order to diffuse from N region to P region. The diffusion process of the electron and hole stops as the electric filed is sufficiently established.

This situation of PN Junction is shown in figure 7.19. A graph also shows the established electric potential near the junction region. Two points can be concluded from the figure 7.19.

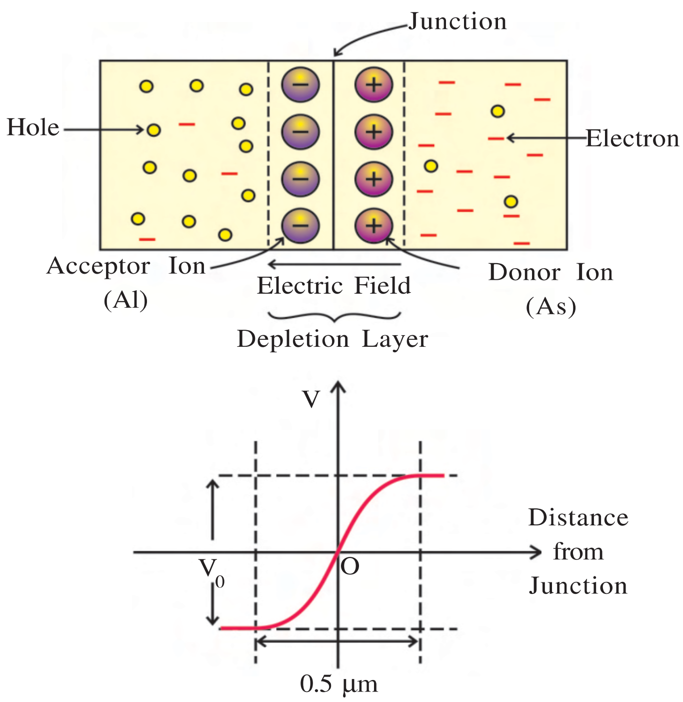


Figure 7.19 Depletion Layer of PN Junction

(1) Electrons are no longer the majority charge carriers in the small region of the N-type material near the junction. Similarly holes are not the majority charge carriers in the small region of the P-type semi-conductors near the junction. These regions are known as depletion region since they are depleted of the respective majority charge carriers. This region is known as depletion layer or space charge region. The width of depletion region is approximately $0.5\,\mu m$.

(2) The distribution of electric potential in the depletion layer is called the depletion barrier or potential barrier. This potential barrier is in order of 0.1 V. This value is about 0.7 V for Si and 0.3 V for Ge.

In PN Junction, the magnitude of depletion barrier and width of depletion region are dependent on the concentration of the impurity added to the P and N type semiconductor. The depletion region is wider if the amount of impurity atom added is less and the electric field becomes weaker near the junction. The width of the depletion region decreases with the increase in the impurity concentration. This increases the intensity of electric field near the junction. Thus, the characteristics of the junction can be changed by increasing or decreasing the impurity concentration. As a result we can fabricate different types of the semiconductor devices. The symbol of PN junction diode is shown in figure 7.20.

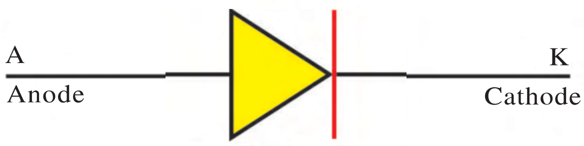


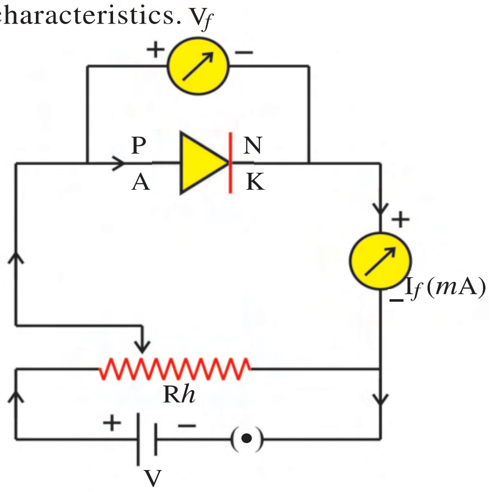
Figure 7.20 Symbol of PN Junction

Here, P region is referred to as anode (A) and N is referred to as cathode (K). Since, there are two electrodes, it is known as PN junction diode.The arrow shows the direction of conventional flow of current (when diode is in forward bias) in PN junction diode. Now we will discuss the characteristics of the diode.

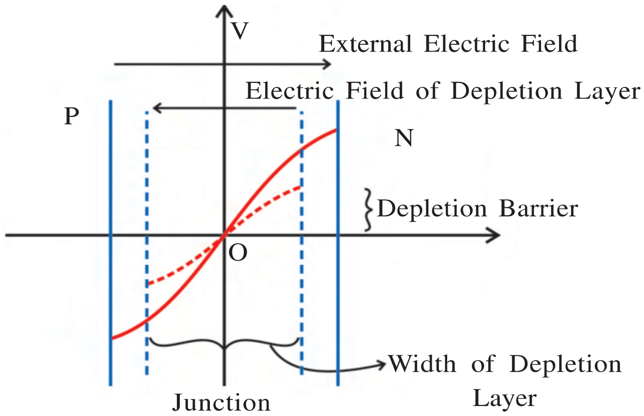
7.6 Static Characteristics of PN Junction Diode

We shall study the I-V curve of the PN junction diode, which is also known as the characteristics of the P-N junction diode.

The circuit diagram to study the characteristic of diode is shown in figure 7.21 (*a*) and 7.23 (*a*). Continuous voltage can be varied across the diode with the help of the rheostat connected in a parallel connection with the battery. The voltmeter measures this applied voltage. The milliammeter or the microammeter (depending on the value of the current)measures the current. There are two different types of the voltage applied across the diode to study its I-V characteristics.



(*a*) Electric Circuit



(*b*) Width of depletion region and reduction in barrier potential (dotted line) in forward bias mode

Figure 7.21 Forward Bias Connection of P-N Junction

Forward Bias : When the positive terminal of battery is connected to P side of junction and negative terminal connected to N side of junction such a connection is known as forward bias.

In such a connection the electric field due to external battery and electric field of depletion layer are in opposite direction. The emf (V) of the external battery and the potential difference (V_0) existing at the depletion region oppose each other. As a result the width and height of the depletion barrier reduces (See figure 7.21 (*b*)). Now, the work done by electron will be less to move from N-type to P-type and more and more electrons cross the junction easily. Similarly, hole can easily cross the junction from P-type to N-type. Thus, there is a flow of current in the junction due to both types of majority charge carriers. In forward bias the total current is sum of the hole diffusion current and electron current. This direction of the current in the junction is from P-type towards N-type. The magnitude of this current is in order of mA. If the battery voltage increase, the current in the junction also increase as shown in figure 7.22.

As shown in the figure 7.22, the initial increase in current is very less compared to the increase in the voltage. As the value of the voltage increases beyond a point, the current starts increasing rapidly (exponentially). This voltage is known as the threshold voltage or cut in voltage. The approximate value of threshold voltage for Ge and S*i* is ≈ 0.3 V and ≈ 0.7 V respectively.

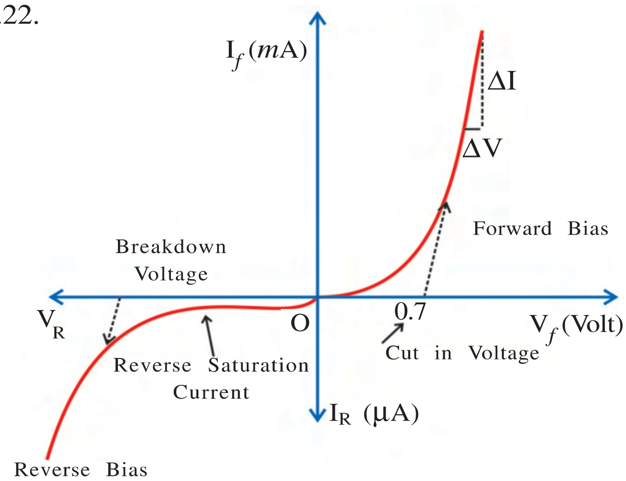


Figure 7.22 Characteristics of PN Junction

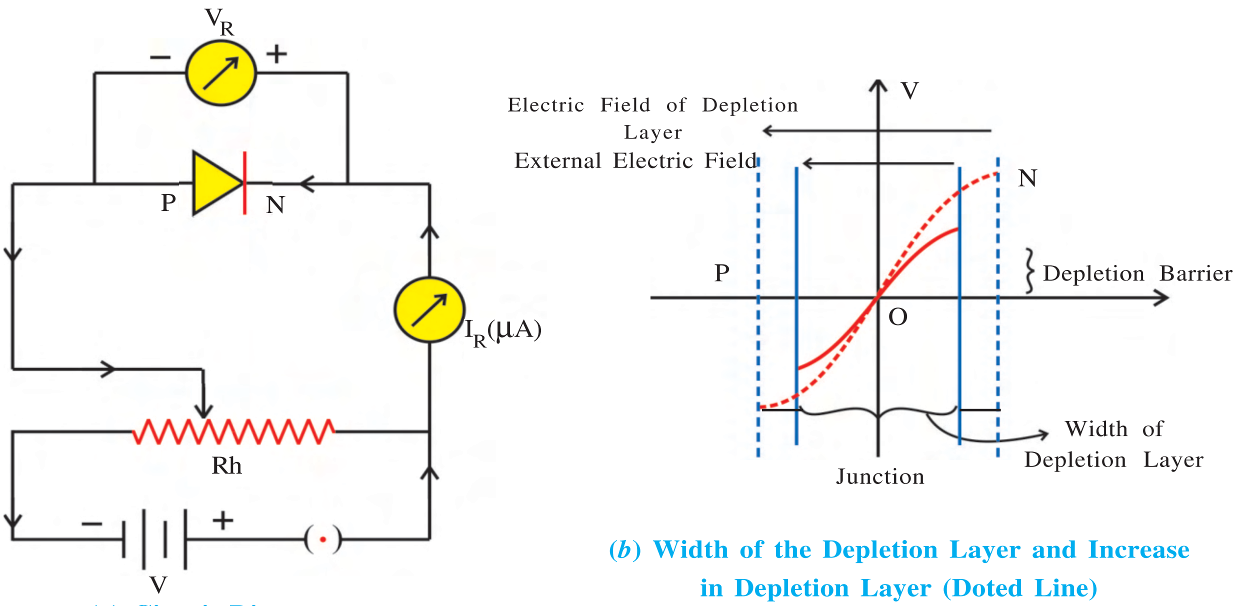
The current and the voltage do not have a linear relationship. Hence, the Ohm's law cannot be used to measure the resistance of the PN junction diode. But we can find its resistance by following method.

The dynamic resistance (r_f) of the diode can be found at any point on the characteristics curve by taking small changes in voltage (ΔV) and small changes in current (ΔI) and taking their ratio.

$$\therefore \; r_f = \frac{\Delta V}{\Delta I}$$

The values of r_f will be different at different points on the curve. The resistance of the diode in forward bias mode is approximately between 10 Ω to 100 Ω.

Reverse bias : When the positive terminal of battery is connected to N side of junction and negative terminal connected to P side of junction such a connection is known as reverse bias.



(*a*) Circuit Diagram

(*b*) Width of the Depletion Layer and Increase in Depletion Layer (Doted Line)

Figure 7.23 Reverse Bias Connection of P-N-Junction

In such connection the electric field due to external battery and electic field of depletion layer are in same direction, means potential difference of external battery and potential of deplation layer are in helping position. As a result the width and height of the deplation barrier increases. (See figure 7.23 (*b*)). As a result electrons find it more difficult tomove from N to the P region of the dicide as well as holes to move from pregieon to N region.

But resultant electric field is in such a direction that minority charge carriers in P and N section cross the junction. In reverse bias, due to minority charge carrier, current produced in μA range. This current remains constant with battery voltage. So it is called reverse saturated current. There is sudden rise in current when the voltage is increased beyond point. This value at voltage is known as breakdown voltage (V_R). Voltage given to PN junction greater than breakdown voltage may damage it.

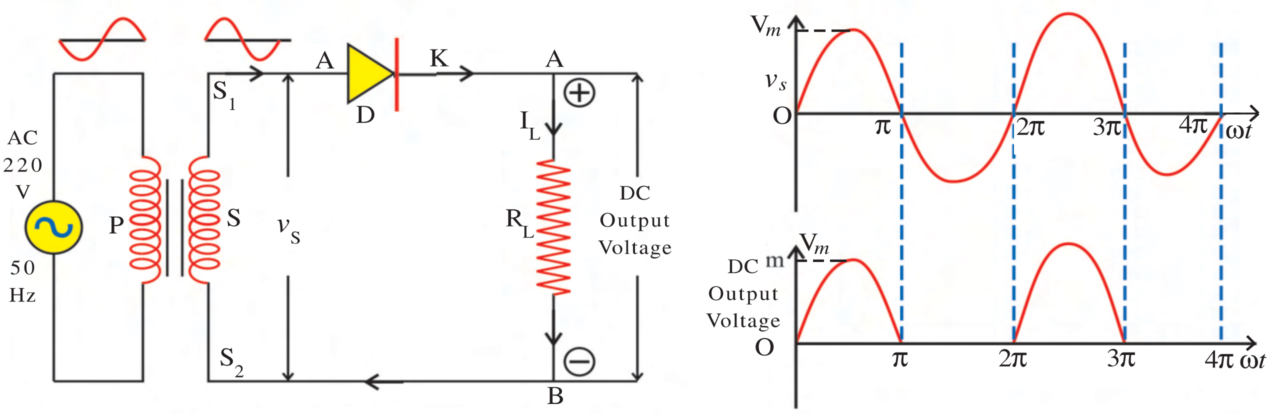
In reverse bias mode Dynamic resistance (r_{rb}) of PN junction is very of the order ($\approx 10^6$ Ω.). It is range of 10^6 Ω.

7.7 PN Junction Diode as a Rectifier

Most of the electronics devices and instruments require the DC energy for their operation. For example, radio, TV, cellphone etc. This DC energy we can be obtained from the different types of the batteries. But during their operation it gets discharged as well as being very costly. AC energy is easily available at our home as well as it is also very cheap. So that we required the circuit which can convert cheap AC energy into DC energy. The process of converting AC energy inot DC energy is called rectification. The circuit which performs this process is called the rectifier. We can use the PN junction diode for making rectifier circuit.

We have seen that the conventional current flows from P towards N when the P-N junction is forward biased. When the P-N junction is reverse biased the current flowing from N towards P is almost zero. This clearly tells us that when AC voltage is applied to the diode, current will flow in the circuit only during that half cycle for which the P-N diode is forward biased. During the next half cycle the diode becomes reverse biased since the P end is at a negative potential with respect to the N end. In this situation, if we place a resistor in the circuit we would obtain unidirectional current which will be varying with time and producing pulsating DC voltage. The circuit diagram which can realize the above process is shown in figure 7.24 and 7.25.

Half Wave Rectifier : The circuit diagram of half wave rectifier is shown in figure 7.24. The primary coil of transformer is connected to AC mains voltage (220 V, 50 Hz). The secondary coil of transformers is connected in series with the PN junction diode D and load resistance R_L. Figure shows how the AC voltage in secondary coil of transformer is changes when AC mains voltage is connected to primary coil.



(*a*) Electric Circuit

(*b*) Waveforms of HW Rectifier

Figure 7.24 Half Wave Rectifier

During the first positive half cycle of v_S ($0 \leq \omega t \leq \pi$) the S_1 end of the secondary coil is positive with respect to S_2 as a result PN junction diode will be in forward bias. The conventional current flows through secondary coil of transformer, PN junction diode and load resistance R_L. In this situation, current flows from A towards B through the load resistor R_L. Here, A end becomes positive and B end becomes negative. The output voltage obtained during this half cycle is shown in figure 7.24 (*b*).

Now, during the second half cycle ($\pi \le \omega t \le 2\pi$) S_1 end of secondary coil becomes negative with respect to S_2. As a result PN junction will be in reverse bias and no current will flow in the circuit. The output voltage developed across R_L will be zero. [See figure 7.24 (*b*)].

Thus, the sequence of events taking place in the first two half-cycles is repeated. Now you can understand that at every half-alternate half cycle, the current flows through R_L only in one direction (i.e. from A towards B) which is a direct current (DC). As a result the voltage developed across R_L will be also DC voltage.

In this arrangement we get the output voltage during only one half-cycle, therefore, it is called half-wave ractified.

Full Wave Rectifier : In order to get the output voltage during both the half cycle, two PN junction diodes are used. The circuit diagram of full wave rectifier is as shown in figure 7.25.

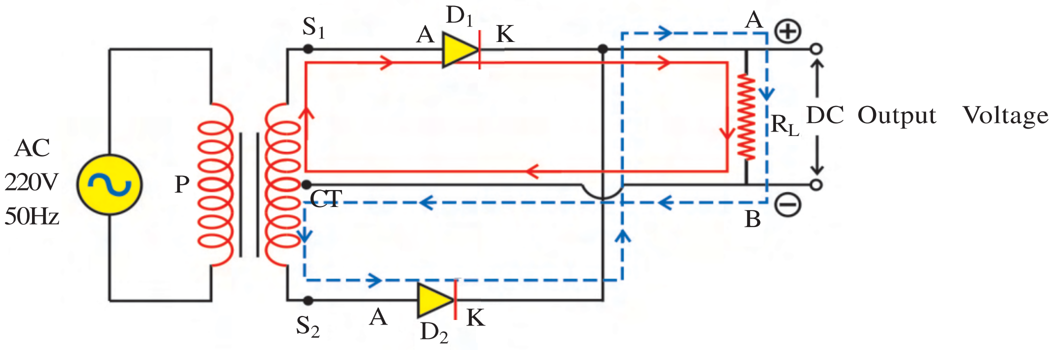


Figure 7.25 Full Wave Rectifier

As shown in the figure 7.25 the anode of diodes D_1 and D_2 are connected to S_1 and S_2 of secondary coil of centretaped transformer.

The load resistance R_L is connected between the two cathodes of diodes and centre tap of the transformer.

The applied voltage to both the diodes are same ($v_{s_1} = v_{s_2}$) but phase difference between them is 180°. Since the number of turns are equal on both the sides of centre tapped transformer. Let at any instant of the input voltage, S_1 end of the secondary coil becomes positive and S_2 end become negative with respect to centre tap ($0 \le \omega t \le \pi$). In this situation D_1 diode is forward biased and D_2 diode is reverse biased. Hence the conventional current flows in the $S_1 - D_1 - A - R_L - B - CT - S_1$ direction. The A end of the R_L becomes positive and B end becomes negative.

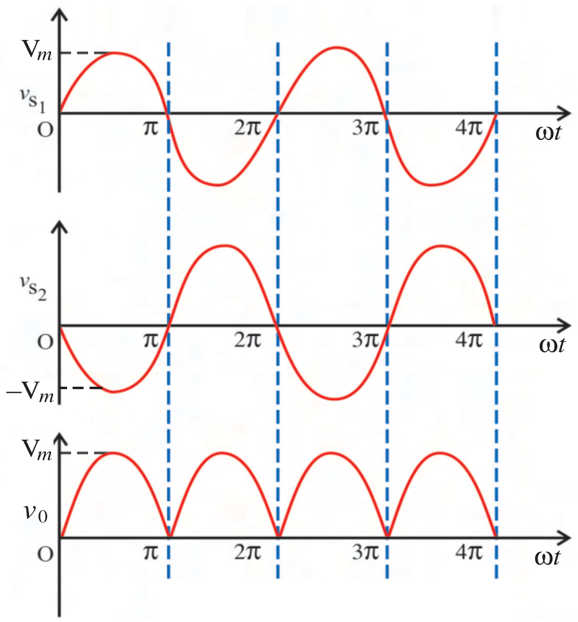


Figure 7.26 Wave forms of full Wave Rectifier

During the next half cycle S_2 end of secondary coil becomes positive and S_1 end becomes negative ($\pi \le \omega t \le 2\pi$) with respect to centre tap (CT). Now D_2 diode is forward biased and D_1 diode is reverse biased. The conversional current-during this half cycle flows through the $S_2 - D_2 - A - R_L - B - C_T - S_2$ direction. (The path of the current is shown with dotted line in the figure 7.26). Even during this half cycle current-flows from A towards B in the load