13. Nuclear chemistry and radioactivity

13.1 Introduction: Nuclear chemistry is a branch of physical chemistry : It is the study of reactions involving changes in atomic nuclei. This branch started with the discovery of natural radioactivity by a physicist Antoine Henri Becquerel (1852-1908). Most of the 20th century research has been directed towards understanding of the forces holding the nucleus together. To understand the changes occuring on the earth, Geologists explore nuclear reactions. Astronomers study nuclear reactions taking place in stars. In biology and medicine, the interactions of radiation emitted from nuclear reactions with the living system are important.

Examples of nuclear reactions are : radioactive decay, artificial transmutation, nuclear fission and nuclear fusion.

We briefly discuss these in this chapter. We have studied the structure of atom in Chapter 4.

13.1.1 Similarity between the solar system and structure of atom: Our solar system is made up of the Sun and planets. The Sun is at the centre of solar system and planets moving around it under the force of gravity. Analogous to this in atomic systems, the forces which hold nucleus and extranuclear electrons are attractive electrostatic.

As studied in Chapter 4, the atom consists of tiny central core called nucleus consisting of protons and neutrons and surrounding region of space being occupied by fast moving electrons.

The radius of nucleus is of the order of 10^{-15} m whereas that of the outer sphere is of the order of 10^{-10} m. The size of outer sphere, is 10^5 times larger than the nucleus. There is a large space vacant outside the nucleus.

Composition of an atom is denoted as ${}^{A}_{Z}X$ where X is the symbol of the element. *Z* equals number of protons and is called atomic number of the element. (Refer to chapter 4, section 4.2)

Do you know ?

How small is the nucleus in comparison to the rest of atom ?

If the atom were of the size of football stadium, the nucleus at the centre spot would be the size of a pea.

'*A*' is the mass number or the sum of number of protons and neutrons in an atom. *N* is the number of neutrons in an atom.

$$A = Z + N$$

The number of neutrons can be obtained by subtracting the atomic number, *Z*, from the mass number *A*.

The atomic number, appearing as a subscript to the left of the elemental symbol, gives the number of protons in the nucleus. The mass number written as a superscript to the left of element symbol, gives the total number of nucleons that is the sum of protons (p) and neutrons (n). The most common isotope of carbon, for example, has 12 nucleons : 6 protons and 6 neutrons,

Mass number (A) → 12
Atomic number (Z) → 6
${}^{12}_{6}C$
Carbon 12

6 protons
6 neutrons
———————
12 nucleons

As you know, atoms with identical atomic numbers but different mass numbers are called isotopes. The nucleus of a specific isotope is called **nuclide**.

The charge on the nucleus is +*Ze* and that of outer sphere is –*Ze*, ('*e*' is the magnitude of electronic charge). The atom as a whole is, thus, electrically neutral. The mass of an electron is negligible (1/1837th of the mass of proton) in comparison to pronton or neutron. The entire mass of atom is concentrated in its nucleus. The density of nucleus is considerably higher, typically 10^5 times the density of ordinary matter.

The radius of nucleus is given by $R = R_o A^{1/3}$ where R_o is constant, common to all nuclei and its value is 1.33 x 10^{-15} m. The volume of nucleus, $V \propto R^3$ and hence, $V \propto A$.

13.2 Classification of nuclides

13.2.1 Classification on the basis of number of nucleons : On the basis of the number of neutrons and protons constituting the nucleus, the nuclides (which refer to atomic nucleus without relation to the outer sphere) are classified as

i. Isotopes : These are nuclides which the same number of protons but different number of neutrons For example, $^{22}_{11}Na$, $^{23}_{11}Na$, $^{24}_{11}Na$. The number of neutrons in each being 11, 12 and 13, respectively.

ii. Isobars : These are nuclides which have the same mass number and different number of protons and neutrons. For example, $^{14}_{6}C$, the number of neutrons in each are 8 and 7, respectively. Likewise $^{3}_{1}H$ and $^{3}_{2}He$, or $^{14}_{6}C$ and $^{14}_{7}N$ are the pairs of isobars (Table 13.1).

Table 13.1 : Isobars

Isobars of A = 3	$^{3}_{1}H$ (N = 2), $^{3}_{2}He$ (N = 1)
Isobars of A = 14	$^{14}_{6}C$ (N = 8), $^{14}_{7}N$ (N = 7)
Isobars of A = 24	$^{24}_{11}Na$ (N = 32), $^{24}_{12}Mg$ (N=12)

iii. Mirror nuclei : These are isobars in which the number of protons and neutrons differ by 1 and are interchanged. Examples: $^{3}_{1}H$ and $^{3}_{2}He$, $^{13}_{6}C$ and $^{13}_{7}N$

iv. Isotones : Isotones are nuclides having the same number of neutrons but different number of protons and hence, different mass numbers. For example, carbon, nitrogen, sodium, magnesium.

$^{13}_{6}C$ and $^{14}_{7}N$, $^{23}_{11}Na$ and $^{24}_{12}Mg$

v. Nuclear isomers : The nuclides with the same number of protons (Z) and neutrons (N) or the same mass number (A) which differ in energy states are called nuclear isomers. For example, ^{60m}Co and ^{60}Co. An isomer of higher energy is said to be in the meta stable state. It is indicated by writing m after the mass number.

13.2.2 Classification on the basis of nuclear stability

i. Stable nuclides : The number of electrons and the location of electrons may change in outer sphere but the number of protons and neutrons the nucleus is unchanged.

ii. Unstable or radioactive nuclides : These nuclides undergo spontaneous change in their comppositon of radiation forming new nuclides.

13.3 Nuclear stability : Why are some nuclei stable while others are radioactive and undergo spontaneous change? To answer this question we need to know the factors governing stability of the nucleus.

13.3.1 Even-odd nature of proton number (Z) and neutrons (N)

Table 13.2 : Distribution of naturally occurring nuclides.

Number of protons Z	Number of neutrons N	Number of such nuclides
Even	Even	165
Even	Odd	55
Odd	Even	50
Odd	Odd	04

The distribution of naturally occuring nuclides in accordance with even/odd values of N and Z is useful to understand stability of nuclides.

a. The nuclides with the even Z and even N constitute 85% of earth crust. It indicates that nuclides with even Z and even N are stable. They tend to form proton-proton and neutron-neutron pairs and impart stability to the nucleus.

b. The number of stable nuclides with either Z or N odd is about one third of those in which both are even. This suggests that these nuclides are less stable than those having even number of protons and neutrons. In these nuclides one nucleon has no partner. Further the nuclides with odd Z or odd N are nearly the same. This indicates that protons and neutrons behave similarly in the respect of stability.

c. The stable naturally occureing nuclides with odd Z and odd N are only four. The small number is indicative of instability; which can be attributed to the presence of two unpaired nucleons. This also indicates the separate pairing of neutrons and protons (The nucleon pairing does not take place between proton and neutron). Only 2% of the earth's crust consists of such nuclides.

13.3.2 Neutron to Proton ratio (*N/Z*) :

i. Figure 13.1 shows a plot of the neutron number (*N*) as a function of proton number (*Z*) in stable nuclides. A large number of elements have several stable isotopes. Hence, the curve appears as a belt or zone called **Stability zone**. All the stable nuclides fall within this zone. The nuclides which form outside such belt are radioactive. The straight line below the belt represents the ratio *N/Z* to be unity.

ii. As may be noticed for nuclei lighter than $^{40}_{20}Ca$, one observes the straight line ($N=Z$) passing through the belt. The lighter nuclides are therefore stable when their *N/Z* is nearly 1.

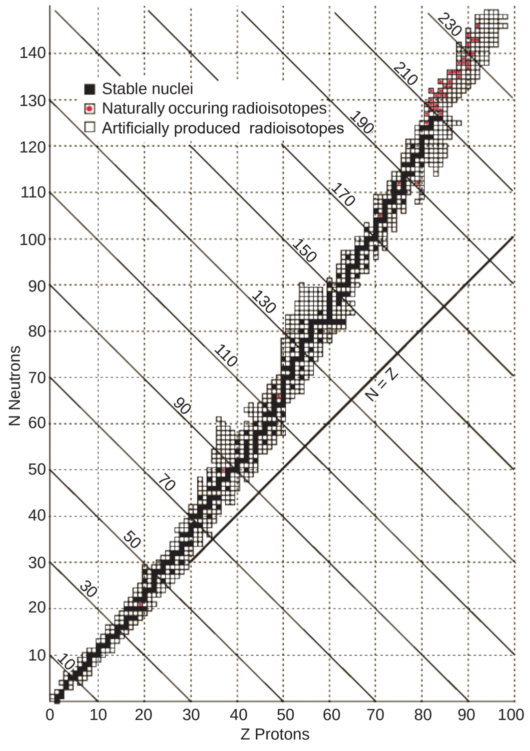

Fig. 13.1 : Neutron to Proton (*N/Z*) ratio

iii. The *N/Z* ratio for the stable nuclides heavier than calcium gives a curved appearance to the belt with gradually increase of *N/Z* (> 1). The heavier nuclides therefore, need more number of neutrons (than protons) to attain stability. What is the reason for this? The heavier nuclides with the increasing number of protons render large coulombic repulsions. With increased number of neutrons the protons within the nuclei get more separated, which renders them stable.

13.3.3 Magic numbers : The nuclei with 2, 8, 20, 28, 50, 82 and 126 neutrons or protons are particularly stable and abundant in nature. These are magic numbers. Lead ($^{208}_{82}Pb$) has two magic numbers, 82 protons and 126 neutrons.

13.3.4 Nuclear Potential : Within the nucleus, all protons are positively charged. What are the consequences of the Coulomb repulsions between these protons?

The distance between two protons present in the nucleus is typically 10^{-15} m. Obviously, the repulsion between them has to be large. If the coulomb repulsion had been the only force in operation the nucleus would not exist. However the nucleus does exist. This indicates that there are nuclear forces of attraction between all the nucleons holding them together within the nucleus. These are attractions between proton-proton, neutron-neutron and proton-neutron. These attractive forces are independent of the charge on nucleons. Hence p-p, n-n and p-n attractions are equal. These attractive forces operate over short range within the nucleus.

The p-p, n-n and p-n attractions constitute what is called the nuclear potential which is responsible for the nuclear stability.

13.3.5 Nuclear binding energy and mass defect : Binding energy of a nucleus gives a measure of how strongly nucleons are held together within the nucleus.

The energy required for holding the nucleons together within the nucleus of an atom is called as the **nuclear binding energy**. It is defined as the energy required to break the nucleus into its constituents. Here the binding of electrons to the nucleus has been neglected.

Atoms are composed of protons, neutrons and electrons. The actual mass of atom is observed to be less than sum of the masses of its constituents.

Protons and neutrons are held in a nucleus together. During the formation of nucleus, a certain mass is lost. This is known as mass defect, Δm. **An energy equivalent to the mass lost is released during the formation of nucleus. This is called the nuclear binding energy**.

In general, the exact mass of a nucleus is slightly less than sum of the exact masses of the constituent nucleons. The difference is called mass defect, **(Δm)**.

Δm = Calculated mass – Observed mass.

The conversion of mass into energy is etablished through Einstein's equation, **$E = mc^2$**. where m is the mass of matter converted into energy E and c velocity of light.

Units of nuclear masses and energy : The nuclear mass is usually expressed in unified mass unit (u) which is exactly 1/12th of the mass of ^{12}C atom. Thus, 1u = 1/12th mass of C-12 atom = 1.66×10^{-27} kg.

The energy released (in Joules) in the conversion of 1 u mass into energy is given by the expression :

$E = mc^2 = (1.66 \times 10^{-27} kg) \times (3 \times 10^8 m\ s^{-1})^2$

Expression for nuclear binding energy :

Consider a nuclide ^A_ZX that contains *Z* protons and (*A* - *Z*) neutrons. Suppose the observed mass of the nuclide is m. The mass of proton is m_p and that of neutron is m_n.

Calculated mass = $(A-Z)\, m_n + Z\, m_p + Z\, m_e$ … (13.1)

$\Delta m = [(A-Z)\, m_n + Z\, m_p + Z\, m_e] - m$

$= [(A-Z)\, m_n + Z\, (m_p + m_e)] - m$

$= [(A-Z)\, m_n + Z\, m_H] - m$ …(13.2)

where $(m_p + m_e) = m_H$ = mass of H atom.

Thus $(\Delta m) = [Zm_H + (A-Z)\, m_n] - m$

Where *Z* is atomic number, *A* is the mass number, (*A-Z*) is neutron number, m_H and m_n are masses of hydrogen atom and neutron, respectively, and *m* is the mass of nuclide.

The mass defect, Δ*m* is related to binding energy of nucleus by Einstein's equation

$\Delta E = \Delta m \times c^2$

where, ΔE is the binding energy, Δ*m* is the mass deffect. Nuclear energy is usually expressed in million electron volt (MeV), where

1 MeV = 1.602×10^{-13} J

When mass equal to in is converted into energy it is 931.4 MeV.

The total binding energy is then given by

B.E. = Δ*m* (u) x 931.4 (MeV per u)

B.E.= $931.4(Zm_H + (A-Z)\, m_n) - m$ … (13.3)

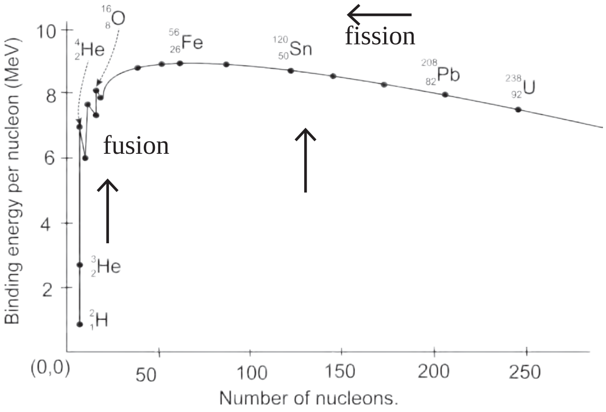

Fig. 13.2 : Binding energy per nucleon

Total binding energy of nucleus containing *A* number of nucleons is denoted as *B.E.* The binding energy per nucleon is then given by,

$\overline{B}$ = *B.E.* / *A* … (13.4)

Binding energy per nucleon and nuclear stability : Mean binding energy per nucleon for the most stable isotopes as a function of mass number is shown in Fig. 13.2. This plot leads to the following inferences.

(i) Light nuclides (*A* < 30)

The peaks with *A* values in multiples of 4. For example, ^4_2He, $^{12}_6C$, $^{16}_8O$ are more stable.

(ii) Medium mass nuclides : (30 < *A* < 90)

$\overline{B}$ increases typically from 8 MeV for *A*=16 to nearly 8.3 MeV for A between 28 and 32 and it remains nearly constant 8.5 MeV. Beyond this it shows a broad maximum. The nuclides falling on the maximum are most stable as they possess high $\overline{B}$ values. Accordingly ^{56}Fe with $\overline{B}$ value of 8.79 MeV is the most stable nuclide.

(iii) Heavy nuclides (*A* > 90)

$\overline{B}$ decreases from maximum 8.79 MeV to 7.7 MeV for *A* ≅ 210, ^{209}Bi is the heaviest stable nuclide. Beyond this all nuclides are radioactive (α- emitters).

Problem : 13.1 : Calculate the mean binding energy per nucleon for the formation of ${}^{16}_{8}O$ nucleus. The mass of oxygen atom is 15.994 u. The masses of H atom and neutron are 1.0078 u and 1.0087 u, respectively.

Solution :

i. The mass defect, $\Delta m = Zm_H + (A - Z)\, m_n - m$

$m_H = 1.0078$ u, $m_n = 1.0087$u and m = 15.994 u , Z = 8, A = 16

$\Delta m = 8 \times 1.0078u + 8 \times 1.0087u - 15.994$ u

= 0.137144 u

ii. Total binding energy, B.E. (MeV) = Δm (amu) x 931.4

Hence, B.E. = 0.137144 x 931.4 = 127.73 MeV

iii. Binding energy per nucleon, $\overline{B} = \frac{BE}{A}$

Hence, $\overline{B} = \frac{127.73 MeV}{16}$

= 7.98 MeV/nucleon

Calculate the binding energy per nucleon for the formaton of ${}^{4}_{2}He$ nucleus ? Mass ${}^{4}_{2}He$ atom = 4.0026 u.

13.4 Radioactivity :

You know that some elements such as uranium and radium are radioctive elements. An element is radioactive if the nuclei of its atoms are unstable. The phenomenon in which the nuclei spontaneously emit a nuclear particle and gamma radiation transforming to a different nuclide is called radioactivity. The elements which undergo nuclear changes are radioactive elements The radioactivity is the phenomenon related to the nucleus.

The radiations emitted by radioactive elements are : alpha (α), beta (β) and gamma (Υ) radiations. Earlier you have studied the properties of α, β and Υ rays.

Try this

Prepare a chart of comparative properties of the above three types of radiations.

13.5 Radioactive decay :

The probability of decay of a radioelement does not depend on state of chemical combination, temperature, pressure, presence of catalyst or even the age of nucleus.

13.5.1 Rate of decay :

Rate of decay of a radioelement denotes number of nuclei of its atoms which decay in unit time. It is also called activity of radioelement.

If dN is the number of nuclei that decay within time interval dt, then rate of decay at any time t is given by

$$\text{rate of decay (activity)} = -\frac{dN}{dt}$$

Why is minus sign required ? The number of nuclei decreases with time. So *dN* is a negative quantity. However the rate of decay is a positive quantity. The negative sign is introduced in the rate expression to make the rate positive. The rate of decay is expressed as disintegrations per second (dps).

13.5.2 Rate law :

The rate of decay of a radioelement at any instant is proportional to the number of nuclei (atoms) present at that instant. Thus,

$$-\frac{dN}{dt} \propto N, \text{ or } -\frac{dN}{dt} = \lambda N \qquad \text{........ (13.5)}$$

$$\therefore \lambda = -\frac{dN}{dt} \times \frac{1}{N}$$

where $-\frac{dN}{dt}$ being the rate of decay at any time t. *N* is the number of nuclei present at time *t*, λ the decay constant. That is the fraction of nuclei decaying in unit time.

13.5.3 Expression for decay constant :

Rearranging the Eq. (13.5)

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

Integrating,

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

On performing the integration, we get

$$\ln N = -\lambda t + C \qquad \text{........ (13.6)}$$

where C is the constant of integration whose value is obtained as follows :

Let N_0 be the number of nuclei present at some arbitrary zero time. At time t, the number of nuclei is N. So at $t = 0$, $N = N_0$. Substituting in Eq. (13.6),

$\ln N_0 = C$.

with this value of C, Eq. (13.6) becomes

$\ln N = -\lambda t + \ln N_0$

$$\text{or } \lambda t = \ln N_0 - \ln N = \ln \frac{N_0}{N} \quad \text{....... (13.7)}$$

$$\text{Hence, } \lambda = \frac{1}{t} \ln \frac{N_0}{N} \quad \text{....... (13.8)}$$

Converting natural logarithm (ln) to logarithm to the base 10, the eqn (13.8) becomes

$$\lambda = \frac{2.303}{t} \log_{10} \frac{N_0}{N} \quad \text{....... (13.9)}$$

The Eq. (13.7) can be expressed as $\ln \frac{N}{N_0} = -\lambda t$. Taking antilog of both sides, we get

$$\frac{N}{N_0} = e^{-\lambda t} \text{ or } N = N_0 e^{-\lambda t} \quad \text{....... (13.10)}$$

The Eq. (13.9) and Eq. (13.10) give the decay constant.

13.5.4 Half life of radioelement ($t_{1/2}$) :

The half life of a radioelement is the time needed for a given number of its nuclei (atoms) to decay exactly to half of its initial value. Each radio isotope has its own half life denoted by $t_{1/2}$ and expressed in seconds, minutes, hours, days or years. At any time t, number of nuclei $= N$.

At $t = 0$, $N = N_0$. Hence at $t = t_{1/2}$, $N = N_0/2$ substitution of these values of N and t in Eq. (13.9) gives

$$\lambda = \frac{2.303}{t_{1/2}} \log_{10} \frac{N_0}{N_0/2}$$

$$= \frac{2.303}{t_{1/2}} \log_{10} 2 = \frac{2.303}{t_{1/2}} \times 0.3010 = \frac{0.693}{t_{1/2}}$$

$$\text{Hence, } \lambda = \frac{0.693}{t_{1/2}} \text{ or } t_{1/2} = \frac{0.693}{\lambda}$$

13.5.5 Graphical representation of decay

i. From Eq. (13.9)

$$\log_{10} N = \frac{-\lambda}{2.303} t + \log_{10} N_0$$

A plot of $\log_{10} N$ versus t gives a straight line. However, $N \propto \left(-\frac{dN}{dt}\right)$. Hence, instead of $\log_{10} N$ versus t, $\log_{10}\left(-\frac{dN}{dt}\right)$ which is $\log_{10}$ (activity) is plotted versus. The graph is a straight line as shown in Fig. (13.3).

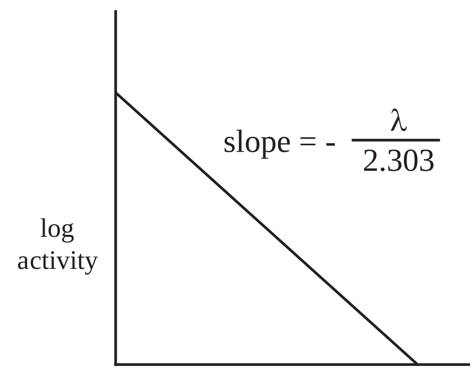

Fig. 13.3 : Plot of $\log_{10}$ activity Vs time

ii. Rate of radioactive decay at any instant is proportional to number of atoms of the radioactive element present at that instant. It is evident that as decay progresses, the number of radioactiv atoms decrease with time and so does the rate of decay. A plot of a rate or activity versus t is shown in Fig 13.4.

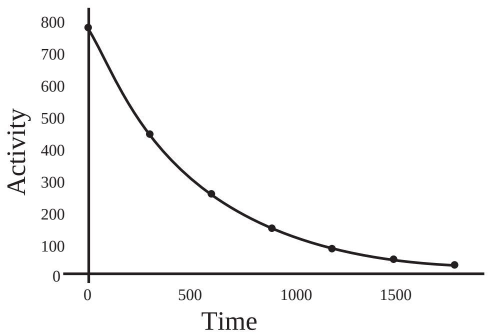

Fig. 13.4 : Plot of activity versus time

Fig. 13.4 shows a decrease in the rate of decay, that is, decrease in number of radioactive atoms with time.

Problem : 13.2

^{41}Ar decays initially at a rate of 575 Bq. The rate falls to 358 dps after 75 minutes. What is the half life of ^{41}Ar ?

Solution :

$$\lambda = \frac{2.303}{t} \log_{10}\left(\frac{N_0}{N}\right)$$

where $-\frac{dN_0}{dt} = 575$ dps

$-\frac{dN}{dt} = 358$ dps and $t = 75$ min.

Hence, $\lambda = \frac{2.303}{75\ min} \log_{10} \frac{575\ dps}{358\ dps}$

$= 6.32 \times 10^{-3}\ min^{-1}$

$t_{1/2} = \frac{0.693}{\lambda} = = \frac{0.693}{6.32 \times 10^{-3}\ min^{-1}}$

$= 109.7$ min

Problem : 13.3

The half life of ^{32}P is 14.26 d. What percentage of ^{32}P sample will remain after 40 d?

Solution :

$t_{1/2} = \frac{0.693}{t_{1/2}} = \frac{0.693}{14.26\ d} = 0.0486\ d^{-1}$

Now, $\lambda = \frac{2.303}{t} \log_{10}\left(\frac{N_0}{N}\right)$

$N_0 = 100$, $N = ?$, $t = 40$ d

Hence, $\log_{10} \frac{N_0}{N} = \frac{\lambda t}{2.303}$

$= \frac{0.0486\ d^{-1} \times 40\ d}{2.303} = 0.8441$

Taking antilog of both sides we get

$\frac{N_0}{N} = $ antilog $(0.8441) = 6.984$

$\frac{100}{N} = 6.984$ or $N = \frac{100}{6.984} = 14.32$

% ^{32}P that remains after 40 d = 14.32 %

Problem : 13.4

The half life of ^{34}Cl is 1.53 s. How long does it take for 99.9 % of sample of ^{34}Cl to decay?

Solution :

$\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{1.53s} = 0.453\ s^{-1}$

Now, $\lambda = \frac{2.303}{t} \log_{10}\left(\frac{N_0}{N}\right)$

$N_0 = 100$, $N = 100 - 99.9 = 0.1$, $t = ?$

Hence, $0.453\ s^{-1} = \frac{2.303}{t} \log_{10} \frac{100}{0.1}$

or $t = \frac{2.303}{0.453\ s^{-1}} \times \log_{10}(1000)$

$= \frac{2.303}{0.453\ s^{-1}} \times 3 = 15.25$ s

Problem : 13.5

The half life of $^{209}P_0$ is 102 y. How much of 1 mg sample of polonium decays in 62 y?

Solution :

$\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{102\ y} = 6.794 \times 10^{-3}\ y^{-1}$

$\lambda = \frac{2.303}{t} \log_{10}\left(\frac{N_0}{N}\right)$

Hence, $\log_{10}\left(\frac{N_0}{N}\right) = \frac{\lambda t}{2.303}$

or, $\log_{10}\left(\frac{N_0}{N}\right)$

$= \frac{6.794 \times 10^{-3}\ y^{-1} \times 62\ y}{2.303} = 0.1829$

It then follows that

$\frac{N_0}{N} = $ antilog $(0.1829) = 1.524$

$N = \frac{N_0}{1.524} = \frac{1\ mg}{1.524} = 0.656$ mg

N the amount that remains after 62 y. Hence, the amount decayed in

62 y = 1 mg - 0.656 mg = 0.344 mg

13.5.6 Units of radioactivity : Rate of radioactive decay is expressed in dps. The unit for the radioactivity is curie (Ci).

1 Ci = 3.7 x 10^{10} dps (disintegrations per second)

Another unit of radioactivity is Becquerel (Bq) 1 Bq = 1 dps. Thus, 1Ci = 3.7 x 10^{10} dps = 3.7 x 10^{10} Bq

13.6 Modes of decay : Radioelements decay by 3 ways, namely, α- decay, β- decay and γ-emission.

13.6.1 Alpha decay : The emission of ∝-particle from the nuclei is called ∝- decay. You have learnt that the charge of an ∝- particle is +2 and its mass is 4 u. It is identical with helium nucleus and hence an ∝- particle is also designated as ${}^{4}_{2}He$.

In the ∝- decay process, the parent nucleus ${}^{A}_{z}X$ emits an α- particle and produces daughter nucleus Y. The parent nucleus thus loses two protons (charge +2) and two neutrons. The total mass lost is 4 u. The daughter nucleus will, therefore, have mass 4 units less and charge 2 units less than its parent. The ∝- decay process is, then, written as a general equation :

$$\underset{\text{parent}}{{}^{A}_{z}X} \longrightarrow \underset{\text{Daughter}}{{}^{A-4}_{z-2}Y} + \underset{\text{emitted particle}}{{}^{4}_{2}He}$$

For example,

Radium 226 decays to form Radium 222 :

$$\underset{\text{parent}}{{}^{226}_{88}Ra} \longrightarrow \underset{\text{Daughter}}{{}^{222}_{86}Rn} + \underset{\text{emitted particle}}{{}^{4}_{2}He}$$

Uranium 238 decays to give Thorium 234 :

$$\underset{\text{parent}}{{}^{238}_{92}U} \longrightarrow \underset{\text{Daughter}}{{}^{234}_{90}Th} + \underset{\text{emitted particle}}{{}^{4}_{2}He}$$

Note that in ∝- decay, the daughter nucleus formed belongs to an element that occupies two places to the left of the periodic table.

13.6.2 β- decay : β^- - decay : The emission of negatively charged stream of β^- particles from the nucleus is called β^- - decay. You know that β^- - particles are electrons with a charge and mass of an electron, mass being negligible as compared to the nuclei. A nucleus decays by emitting a high speed electron called a beta particle (β). A new daughter nucleus is formed with the same mass number as the original parent nucleus but an atomic number that is one unit greater.

$$\underset{\text{parent}}{{}^{A}_{z}X} \longrightarrow \underset{\text{Daughter}}{{}^{A}_{z+1}Y} + \underset{\text{emitted particle}}{{}^{0}_{-1}e}$$

Note that the mass number A does not change, the atomic number changes. Examples of beta decay :

Neptunium 238 decays to form plutonium 238:

$$\underset{\text{parent}}{{}^{238}_{93}Np} \longrightarrow \underset{\text{Daughter}}{{}^{238}_{94}Pu} + \underset{\text{emitted particle}}{{}^{0}_{-1}e}$$

Plutonium 241 decays to form americium 241:

$$\underset{\text{parent}}{{}^{241}_{94}Pu} \longrightarrow \underset{\text{Daughter}}{{}^{241}_{95}Am} + \underset{\text{emitted particle}}{{}^{0}_{-1}e}$$

13.6.3 γ - decay : γ-Radiation is almost always accompanied with α and β^- decay processes. In α and β^- decay process, the daughter nucleus formed is in energetically excited state. Ground state product are formed with emission of γ - rays.

For example, ${}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He + \gamma$

${}^{238}_{92}U$ emits α-particles of two different energies, 4.147 MeV (23%) and 4.195 MeV (77%). When α- particles of energy 4.147 MeV are emitted, ${}^{234}Th$ is left in an excited state which de-excites to the ground state with emission of γ- ray photons energy 0.048 MeV.

13.7 Nuclear reactions : We have so far discussed natural (spontaneous) nuclear rections through α and β- decay processes. Now we consider the non-spontaneous (man-made) nuclear reactions or nuclear transmutations.

13.7.1 Transmutation : The nuclear transmutation is transformation of a stable nucleus into another nucleus be it stable or unstable. The nuclear transmutation where the product nucleus is radioactive is called artificial radioactivity.

Table 13.3 : Comparison of chemical reactions and nuclear reactions

Chemical Reactions	Nuclear Reactions
1. Rearrangement of atoms by breaking and forming of chemical bonds.	1. Elements or isotopes of one elements are converted into another element in a nuclear reaction.
2. Different isotopes of an element have same behaviour.	2. Isotopes of an element behave differently.

3. Only outer shell electrons take part in the chemical reaction.	3. In addition to electrons, protons, neutrons, other elementary particles may be involved.
4. The chemical reaction is accompanied by relatively small amounts of energy. e.g. chemical combustion of 1.0 g methane releases only 56 kJ energy.	4. The nuclear reaction is accompanied by a large amount of energy change. e.g. The nuclear transformation of 1 g of Uranium - 235 releases 8.2 x 10^7 kJ
5. The rates of reaction is influenced by the temperature, pressure, concentration and catalyst.	5. The rate of nuclear reactions are unaffected by temperature, pressure and catalyst.

13.7.2 Induced or artificial radioactivity :

It is type of nuclear transmutation in which the stable nucleus is converted into radioactive nucleus. The product nucleus decays spontaneously with emission of radiation and particles. For example, the stable element ^{10}B, when bombarded with α- particles, transforms into ^{13}N which spontaneously emits positrons.

$$^{10}_{5}B + ^{4}_{2}He \longrightarrow ^{13}_{7}N + ^{1}_{0}n \ ,$$

$$^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{1}e$$

stable Radioactive

(spontaneous emission of positron)

Try this

^{24}Mg and ^{27}Al, both undergo (α,n) reactions and the products are radioactive. These emit β particles having positive charge (called positrons). Write balanced nulcear reactions in both.

13.7.3 Nuclear fission : Nuclear fission is splitting of the heavy nucleus of an atom into two nearly equal fragments accompanied by release of the large amount of energy. When a uranium nucleus absorbs neutron, it breaks and releases energy (Heat), more neutrons, and other radiation.

For example, ^{235}U nucleus captures neutrons and splits into two lighter fragments.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{142}_{56}Ba + ^{91}_{36}Kr + 3\,^{1}_{0}n + \text{Energy}$$

Each fission may lead to different products. The mass of the fission products is less than the parent nucleus. A large amount of energy corresponding to the mass loss is released in each fission. When one Uranium 235 nucleus undergoes fission, three neutrons are emitted, which subsequently disintegrate three more Uranium nuclei and thereby produce nine neutrons. Such a chain continues by itself. In a very short time enormous amount of energy is liberated, which can be utilized for destructive (dangerous explosives) or peaceful purposes (nuclear reactor - Power Plant).

There is no unique way for fission of ^{235}U that produces Ba and Kr, and 400 ways for fission of ^{235}U leding to 800 fission products are known. Many of these are radioactive which undergo spontaneous disintegrations giving rise to new elements in the periodic table.

Interestingly each fission emits 2 to 3 neutrons (on an average 2.5 neutrons). Can you imagine what will happen due to neutron emission? Obviously these neutrons emitted in fission cause more fission of the uranium nuclei which yield more neutrons. These neutrons again bring forth fission producing further neutrons. The process continues indefinitely leading to chain reaction which continues even after the removal of bombarding neutrons. Energy released per fission is ~ 200 MeV.

Do you know ?

The chain reaction in fission of ^{235}U becomes self sustaining. What is the critical mass of ^{235}U ?

The chain reaction occurs so rapidly that nuclear explosion results. This is what happens in atom bomb.

13.7.5 Nuclear fusion : Energy received by earth from the Sun is the result of nuclear fusion. In the process, the lighter nuclei combine (fuse) together and form a heavy nucleus which is accompanied by an enormous amount of energy. Representative fusion reactions occuring in the Sun and stars are

i. ${}_{1}^{1}H + {}_{1}^{1}H \longrightarrow {}_{1}^{2}H + {}_{-1}^{0}e$

ii. ${}_{1}^{1}H + {}_{1}^{2}H \longrightarrow {}_{2}^{3}He$

iii. ${}_{2}^{3}He + {}_{2}^{3}He \longrightarrow {}_{2}^{4}He + 2\,{}_{1}^{1}H$

iv. ${}_{2}^{3}He + {}_{1}^{1}H \longrightarrow {}_{2}^{4}He + {}_{1}^{0}e$

Problem : 13.6

How many α and β- particles are emitted in the following ?

${}_{93}^{237}Np \longrightarrow {}_{83}^{209}Bi$

Solution : The emission of one α - particle decreases the mass number by 4 whereas the emission of β- particles has no effect on mass number.

Net decrease in mass number = 237 - 209 = 28. This decrease is only due to α- particles.

Hence number of α- particles emitted

$= \frac{28}{4} = 7$

Now the emission of one α-particle decreases the atomic number by 2 and β-particle emission increases by 1.

The net decrease in atomic number = 93 - 83 = 10

The emission of 7 α-particles causes decrease in atomic number by 14. However the actual decrease is only 10. It means atomic number increses by 4. This increase is due to emission of β-particles. Thus, 4 β- particles are emitted.

Problem : 13.7

Estimate the energy released in the fusion reaction

${}_{1}^{2}H + {}_{2}^{3}He \longrightarrow {}_{2}^{4}He + {}_{1}^{1}H$

Given atomic masses : ^{2}H = 2.041 u

^{3}He = 3.0160 u, ^{4}He = 4.0026 u, ^{1}H = 1.0078 u

Solution :

Mass defect Δm = (mass of ^{2}H + mass of ^{3}He) - (mass of ^{4}He + mass of ^{1}H)

= 2.0141 u + 3.0160 u - 4.0026 u - 1.0078 u = 0.0197 u.

E = Δm (u) x 931.4 = 0.197 u x 931.4 = 18.35 MeV.

Problem : 13.8

Half life of ^{209}Po is 102 y. How many α-particles are emitted in 1s from 2 mg sample of Po?

Solution :

Activity = number of α (or β) particles emitted

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

$$\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{(102 \times 365 \times 24 \times 3600)s}$$

$= 2.154 \times 10^{-10}\,s^{-1}$.

$$N = \frac{2 \times 10^{-3} \times 6.022 \times 10^{23}}{209}$$

$= 5.763 \times 10^{18}$ atoms of nuclei

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

$= 2.154 \times 10^{-10} s^{-1} \times 5.763 \times 10^{12}$ atoms

$= 1241$ particles s^{-1}.

Nuclear fusion has certain advantages over nuclear fission. Fusion produces relatively more energy per given mass of fuel.

The only difficulty with fusion is it requires extremely high temperature typically 10^{8} K.

13.8 Applications of Radio isotopes

13.8.1 Radiocarbon dating : The technique is used to find the age of historic and archaelogical organic samples such as old wood samples and animal or human fossils.

i. Radioactive ^{14}C is formed in the upper atmosphere by bombarment of neutrons from cosmic rays on ^{14}N.

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

ii. ^{14}C combines with atmospheric oxygen to form $^{14}CO_2$ which mixes with ordinary $^{12}CO_2$.

iii. Carbon di oxide is absorbed by plants during photosynthesis. Animals eat plants. Hence, ^{14}C becomes a part of plant and animal bodies.

Do you know ?

The oldest rock found so far in Northern Canada is 3.96 billion years old.

iv. As long as plant is alive, the ratio $^{14}C/^{12}C$ remains constant. When the plant dies, photosynthesis occurs no more and the ratio $^{14}C/^{12}C$ decreases with the decay of ^{14}C (half life 5730 years).

$$^{14}_{6}C \longrightarrow \; ^{14}_{7}N + \, ^{0}_{-1}e$$

Activity :

You have learnt in Std. 9th, medical, industrial and agricultural applications of radioisotopes. Write at least two applications each.

v. The activity (N) of given wood sample and that of fresh sample of live plant (N_0) is measured. N_0 denotes, the activity of the given sample at the time of death.

vi. The age of the given wood sample, rather the period over which it has remained dead can be determined.

$$t = \frac{2.303}{\lambda} \log_{10} \frac{N_0}{N}$$

where $\lambda = \dfrac{0.693}{5730 \text{ y}} = 1.21 \times 10^{-4} \text{ y}^{-1}$.

13.8.2 Electrical energy from Nuclear fission

Do you know what is the Nuclear Power ?

It is simply the electricity made from fission of uranium and plutonium.

Why should we care about the Nuclear power?

a. It offers huge environmental benefits in producing electricity.

b. It releases zero carbon dioxide.

c. It releases zero sulfur and nitrogen oxides. These are atmospheric pollutants which pollute the air. Thus it is a clean energy.

We are intersted in Nuclear power because :

Fission of 1 gram of uranium-235 produces about 24,000 kW/h of energy.

This is the same as burning 3 tons of coal or 12 barrels of oil, or nearly 5000 m^3 of natural gas.

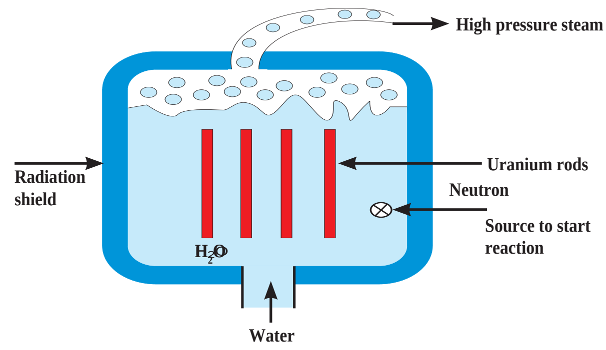

Fig. 13.4 (a) : simplified nuclear reactor

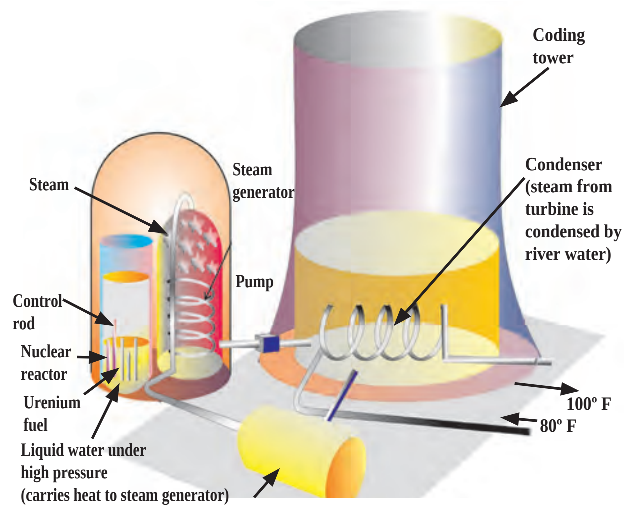

Fig. 13.4 (b) : Schematic diagram of nuclear power plant

The nuclear fission is an alternative enegy source. Traditionally, the steam comes from boilers fuelled by oil, gas, or coal. **These sources are depleting. The increasing costs of petroleum suggest we need to depend on the nuclear fission energy for electricity.**

Nuclear Reactor : Nuclear reactor is a device for using atomic energy in controlled manner for peaceful purposes. During nuclear fission energy is released. The released energy can be utilized to generate electricity in a nuclear reactor.

In a nuclear reactor, U^{235} or P^{239}, a fissionable material is stacked with heavy water (D_2O Deuterium oxide) or graphite called moderator. The neutrons produced in the fission pass through the moderator and lose a part of their energy. Subsequently the slow neutrons are captured which initiate new fission.

Table 13.4 (a) : Diagnostic Radioisotopes

	Isotope	Half-life	Emitted particles	Uses
(i) $^{51}_{24}Cr$	Chromium-51	28 days	gamma	spleen imaging
(ii) $^{59}_{26}Fe$	Iron-59	45 days	beta, gamma	bone marrow function

Table 13.4 (b) : Therapeutic Radioisotopes

	Isotope	Half-life	Emitted particles	Uses
(i) $^{35}_{15}P$	phosphours-32	14 days	beta	treatment of leukemia
(ii) $^{60}_{27}Co$	cobalt-60	5.3 years	beta, gamma	external radiation source for cancer treatment
(iii) $^{131}_{53}I$	iodine-131	8 days	beta, gamma	treatment of thyroid cancer
(iv) $^{226}_{88}Ra$	radium- 226	1620 years	beta, gamma	implanted in tumours

Cadmium rods are inserted in the moderator and they have ability to absorb neutrons. The rate of chain reaction thus is controlled. The energy released in such reaction appears as heat and removed by circulating a liquid (coolant). The coolant which has absorbed excess of heat from the reactor is passed over a heat exchanger for producing steam, which is then passed through the turbines to produce electricity. **Thus, the atomic energy produced with the use of fission reaction can be controlled in the nuclear reactor explored for peaceful purposes such as conversion into electrical energy generating power for civilian purposes, ships, submarines etc.**

13.8.3 Applications in medicine :

Hospitals and larger medical clinics typically have a Department of Nuclear Medicine.

Several radioisotopes are used for the treatment of fatal diseases like Cancer.

Table shows medical uses in two different categories, namely diagnostic and therapeutic. For diagnostic purpose, short-lived isotopes are used to limit the exposure time to radiation, while therapeutic radioisotopes are used to destroy abnormal, usually Cancerous cells.

13.8.4 Other applications of radioisotopes :

Radioisotopes find a variety of applications in the diverse areas Agricultural products those are preserved by irradiating with gamma rays from Cobalt - 60 or Caesium - 137.

Another application is radio-tracer technique wherein one or more atoms of a chemical compound are replaced by a radionuclide to trace the path followed by that chemical in the system under study by radioactivity measurement.

Do you know ?

Bhabha Atomic Research Centre (BARC) Mumbai has set up irradiation plants for preservation of agricultural produce such as mangoes, onion and potatoes at Vashi (Navi Mumbai) and Lasalgaon (Nashik).

Internet my friend

1. Isotopic tracer technique : www.iaea.org>topics>radiotracers
2. Collect information about Nuclear Reactions.

Exercises

1. Choose correct option.

A. Identify nuclear fusion reaction

a. ${}^{1}_{1}H + {}^{1}_{1}H \longrightarrow {}^{2}_{1}H + {}^{0}_{1}e$

b. ${}^{2}_{1}H + {}^{1}_{1}H \longrightarrow {}^{3}_{2}He$

c. ${}^{3}_{1}H + {}^{1}_{1}H \longrightarrow {}^{3}_{1}H + {}^{1}_{1}p$

B. The missing particle from the nuclear reaction is

${}^{27}_{13}Al + {}^{4}_{2}He \longrightarrow ? + {}^{1}_{0}n$

a. ${}^{30}_{15}P$ b. ${}^{32}_{16}S$ c. ${}^{14}_{10}Ne$ d. ${}_{14}Si$

C. ${}^{60}_{27}CO$ decays with half-life of 5.27 years to produce ${}^{60}_{28}Ni$. What is the decay constant for such radioactive disintegration ?

a. 0.132 y^{-1} b. 0.138 c. 29.6 y d. 13.8%

D. The radioactive isotope used in the treatment of Leukemia is

a. ${}^{60}Co$ b. ${}^{226}Ra$

c. ${}^{32}P$ d. ${}^{226}I$

E. The process by which nuclei having low masses are united to form nuclei with large masses is

a. chemical reaction

b. nuclear fission

c. nuclear fusion

d. chain reaction

2. Explain

A. On the basis of even-odd of protons and neutrons, what type of nuclides are most stable ?

B. Explain in brief, nuclear fission.

C. The nuclides with odd number of both protons and neutrons are the least stable. Why ?

D. Referring the stabilty belt of stable nuclides, which nuclides are $\overline{\beta}$ and $\overset{+}{\beta}$ emitters ? Why ?

E. Explain with an example each nuclear transmutation and artificial radioactivity. What is the difference between them ?

F. What is binding energy per nucleon ? Explain with the help of diagram how binding energy per nucleon affects nuclear stability ?

G. Explain with example α - decay.

H. Energy produced in nuclear fusion is much larger than that produced in nuclear fission. Why is it difficult to use fusion to produce energy ?

I. How does *N/Z* ratio affect the nuclear stability ? Explain with a suitable diagram.

J. You are given a very old sample of wood. How will you determine its age ?

3. Answer the following question

A. Give example of mirror nuclei.

B. Balance the nuclear reaction:

${}^{118}_{54}Xe \longrightarrow ? + I^{118}_{54}$

C. Name the most stable nluclide known. Write two factors responsible for its stability.

D. Write relation between decay constant of a radioelement and its half life.

E. What is the difference between an α - particle and helium atom ?

F. Write one point that differentiates nuclear reations from chemical reactions.

G. Write pairs of isotones and one pair of mirror nuclei from the following :

${}^{10}_{5}B$, ${}^{12}_{6}C$, ${}^{27}_{13}Al$, ${}^{11}_{6}C$, ${}^{28}_{14}S$:

H. Derive the relationship between half life and decay constant of a radioelement.

I. Represent graphically $\log_{10}$ (activity / dps) versus t/s. What is its slope ?

J. Write two units of radioactivity. How are they interrelated ?

K. Half life of ${}^{24}Na$ is 900 minutes. What is its decay constant?

L. Decay constant of ${}^{197}Hg$ is 0.017 h^{-1}. What is its half life ?

M. The total binding energy of ${}^{58}Ni$ is 508 MeV. What is its binding energy per nucleon ?

N. Atomic mass of ${}^{32}_{16}S$ is 31.97 u. If masses of neutron and H atom are 1.0087 u and 1.0078 u respectively. What is the mass defect ?

O. Write the fusion reactions occuring in the Sun and stars.

P. How many α and β - particles are emitted in the trasmutation

$$^{232}_{90}Th \longrightarrow ^{208}_{82}Pb \ ?$$

Q. A produces B by $\propto$- emission. If B is in the group 16 of periodic table, what is the group of A ?

R. Find the number of α and β- particles emitted in the process

$$^{222}_{86}Rn \longrightarrow ^{214}_{84}Po$$

4. Solve the problems

A. Half life of ^{18}F is 110 minutes. What fraction of ^{18}F sample decays in 20 minutes ?

(Ans. : 0.118)

B. Half life of ^{35}S is 87.8 d. What percentage of ^{35}S sample remains after 180 d ?

(Ans. : 24.2%)

C. Half life ^{67}Ga is 78 h. How long will it take to decay 12% of sample of Ga ?

(Ans.14.44)

D. 0.5 g Sample of ^{201}Tl decays to 0.0788 g in 8 days. What is its half life ?

(Ans.3.0 d)

E. 65% of ^{111}In sample decays in 4.2 d. What is its half life ?

(Ans. : 2.77 d)

F. Calculate the binding energy per nucleon of $^{84}_{36}Kr$ whose atomic mass is 83.913 u. (Mass of neutron is 1.0087 u and that of H atom is 1.0078 u).

(Ans.: 8.7 MeV)

G. Calculate the energy in Mev released in the nuclear reaction

$$^{174}_{77}Ir \longrightarrow ^{170}_{75}Re + ^{4}_{2}He$$

Atomic masses : Ir = 173.97 u,

Re = 169.96 u and

He = 4.0026 u

(Ans.6.89 MeV)

H. A 3/4 of the original amount of radioisotope decays in 60 minutes. What is its half life ?

(Ans.: 30 min)

I. How many - particles are emitted by 0.1 g of ^{226}Ra in one year?

(Ans. : 1.154×10^{17})

J. A sample of ^{32}P initially shows activity of one Curie. After 303 days the activity falls to 1.5×10^{4} dps. What is the half life of ^{32}P ?

(Ans.14.27 d)

K. Half life of radon is 3.82 d. By what time would 99.9 % of radon will be decayed.

(Ans.38.05 d)

L. It has been found that the Sun's mass loss is 4.34×10^{9} kg per second. How much energy per second would be radiated into space by the Sun ?

(Ans.: 3.9×10^{23} kJ/s)

M. A sample of old wood shows 7.0 dps/g. If the fresh sample of tree shows 16.0 dps/g, How old is the given sample of wood ? Half life of ^{14}C 5730 y.

(Ans. 6833 g)

Activity :

1. Discuss five applications of radioactivity for peaceful purpose.

2. Organize a trip ot Bhabha Atomic Reasearch Centre, Mumbai to learn about nuclear reactor. This will have to be organized through your college.