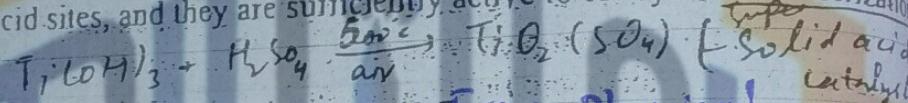


Solid Acid and Base Catalysts

While they are not solvents and solutions in the usual sense of the word, it is convenient here to extend the concept of solid acids and bases. For example, consider the class of compounds known as zeolites, which are aluminosilicate structures with variable amounts of Al(III), Si(IV), metal cations, and water.

Zeolites may behave as Lewis acids at Al³⁺ sites, or as Brønsted-Lowry acids by means of H⁺ ions. Because they have relatively open structures, a variety of small molecules may be adsorbed within the $\text{O}-\text{Al}-\text{O}-\text{Si}$ framework. These molecules may then be catalyzed to react at centers. Coordinatively, unsaturated oxide ions can act as basic sites, and in some catalytic types of centers are believed to be important. Catalysis by zeolites is discussed further in Chapter 11.

Solid superacids may be made by treating ordinary solid acid catalysts with strong Brønsted acids. For example, if freshly precipitated titanium hydroxide or zirconium hydroxide is treated with concentrated sulfuric acid and calcined in air at 500 °C, a very active solid acid catalyst results. The solids consist of metal dioxides with sulfate ions coordinated to the metal ions on the surface. Likewise, a solid catalyst can be made by treating these metal oxides with antimony pentafluoride. Both catalysts contain both Brønsted and Lewis acid sites, and they are sufficiently active to catalyze the isomerization of alkenes at room temperature.²⁰

(Electrode Potentials and Electromotive Forces)

From Physical Chemistry Books

As we have seen, acidity and basicity are intimately connected with electron transfer. When transfer involves an integral number of electrons it is customary to refer to the process as a redox reaction. This is not the place for a thorough discussion of the thermodynamics of electrochemistry, found in any good textbook of physical chemistry. Rather, we shall investigate the application of the electromotive force (emf) of interest to the inorganic chemist. Nevertheless, a very brief account of the conventions and thermodynamics of electrode potentials and half-reactions will be presented.

1. The standard hydrogen electrode ($a_{\text{H}_2} = 1.00$; $f_{\text{H}_2} = 1.00$) is arbitrarily assigned an electrode potential of 0.00 V.
2. If we construct a cell composed of a hydrogen electrode and a second electrode (M^{n+}/M) immersed in a solution of M^{n+} of unit activity, we can measure the potential between the two electrodes. Since the hydrogen electrode was assigned a potential of 0.00 V, the potential of the M^{n+}/M electrode is by definition the same as the measured potential of the cell. If the metal electrode becomes positively charged with respect to the hydrogen electrode (e.g., Cu^{2+}/Cu), the electrode potential is assigned a positive sign ($E_{\text{Cu}^{2+}/\text{Cu}} = +0.337$ V). If the metal tends to lose electrons more easily than hydrogen and thus becomes negatively charged (e.g., Zn^{2+}/Zn), the electrode is assigned a negative sign ($E_{\text{Zn}^{2+}/\text{Zn}} = -0.763$ V). This convention is convenient in that it results in a single, invariant sign for the electrode potential for each electrode (the zinc electrode is always electrostatically negative). Whether the reaction under consideration occurs in a galvanic cell or an electrolytic cell, inorganic chemists are more interested in the thermodynamics of half-reactions rather than in the electrostatic potential that obtains in conjunction with the standard hydrogen electrode. The quantity related to thermodynamics may be termed the *thermodynamic convention*. This convention relates the electromotive force (E) a sign such that

where ΔG is a constant, proceeding

and find

For the reaction

$$\Delta G > 0,$$

According to the law of thermodynamics, ΔG is always negative.

3. The Nernst equation

where K is the equilibrium quotient.

The value of K depends on the temperature.

4. Reaction rates and second-order reactions

5. In aqueous solution

water

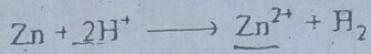
21. In the presence of a popular author, Eglewhite, "Stockholm," quantity, the possibility

22. For the reaction

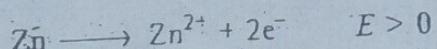
$$E = \frac{\Delta G}{F}$$

$$\Delta G = -nFE$$

where ΔG is the change in Gibbs free energy, n is the number of equivalents reacting, and F is Faraday constant, 96,485 coulombs equivalent⁻¹. It is necessary to specify the direction in which a reaction is proceeding. Thus if we consider the reaction



and find that for the reaction, as written, $\Delta G < 0$, then (since H^+/H_2 is defined as 0.00 V):



For the nonspontaneous reaction:



$\Delta G > 0$, and so for



Accordingly, the sign of the emf of either a half-reaction ("electrode") or the overall redox reaction depends upon the direction in which the equation for the reaction is written (as is true for any thermodynamic quantity such as enthalpy, entropy, or free energy). The sign of the reduction electromotive force is always algebraically the same as that of the electrostatic potential.²¹

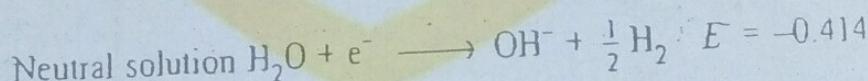
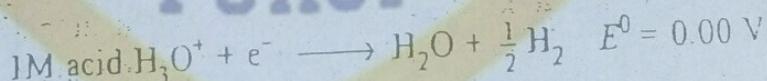
3. The Nernst equation applies to the potentials of both half-reactions and total redox reactions:

$$E = E^\circ - \frac{RT}{nF} \ln Q$$

where E° represents the overall potential with all species at unit activity and Q represents the activity quotient.

The Nernst equation can be used for calculating the potentials under non-standard conditions if the value of E° and equilibrium concentrations of the various species are known. For example, the potential of the H^+/H_2 couple of pH 7.0 is calculated to be²² -0.414 V.

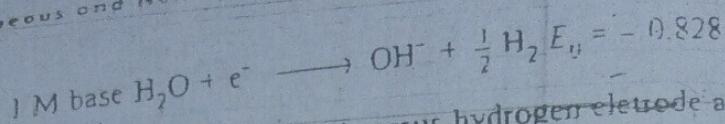
4. Reactions resulting in a decrease in free energy ($\Delta G < 0$) are spontaneous. This is a requirement of the second law of thermodynamics. Concomitantly, redox reactions in which $E > 0$ are therefore spontaneous.
5. In aqueous solutions two half-reactions are of special importance: (a) the reduction of hydrogen, water or hydronium ions:



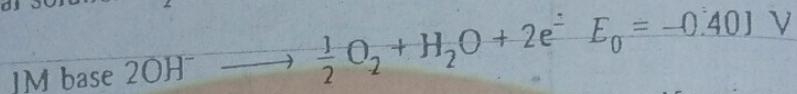
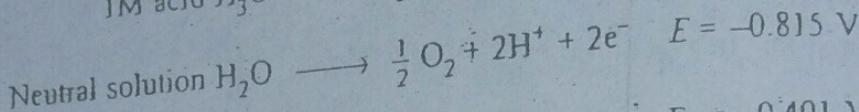
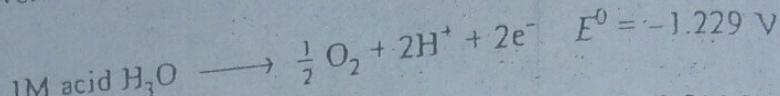
²¹ In the past the electrostatic convention has often been called the "European convention" and the thermodynamic convention popularized by Latimer (*The Oxidation Potentials of the Elements and Their Values in Aqueous Solution*; Prentice-Hall, Englewood Cliffs, NJ, 1952) the "American convention." In an effort to reduce confusion, the IUPAC adopted the "Stockholm convention" in which electrode potentials refer to the electrostatic potential and emfs refer to the thermodynamic quantity. Furthermore, the recommendation is that standard reduction potentials be listed as "electrode potentials" to reduce the possibility of confusion over signs.

²² For the reaction $2\text{H}^+ + 2e^- \longrightarrow \text{H}_2$,

$$E = E^\circ - \frac{0.059}{2} \log \left(\frac{P_{\text{H}_2}}{P_{\text{H}_2^\circ}} \cdot \frac{A_{\text{H}^+}^2}{A_{\text{H}^+}^\circ} \right)$$



Thus most metals with negative reduction potential versus hydrogen electrode are oxidised by aqueous acids with the evolution of hydrogen (equation 9.89) and (b) the oxidation of oxygen or hydroxide ions:

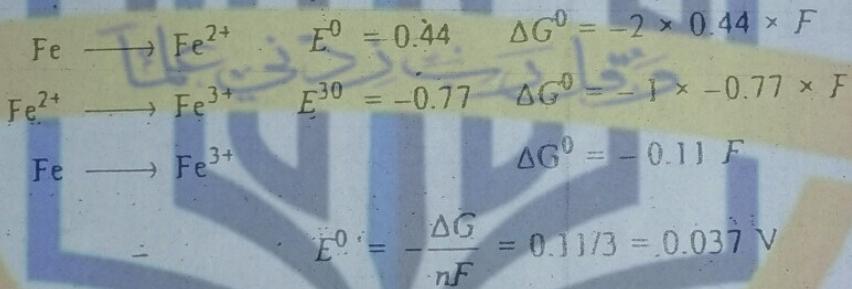


By omitting species

Thus under favourable conditions water can act as a reducing agent by itself getting oxidized to oxygen. However, water is a poor reducing agent in acid medium due to large negative (equation 9.97)

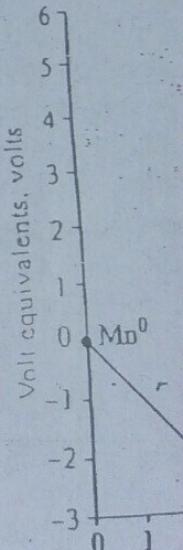
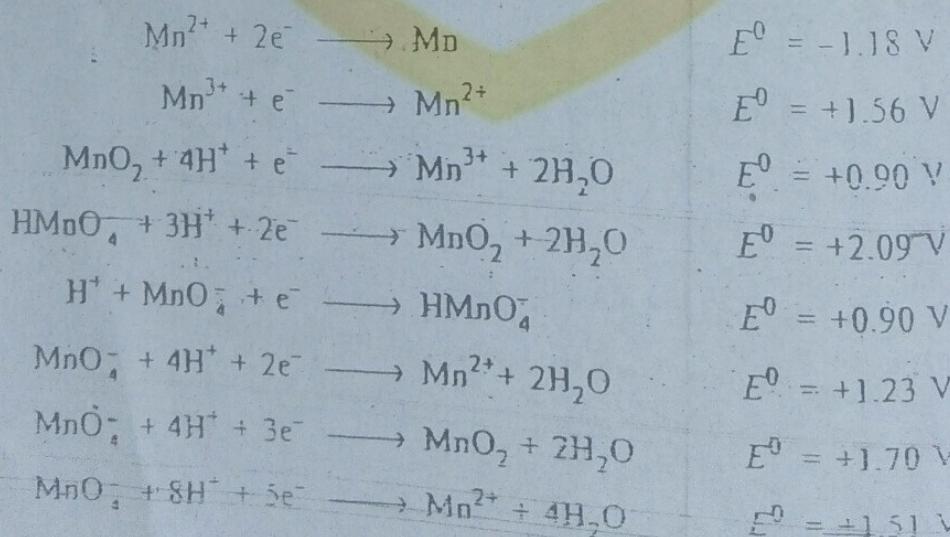
The thermodynamic stability²³ of species in aqueous solution is limited by oxidation and of solvent water. Hence at pH = 0.0 the thermodynamically stable species in aqueous those whose reduction potential lies between 0.0V and -1.229 V (equations 9.94 and 9.95).

6. In calculating the "skip-step emf" for a multivalent species it is necessary to take into account the total change in free energy. Suppose we know the emfs for the oxidation of Fe to Fe^{2+} and Fe^{3+} and wish to calculate the skip-step emf for Fe to Fe^{3+} .



Although the emfs are not additive, the free energies are, allowing simple calculation of emf for the three-electron change.

7. Standard potential or "Latimer" diagrams are useful for summarizing a considerable amount of thermodynamic information about the oxidation states of an element in a convenient way. The following half-reactions may be taken from Table F.1, Appendix F:

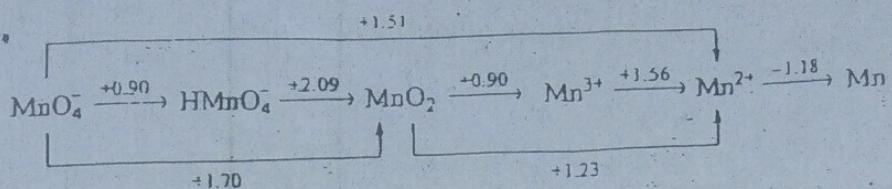


²⁴ This convention of using oxidation numbers resulted in a wide variation in the literature. The spontaneity of reactions recommended.

²⁵ For further details see P.F. Bell, R.W. Ladd, and J. D. Roberts, *Polymer*, 1963, 4, 300-303.

²³ As is always the case when dealing with the

By omitting species such as H_2O , H^+ , and OH^- , all of the above information can be summarized



The highest oxidation state is listed on the left and the reduction emfs are listed between the species and the next reduced form, with the lowest oxidation state appearing on the right.²⁴ If the potential on the right of a species is higher than the potential on the left then the species would undergo disproportionation:

8. Frost diagrams are another useful representation of the standard potential data.²⁵ These diagrams give a rapid graphical account of the trend in redox potential and stability of various oxidation states of an element in its compounds. In a Frost diagram the volt equivalent ($n \times E^\circ$) of a couple $\text{M}^{n+}/(\text{M}^{n+} + ne^- \rightarrow \text{M}^0)$ is plotted against the oxidation number (n) of the element in various oxidation states. Since the volt equivalent (nE°) is proportional to the standard free energy change ($\Delta G = -nFE^\circ$), the most stable oxidation state of an element corresponds to the species with the low value of volt equivalent. The Frost diagram of Manganese is shown in Figure 9.2. In aqueous solution the most stable oxidation state of manganese is Mn^{2+} . The oxidation states Mn^0 , Mn^{2+} , Mn^{7+} in Mn²⁺ are unstable in acid solutions: Mn^0 is oxidised to Mn^{2+} (liberating H_2 gas from H^+ ions), Mn²⁺ disproportionates (to Mn^{3+} and MnO_2), and MnO_4^- is reduced to MnO_2 (liberating O_2 gas from water). Stability of oxidation states and emf of individual elements of Groups 1–12 are further discussed in Chapter 13 (pages 379–389) and page 367.

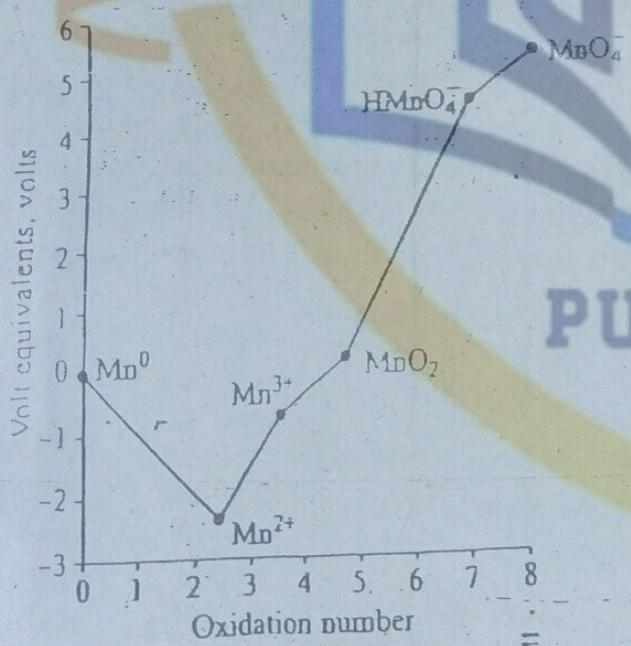


Fig 9.2 The Frost diagram for Manganese in acidic solution.

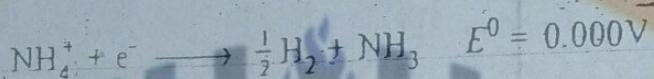
²⁴ This convention originated with Latimer and is widespread in the inorganic chemical literature. Unfortunately, Latimer used oxidation emfs, and so his diagram is a mirror image of the one drawn on the basis of reduction potentials. This resulted in a wide variety of modified "Latimer diagrams," often with no indication of the convention employed concerning the spontaneity of the half-reaction. To avoid confusion, arrows (not present in the original Latimer diagram) are recommended. Further discussion of Latimer diagrams and related topics may be found in Chapter 13.

²⁵ For further details see Shriver, D. F.; Atkins, P. W.; Langford, C. H. Inorganic Chemistry, Oxford University Press, PP300–303.

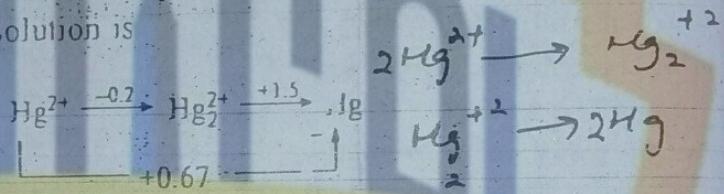
²⁶ Parry, R. W.; Lyons, E. H., Jr. In *The Chemistry of Coordination Compounds*; Bailar, J. C., Jr., Ed.; Van Nostrand-Reinhold: New York, 1960, p. 621.

Electrochemistry in Nonaqueous Solutions

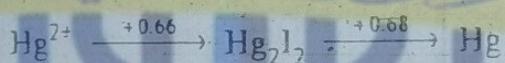
Although the entire discussion of electrochemistry thus far has been in terms of aqueous solution, same principles apply equally well to nonaqueous solvents. As a result of differences in solvation, electrode potentials may vary considerably from those found in aqueous solution. In addition the oxidation and reduction potentials characteristic of the solvent vary with the chemical behavior of the solute. As a result of these two effects, it is often possible to carry out reactions in a nonaqueous solvent which are impossible in water. For example, both sodium and beryllium are too reactive to be electroplated in aqueous solution, but beryllium can be electroplated from liquid ammonia and sodium from pyridine.²⁶ Unfortunately, the thermodynamic data necessary to construct complete tables of potential values are lacking for most solvents other than water. Jolly²⁷ has compiled such data for liquid ammonia. The hydrogen electrode is used as the reference point to establish the scale as follows:



A single example of the application of electrode potentials to chemistry in ammonia will suffice. Latimer diagram for mercury in acidic solution is



and for the insoluble mercury (I) iodide the diagram is

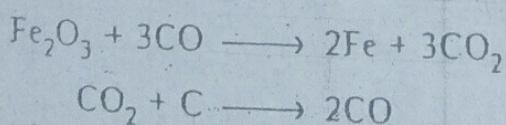


It may readily be seen that the mercurous ion (whether free or in Hg_2^{2+}) is thermodynamically unstable with respect to disproportionation in ammonia, in contrast to its stability in water.

Electrochemistry in nonaqueous solvents is not merely a laboratory curiosity. We have valuable gold batteries made with solid electrolytes (sodium beta alumina, see Chapter 4) that are certainly "not negligible". In looking for high-efficiency cells one desires the cathode and anode to be highly reactive (larger polarization emf) and to have a low equivalent weight. In these terms, lithium appears to be highly desirable. Related hydroxides, or the use of

Hydrometallurgy

Traditionally the winning of metals from their ores has been achieved by pyrometallurgy: the roasting of relatively concentrated metallic ores at high temperatures. The reactions of the blast furnace are typical examples:



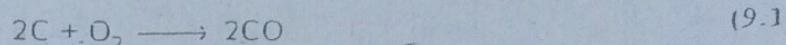
Carbon monoxide for the reduction of the iron is formed not only from the recycling of coke (Eq. 9.114) but also from the direct oxidation of the coke in the charge by hot air.

The energy point of iron, is the hope of Hydrometallurgy. With such favorable:

- 1. Oxygen is the gold. It is
- 2. Such hydrometallurgical processes
- 3. Since the
- 4. Because no

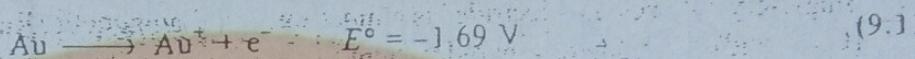
- problems
- 9.1 Suggest
- and 9.4
- 9.2 Using a
- $e(\text{NH}_3)$
- metals.
- 9.3 When
- studies
- sulfuric
- 9.4 What is

9.5 The stab

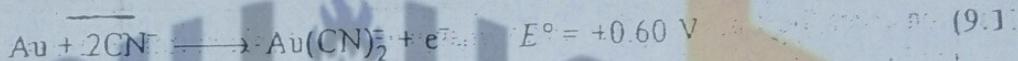


The energy released by the combustion is sufficient to raise the temperature well above the melt point of iron, 1535 °C. One of the incentives for development of alternative methods of producing metal is the hope of finding less energy-intensive processes.

Hydrometallurgy is not new; it has been used for almost a century in the separation of gold from low-grade ores. This process is typical of the methods used. Gold is normally a very unreactive metal.



With such a negative oxidation emf, it is too noble to react with either O_2 ($E^\circ = +1.185 \text{ V}$) or Cl_2 ($= +1.36 \text{ V}$). By complexation of the $Au(I)$ ion, however, the emf can be shifted until it is much more favorable:



Oxygen in the air is now a sufficiently strong (and cheap!) oxidizing agent to effect the solution of the gold. It may then be reduced and precipitated by an active metal such as zinc powder ($E^\circ = -0.77 \text{ V}$). Such hydrometallurgical processes offer definite advantages:

1. Low-grade ores may be leached, with complexing agents if necessary, and profitably exploited.
2. Complex ores may be successfully treated and multiple metals separated under more carefully controlled processes.
3. Since the reactions are carried out at room temperature, energy savings are possible.
4. Because no stack gases are involved, air pollution does not present the problem faced by pyrometallurgy.

These aspects do not form an unmixed blessing, however. If the metal must be reduced by electrolysis, the process may become energy intensive. Thus attractive solutions to this problem are reduction of more valuable gold by less expensive zinc and of more valuable copper by scrap iron. Finally, in view of the large amounts of waste water formed as by-product, one may be trading an air pollution problem for a water pollution problem.

Related hydrometallurgic methods may allow the use of bacteria to release copper from low-grade ores, or the use of algae to concentrate precious metals such as gold (see Chapter 20).²⁸

Problems

- 9.1 Suggest the specific chemical and physical interactions responsible for the reversal of Eqs. 9.1 and 9.4 in water and ammonia solutions.
- 9.2 Using a Born-Haber cycle employing the various energies contributing to the formation of $N_e(NH_3)_2^+$ species in ammonia solutions, explain why such solutions form only with the most active metals.
- 9.3 When 1 mole of N_2O_5 is dissolved in sulfuric acid, 3 equivalents of base are produced. Conductivity studies indicate that $\nu = 6$ for N_2O_5 . Propose an equation representing the solvolysis of N_2O_5 in sulfuric acid.
- 9.4 What is the strongest acid listed in Fig. 9.1? The strongest base?
- 9.5 The stability constant, K , for $Au(CN)_2^-$ is defined as
$$\frac{[Au(CN)_2^-]}{[Au^+][CN^-]}$$

Radioactivity

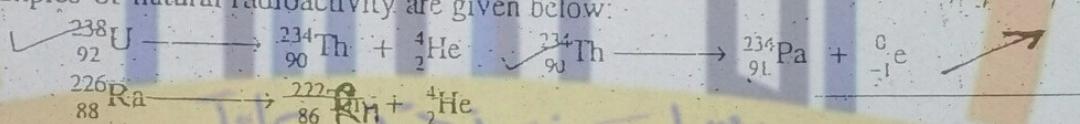
Radioactivity or natural radioactivity

The nuclei of naturally occurring heavy elements like U, Th, Ra and Po are unstable and keep on emitting spontaneously invisible rays or radiations viz α , β or γ -rays and give more stable elements. These heavy elements, which emit α , β or γ -rays are called *radioactive elements* and the property of emitting these rays is called *radioactivity of the elements*. The word "radioactivity" means "*Ray-emitting-activity*".

It is the nucleus of the atom of an element which spontaneously disintegrates, (i.e. disintegrates by itself) to emit α , β or γ -rays. The rays emitted by a radioactive element are called *radioactive rays*.

Thus radioactivity can also be defined as the phenomenon in which the nucleus of the atom of an element undergoes spontaneous and uncontrollable disintegration (or decay) and emits α , β , or γ -rays. Actually the definition given above is the *definition of natural radioactivity*.

Examples of natural radioactivity are given below:



The spontaneous emission of radioactive rays from the nucleus of a radioactive element is called *radioactive disintegration or radioactive decay of the element*.

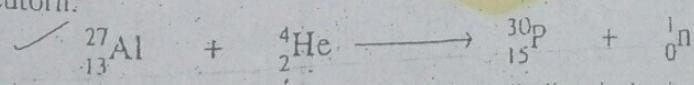
Types of radioactivity

Radioactivity is of the following two types.

(i) *Natural radioactivity*: Radioactivity discussed above is, in fact, natural radioactivity. In this type of radioactivity, the heavy elements like U, Th, Ra etc. emit spontaneously α , β or γ -rays and new elements are produced (also see above).

(ii) *Artificial or induced radioactivity*: Artificial radioactivity is a process in which a stable (non-radioactive) nucleus is changed into an unstable (radioactive) nucleus by bombarding it with appropriate atomic projectiles like α -particles, neutrons, protons, deuterons etc.

As an example, let us mention the experiment performed by Irene Curie and her husband, Frederick Joliet. (1934). They showed that when ${}_{13}^{27}\text{Al}$ isotope which is non-radioactive is bombarded with α -particles, it is converted into ${}_{15}^{30}\text{P}$ isotope (a radioactive isotope) with the emission of a neutron.



Stable (Non-radioactive)

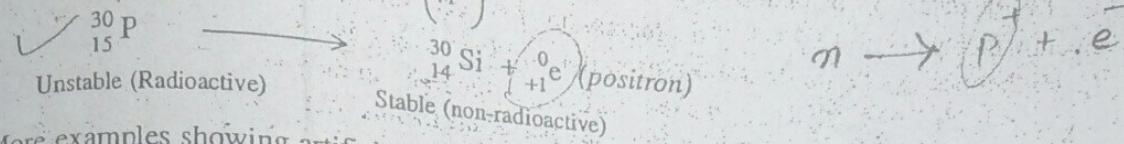
Unstable (Radioactive)

${}_{15}^{30}\text{P}$ obtained as above has been found to be radioactive, i.e., radioactivity is produced in ${}_{15}^{30}\text{P}$ isotope. This type of radioactivity is called *artificial or induced radioactivity*, since it has been

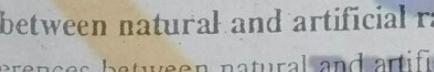
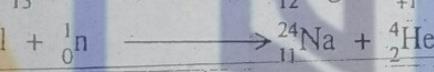
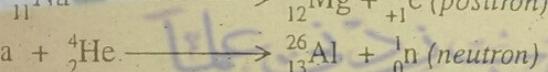
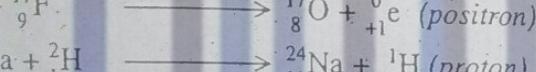
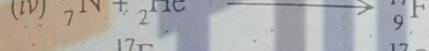
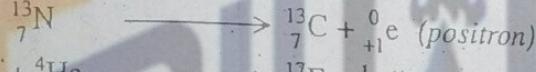
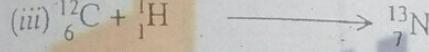
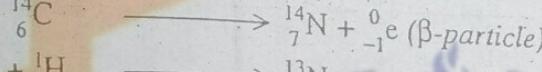
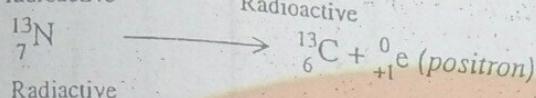
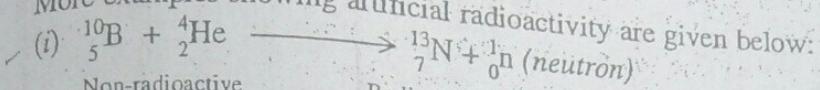
Radioactivity

149

produced by artificial means. Being radioactive, $^{30}_{15}\text{P}$ isotope gets disintegrated into a stable $^{30}_{14}\text{Si}$ isotope with the emission of a positron ($\begin{pmatrix} ^0e \\ +1 \end{pmatrix}$)



More examples showing artificial radioactivity



Differences between natural and artificial radioactivity

The differences between natural and artificial radioactivity are shown in Table 6.1.

Table 6.1: Differences between natural and artificial radioactivity.

Natural radioactivity	Artificial radioactivity
(i) Natural radioactivity is spontaneous, since in natural radioactivity, the nuclei of the heavy atoms disintegrate on their own accord, forming slightly lighter and more stable nuclei and emitting α , β or γ -radiations.	(i) Artificial radioactivity is not spontaneous, since in it the nuclei of the atoms have to be bombarded by fast moving particles like α -particles, neutrons, protons, deuterons etc.
(ii) Natural radioactivity is uncontrollable and hence it cannot be slowed down or accelerated by any means.	(ii) Artificial radioactivity can be controlled by controlling the speed of the bombarding particles used for bringing about the artificial radioactivity.
(iii) Natural radioactivity is usually shown by heavy elements.	(iii) Artificial radioactivity can be induced even in light elements.

Units of radioactivity

The standard unit of radioactivity is *curie* (*c*) which is defined as the mass of a radioactive element which produces 3.7×10^{10} disintegrations per second. Thus *millicurie* (*mc*) and *microcurie* (*μc*) are the masses of a radioactive element that produce respectively $(3.7 \times 10^{10}) / 10^3 = 3.7 \times 10^7$ and $(3.7 \times 10^{10}) / 10^6 = 3.7 \times 10^4$ disintegrations per second. On this basis the statement that P-32, a beta-emitter, has an activity of 50 millicuries per gram means that each gram of P-32 present in any radioactive material has $50 \times 3.7 \times 10^7$ disintegration per second. Another unit of radioactivity is *rutherford* (*r*) which is defined as the mass of a radioactive substance which produces disintegrations per second. Thus *millirutherford* (*mr*) and *microrutherford* (*μr*) are the masses of a radioactive element that produces respectively $10^6 / 10^3 = 10^3$ and $10^6 / 10^6 = 1$ disintegrations per second. Thus we see that *c* and *r* are related as $1c / 1r = 3.7 \times 10^{10} / 10^6$ or $1c = 3.7 \times 10^4 r$.

Detection and measurement of radioactivity

The radioactivity of a radioactive substance is detected and measured by instruments like Geiger-Muller (G-M) counter, (Fig. 6.1), Wilson Cloud Chamber, scintillation counters and dosi-meters. The detection of radioactivity by G-M counter depends on the ionisation of a gas in a tube. Radioactive substance is allowed to enter a tube where it produces the gas which undergoes ionisation in the tube.

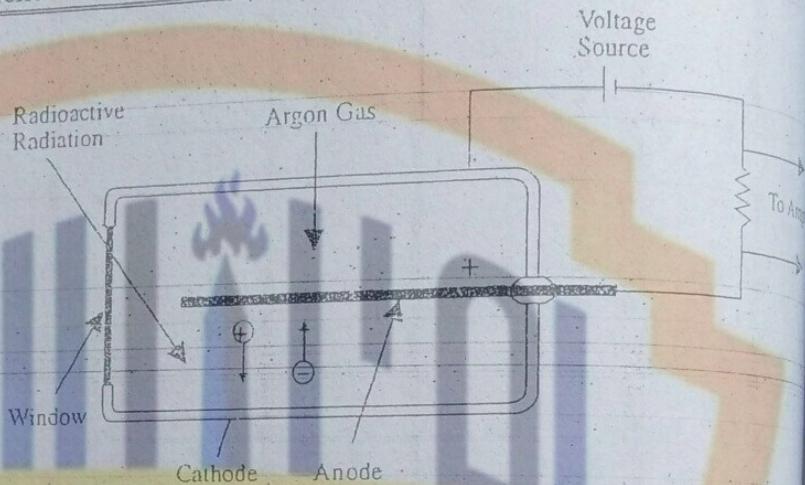


Fig. 6.1 : Geiger-Muller counter used for the detection and measurement of radioactivity of a substance.

Types of radioactive rays

In 1904, Rutherford and his co-workers placed a small piece of radium (a radioactive substance) in thick lead box having a small opening and got a thin beam of radioactive rays by passing through a slit. Now they passed the beam of invisible rays coming from radium between the positive and negative plates of a strong electric field and found that the beam splitted into different rays which are : (i) *Alpha* (α) rays which are deflected towards the negative plate (ii) β rays which are deflected towards the positive plate (iii) *Gamma* (γ) rays which are not deflected at all. It is the nucleus of the radioactive element that is unstable and hence emits, α , β or γ rays.

Nature, mass, charge (atomic number) and representation (symbol) of α , β and γ -rays

(a) α -particle is a helium nucleus which contains two protons and two neutrons and hence its mass (or mass number) is equal to $2 + 2 = 4$ and its atomic number is 2 (due to the presence of two protons). Thus an α -particle is represented as ${}_{+2}^4 \text{He}$ or ${}_{+2}^4 \text{He}^-$ which shows that an α -particle has a positive charge equal to +2, i.e., α -particle is a *positively-charged particle*. Positive charge +2 means that the atomic number of an α -particle is equal to +2 or simply 2.

The mass of an α -particle is equal to +2 or simply 2.

(b) A β -particle has a negative charge equal to -1. Thus a β -particle is a *negatively-charged particle*. -1 charge means that the atomic number of β -particle is equal to -1.

The mass of a β -particle is equal to 1.

Since the mass in amu is so small ($= 0.0005482 \text{ amu}$) that the mass of a β -particle is taken as $1840 \text{ amu} = 0.0005482 \text{ amu} = 0.0005482 \times 0.166 \times 10^{-27} \text{ kg}$

(i) Pen

(ii) Effec
mag

(iii) Ioni

(iv) Kin

(v) Effec
plate

(vi) Effec
and plati

Comp

(a) E

(b) B

(c) W

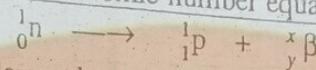
and hence
element) is

the

to zero in nuclear reactions. Thus a β -particle has a negative charge equal to -1 and no mass, i.e., β -particle can be represented as ${}_{-1}^0\beta$. Now we know that since an electron, like a β -particle, also has -1 charge and no mass, a β -particle can also be regarded as an electron and hence can also be represented as ${}_{-1}^0e$.

The fact that a β -particle is a massless particle with atomic number equal to -1 can be explained as follows :

\Rightarrow When the nucleus of the atom of a radioactive element loses a β -particle, one of the neutrons (1_0n) present in the nucleus of the atom is changed into a proton (1_1p or 1_0p) and a β -particle. Let the mass number of β -particle be x and atomic number equal to y . Thus :



Obviously in order to balance the mass numbers we have $1 = 1+x$ or $x = 0$ and on balancing the atomic numbers we have $0 = 1+y$ or $y = -1$. Thus a β -particle is a massless particle ($x = 0$) with atomic number equal to -1 ($y = -1$).

(c) A γ -ray has no charge and no mass. This means that a γ -ray is a chargeless (neutral) and massless ray. Thus a γ -ray can be represented as ${}^0_0\gamma$. γ -rays are high frequency electromagnetic waves like X-rays and have very short wavelength.

Other properties of α , β and γ -rays

Nature, mass and charge of these rays have already been discussed. Here we are giving the properties like speed, penetration power, ionising power etc. of these rays in a tabular form (See Table 6.2).

Table 6.2 : Comparison between some properties of α , β and γ -rays

Property	α -rays (4_2He or 4_0He)	β -rays (${}^0_1\beta$ or ${}^0_{-1}e$)	γ -rays (${}^0_0\gamma$)
(i) Penetration power	Least (1)	More than α -particles (100)	Greatest (10000)
(ii) Effect of electric and magnetic fields	Deflected towards the negative plate/pole	deflected towards the positive plate/pole	Not deflected
(iii) Ionising power	Greatest (10000)	Less (100)	Least (1)
(iv) Kinetic energy	High	Small	Nil
(v) Effect on photographic plate	The plate becomes black	Plate becomes black	Plate becomes black
(vi) Effect on ZnS and barium platinocyanide	Luminosity is produced	Less luminosity is produced	Least luminosity is produced.

Comparison between a β -particle and an electron

(a) Both the particles are negatively charged. Both have a negative charge equal to -1. Thus the atomic number of a β -particle is equal to -1.

(b) Both are massless particles ($m = 0$)

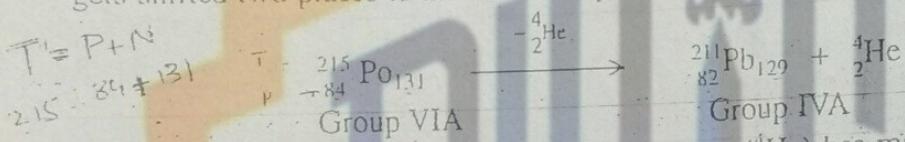
(c) When an atom of an element loses an electron, a cation of the same element is formed and hence the composition of the nucleus of the parent-element remains the same. On the other hand, when the nucleus of an element loses a β -particle a new neutral element (called daughter element) is obtained. Due to the formation of a new element, the composition of the nucleus of the parent element gets changed. The daughter element has one more proton but one less

neutron than the parent element. Thus the sum of the protons and neutrons in the daughter element remains the same as in the parent element. Due to the formation of one more proton, the atomic number of the daughter element is increased by one unit.

Soddy-Fajans and Russel group displacement law (1913)

This law tells us about the nature and the new periodic position of the element produced when a radioactive element loses an α -particle or a β -particle, or a positron or gains an electron. The element losing or gaining the particle is called *parent element* and the element which is produced after the loss or gain of the particle is called *daughter element* or *daughter product*. This law can be studied under the following heads:

(i) Emission of an alpha particle, α or ${}^4_2\text{He}$. We know that an α -particle is a helium nucleus whose mass number is 4 and nuclear charge (i.e., atomic number) is +2. Thus this particle is represented as ${}_{+2}^4\text{He}$ or simply as ${}^4_2\text{He}$. When a radioactive element emits an α -particle (${}^4_2\text{He}$), the mass number of the daughter element is decreased by 4 units (since the mass number of helium nucleus is 4) and atomic number gets decreased by 2 units (since the charge or atomic number of helium nucleus is +2). Due to the decrease in atomic number by two units, the daughter element gets shifted two places to the left in the periodic table. For example :

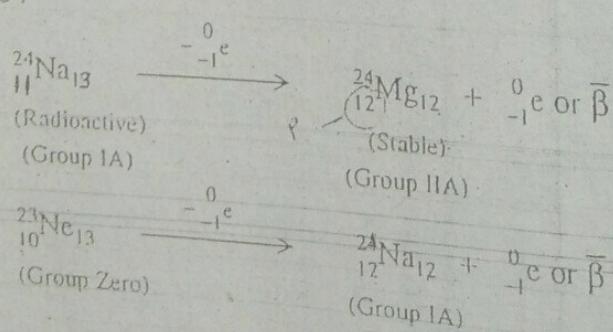


Explanation. We know that a helium nucleus (${}^4_2\text{He}$) has mass number equal to 4 and atomic number equal to 2. Thus this nucleus contains 2 protons and $4 - 2 = 2$ neutrons (${}^4_2\text{He}_2$). Thus the above nuclear reaction can be written as

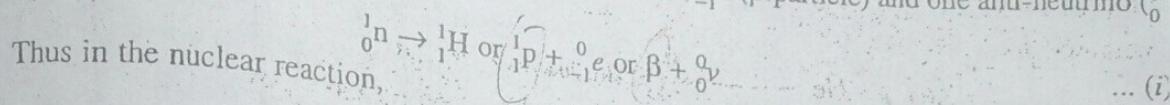


The presence of two protons and two neutrons in helium nucleus implies that when the nucleus of ${}^{215}_{84}\text{Po}_{131}$ loses an α -particle, 2 protons and 2 neutrons are lost by it, i.e., the number of protons (or atomic number) in the daughter element becomes $84 - 2 = 82$ and the number of neutrons becomes equal to $131 - 2 = 129$ and consequently the mass number becomes equal to $82 + 129 = 211$. Thus the loss of 2 protons implies that the atomic number of the daughter element is two units less than that of the parent element while the loss of (2 protons + 2 neutrons) suggests that the mass number of the daughter element becomes four units less than that of the parent element.

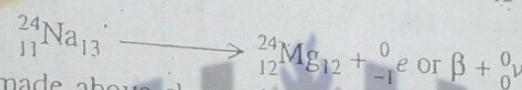
(ii) Emission of a beta particle, β or ${}^0_{-1}\text{e}$. We know that a β -particle is an electron which has mass number equal to zero and its charge or atomic number is -1. Thus it is represented as ${}^0_{-1}\text{e}$. When a radioactive element emits one ${}^0_{-1}\text{e}$ (or β -particle), the mass number of the daughter element remains the same (since the mass number of ${}^0_{-1}\text{e}$ is zero) but its atomic number increases by one unit (since the charge or atomic number of ${}^0_{-1}\text{e}$ is -1). Due to the increase in atomic number by one unit, the newly-formed element gets shifted one place to the right in the periodic table. For example :



Explanation: We know that nucleus does not contain ${}_{-1}^0 e$ (β -particle) as such. Then how β -particle produced in the nuclear reactions like those as given above? In order to explain it, it is assumed that one of the neutrons (${}_{-1}^0 n$) present in the parent element is converted into a proton (${}_{-1}^1 H$ or ${}_{-1}^1 p$) and in this conversion process, one ${}_{-1}^0 e$ (β -particle) and one anti-neutrino (${}_{-1}^0 \nu$) are also produced, i.e.,



one of the 13 neutrons is converted into a proton and hence the newly-formed element has $13 - 1 = 12$ neutrons and $11 + 1 = 12$ protons and in this process one ${}_{-1}^0 e$ (β -particle) and one anti-neutrino (${}_{-1}^0 \nu$) are also produced. Thus the newly-formed element is ${}_{-12}^{24} Mg$ and hence the above reaction should be written as :

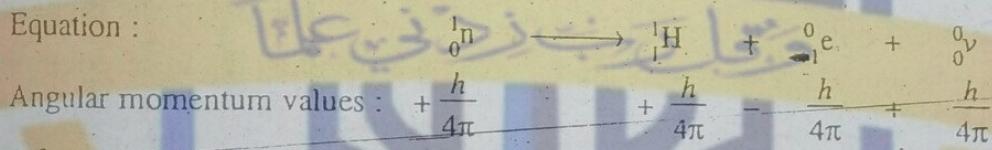


The discussion made above shows that since mass number of the parent element and of the daughter element are the same, these two elements are isobars to each other. Thus we can say that the emission of one or more β -particles (${}_{-1}^0 e$) by a radioactive element produces its isobar(s).

β decay is common over the entire range of nuclides and amongst the naturally occurring heavy radioactive nuclides and in the fission products (see *Nuclear Fission*).

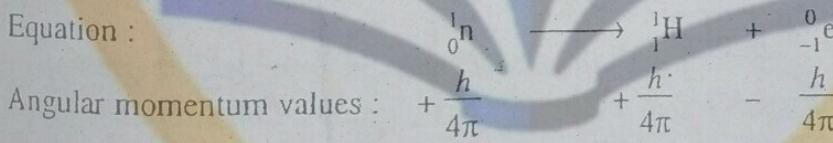
Equation (i) is balanced in so far as angular momentum values of different particles is concerned as shown below:

Equation :

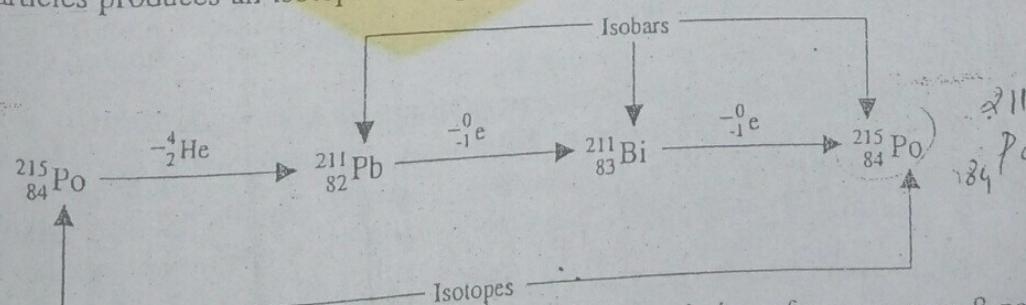


If ${}_{-1}^0 \nu$ is not supposed to be emitted in the above equation, then angular momentum values are not balanced as shown below:

Equation :



\Rightarrow Formation of isotopes and isobars. When a radioactive element emits one α -particle (${}^4_2 He$) and two β -particles (${}_{-1}^0 e$), the daughter element has the same atomic number as the parent element and hence these two elements are isotopes to each other. Thus the combined emission of one α -particle and two β -particles produces an isotope of the parent element, e.g.



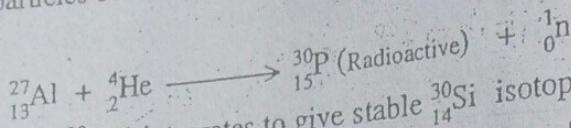
It may be seen from the above nuclear reactions that the emission of one or more β -particles (${}_{-1}^0 e$) by a radioactive element produces its isobar(s).

(iii) **Emission of a positron, ${}_{+1}^0 e$.** We know that a positron is an anti-particle of an electron (${}_{-1}^0 e$),

154 \Rightarrow Same mass # & different atomic number \Rightarrow Advanced
 i.e., a positron has mass number equal to zero (its actual mass = 0.0005486 amu) and its charge or atomic number is +1. Thus positron is represented as ${}_{+1}^0 e$. This particle was discovered by Irene Curie and her husband (name-Frederick Joliet) in 1934. They bombarded ${}^{27}_{13} Al$ nuclide (non-radioactive isotope) with α -particles so that it was converted into radioactive ${}^{30}_{15} P$ isotope with the emission of a neutron (${}_{0}^1 n$).

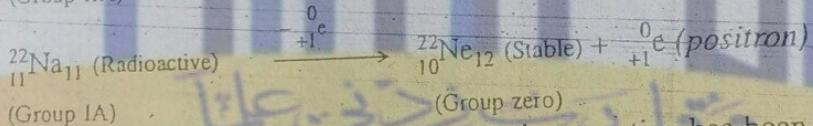
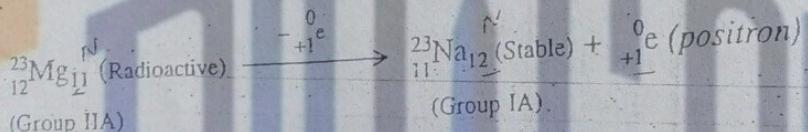
$${}^{27}_{13} Al + {}^{4}_{2} He \longrightarrow {}^{30}_{15} P \text{ (Radioactive)} + {}_{0}^1 n$$

$${}^{30}_{15} P \text{ isotope and a positron } ({}_{+1}^0 e)$$

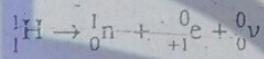


Being radioactive ^{30}P disintegrates to give stable ^{30}Si isotope and a positron

It is evident from the above nuclear reaction that when a radioactive element emits a positron, the mass number of the daughter element remains the same (since the mass number of ${}^0_+e$ is zero) but its atomic number is decreased by one unit (since the charge or atomic number of ${}^0_+e$ is +1). Due to the decrease in the atomic number by one unit, the newly-formed element gets shifted one place to the left in the periodic table. This fact is also evident from the following nuclear reactions:



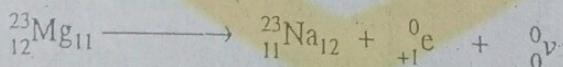
Explanation: How is the positron produced in a nuclear reaction has been explained by assuming that one of the protons (${}^1_1 p$ or ${}^1_1 H$) present in the nucleus of the parent element is converted into a neutron (${}^1_0 n$) and in this process one positron (${}^0_{+1} e$) and one neutrino (${}^0_0 \nu$) are also produced, i.e..



Thus in the nuclear reaction

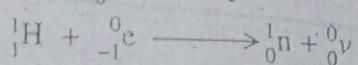


one of the 12 protons is converted into a neutron and hence the daughter element has $12 - 1 = 11$ protons and $11 + 1 = 12$ neutrons and in this process one positron (${}_{+1}^0 e$) and one neutrino (${}_{-1}^0 \nu$) are also produced. Thus the daughter element is ${}_{11}^{23} Na_{12}$ and hence the above equation should be written as :

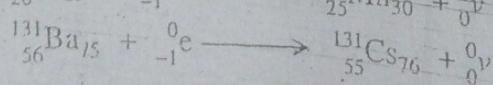
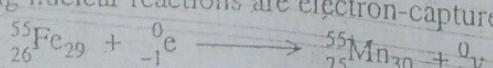


Since the mass number of the parent element and the daughter element are the same, these two elements are isobars to each other. Thus, we see that the emission of one or more positrons (${}_{+1}^0 e$) by a radioactive element produces its isobar(s).

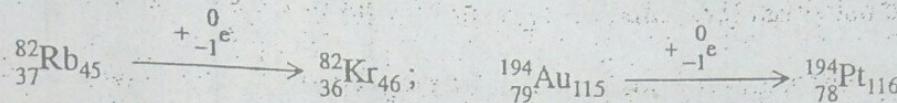
(iv) Addition of an electron: Electron - capture process. In this process an electron from the K or L shell is captured by a proton of the nucleus and this proton is converted into a neutron. In this process a neutrino (ν) is also produced.



The following nuclear reactions are electron-capture reactions:



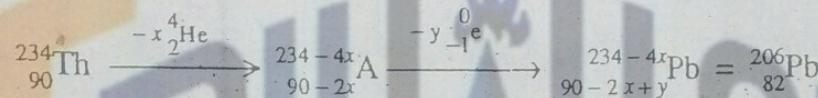
In reaction (i), one of the 26 protons captures an electron and is converted into a neutron and in this process one neutrino is also produced. Thus the number of protons (i.e. atomic number) of the daughter element is decreased by one unit and the number of neutrons is increased by one unit. Consequently the mass number remains the same. Thus we see that the process of electron-capture is similar to that reaction in which a radioactive element emits a positron (${}_{+1}^0 e$). Other examples of electron capture are.



Solved Examples

Example 6.1. ${}_{90}^{234}\text{Th}$ disintegrates to give ${}_{82}^{206}\text{Pb}$ as the final product. How many alpha and beta particles are emitted during this process? (I.I.T 1986)

Solution. If the number of α -and β particles which are emitted from ${}_{90}^{234}\text{Th}$ is x and y respectively, then the formation of ${}_{82}^{206}\text{Pb}$ can be represented as :

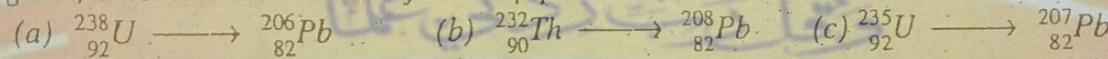


Thus $234 - 4x = 206$ or $x = 7$ and $90 - 2x + y = 82$

or $90 - 2 \times 7 + y = 82$ or $y = 6$

Thus 7 α and 6 β particles are emitted.

Example 6.2. In the following natural radioactive series where only the first and last elements are given, calculate the number of α -and β -particles emitted in each case.



Solution. Apply the same procedure to find the number of α -and β -particles emitted in each reaction [Ans: (a) $\alpha = 8, \beta = 6$ (b) $\alpha = 6, \beta = 4$ (c) $\alpha = 7, \beta = 4$]

Definition of half-life (or half-life period, $t_{1/2}$ or $t_{0.5}$) of a radioactive substance

The time in which half of the total amount (or total number of atoms) of a radioactive substance gets disintegrated is called half-life of that substance.

OR

Half-life of a radioactive substance is that time in which half of the total amount (or total number of atoms) of that substance disintegrates.

OR

The time in which the radioactivity of a given substance falls to half of its original value is called half-life of that substance.

The above discussion shows that in half-life of a radioactive substance, half of the total amount of that substance undergoes disintegration and the remaining half remains undisintegrated (i.e., radioactive). Half-life is denoted by the symbol $t_{1/2}$ or $t_{0.5}$.

To calculate the amount of a radioactive substance left undisintegrated or disintegrated in n half-lives

Suppose that a radioactive substance undergoes disintegration. The initial amount of the substance taken is N_0 and after t time the amount of the substance that remains undisintegrated is N . Thus the amount that has disintegrated in t time is equal to $(N_0 - N)$. Let the half-life of the substance be $t_{0.5}$. If t time is supposed to be composed of n half-lives, then:

$$t = n \times t_{0.5} \quad \text{or} \quad n = t / t_{0.5}$$

Obviously:

- (i) After one half-life (i.e. after $1 \times t_{0.5}$), the amount of the substance that would remain undisintegrated will be one half of its initial (original) amount (i.e., $1/2 N_0$). Thus the weight of the substance that undergoes disintegration = $N_0 - \frac{1}{2} N_0 = \frac{1}{2} N_0$.

$$\begin{aligned} t_{1/2} &= 15 & \dots (i) \\ t &= 60 \end{aligned}$$

(ii) After two half-lives (i.e., after $2 \times t_{0.5}$), the amount of the substance that would remain undisintegrated will be one-fourth of its initial amount [i.e., $\frac{1}{4}N_0 = \left(\frac{1}{2}\right)^2 N_0$]. Thus weight of the substance that undergoes disintegration = $N_0 - \frac{1}{4}N_0 = \frac{3}{4}N_0$.

(iii) After three half-lives (i.e., after $3 \times t_{0.5}$), the amount of the substance that remains will be one-eighth of its initial amount [i.e., $\frac{1}{8}N_0 = \left(\frac{1}{2}\right)^3 N_0$]. Thus the amount of substance that is decomposed = $N_0 - \frac{1}{8}N_0 = \frac{7}{8}N_0$.

(iv) After four half-lives (i.e., after $4 \times t_{0.5}$), the amount of the substance that remains composed will be one-sixteenth of its initial amount [i.e., $\frac{1}{16}N_0 = \left(\frac{1}{2}\right)^4 N_0$]. Thus amount of the substance that gets disintegrated = $N_0 - \frac{1}{16}N_0 = \frac{15}{16}N_0$.

The above discussion shows that after n half-lives (i.e., after $n \times t_{0.5}$ or t), the amount of substance that remains undisintegrated will be equal to $\left(\frac{1}{2}\right)^n N_0$ and hence the amount of substance that gets disintegrated = $N_0 - \left(\frac{1}{2}\right)^n N_0 = \left[1 - \left(\frac{1}{2}\right)^n\right] N_0$. Thus :

Amounts of the radioactive substance that remains (undisintegrated) after n half-lives time ($t = n \times t_{0.5}$)

$$x/t_{0.5} \quad t = n \times t_{0.5} \quad N = N_0 \left(\frac{1}{2}\right)^n = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}}$$

Amount of the radioactive substance that gets disintegrated in n half-lives or t time ($t = n \times t_{0.5}$) = $N_0 - N$.

$$= N_0 - N_0 \left(\frac{1}{2}\right)^n = N_0 \left[1 - \left(\frac{1}{2}\right)^n\right] = N_0 \left[1 - \left(\frac{1}{2}\right)^{t/t_{0.5}}\right]$$

Equation (iii) gives the amount of the product formed by the disintegration of the radioactive substance.

Examples (i) Suppose we start with 24 atoms (= N_0) of a radioactive substance, then one half-life ($1 \times t_{0.5}$) the number of atoms that remain undisintegrated would be equal to $= \frac{1}{2} \times 24 = 12$ and the number of atoms that undergo disintegration would be equal to $\frac{1}{2} N_0 = 24 - \frac{24}{2} = 24 - 12 = 12$.

Similarly in the two half-lives ($2 \times t_{0.5}$) the number of atoms undisintegrated = $\left(\frac{1}{2}\right)^2 N_0 = \left(\frac{1}{2}\right)^2 \times 24 = 6$ and the number of atoms disintegrated $N_0 - \left(\frac{1}{2}\right)^2 N_0 = 24 - 6 = 18$.

In this way the number of atoms left undisintegrated and number of atoms undergone disintegration in the subsequent half-lives can also be found out (See Fig. 6.2).

Fig. 6

(ii)
isotope a
half-lives

Amo

Amo

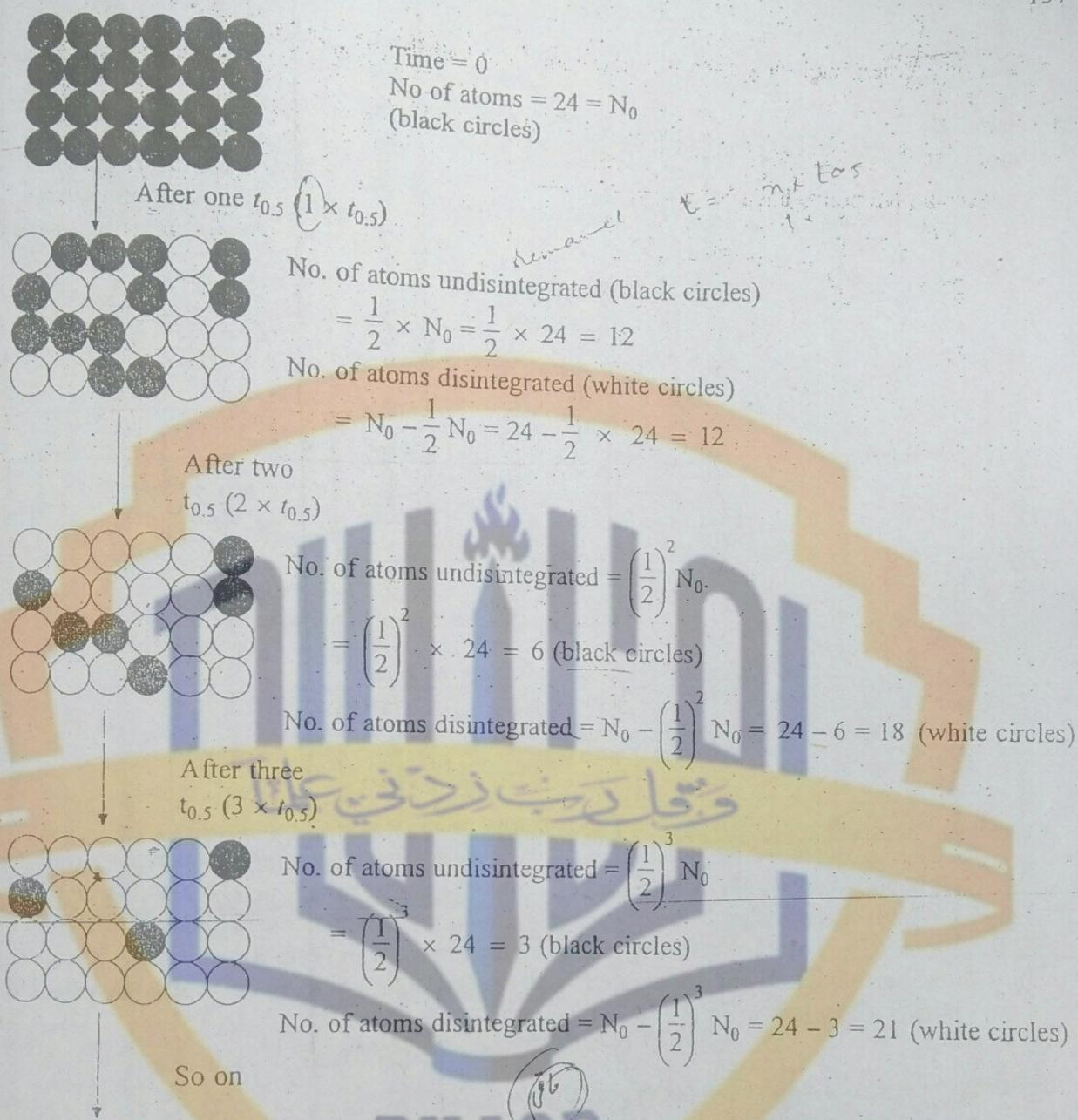


Fig. 6.2: To calculate the number of atoms of a radioactive substance left undisintegrated or disintegrated in n half-lives.

(ii) $^{128}_{53}\text{I}$ isotope has half-life period = 25 minutes. Suppose we start with 1g($= N_0$) of this isotope and allow it to undergo disintegration for a period of 100 minutes which are equal to 4 half-lives. Obviously :

Amount of $^{128}_{53}\text{I}$ left undisintegrated after 25 minutes (one half-life = $1 \times 25 = 25$)

$$= \frac{1}{2} N_0 = \frac{1}{2} \times 1 = 0.50 \text{ g}$$

Amount of $^{128}_{53}\text{I}$ left undisintegrated after 50 minutes (two half-lives = $2 \times 25 = 50$)

$$= \left(\frac{1}{2}\right)^2 N_0 = \left(\frac{1}{2}\right)^2 \times 1 = 0.25 \text{ g}$$

Amount of $^{128}_{53}\text{I}$ left undisintegrated after 75 minutes (three half-lives = $3 \times 25 = 75$)

$$= \left(\frac{1}{2}\right)^3 N_0 = \left(\frac{1}{2}\right)^3 \times 1 = 0.125 \text{ g}$$

Amount of $^{128}_{53}\text{I}$ left undisintegrated after 100 minutes (4 half-lives = $4 \times 25 = 100$)

$$= \left(\frac{1}{2}\right)^4 \times 1 = 0.0625\text{g}$$

All the above points have been shown in Fig. 6.3.

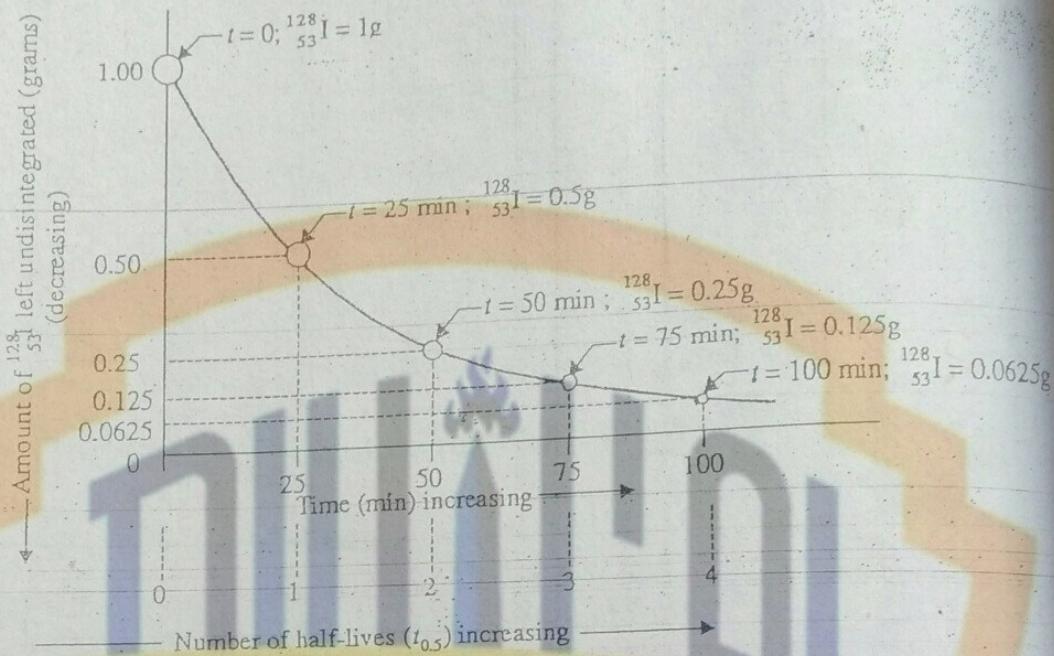
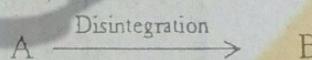


Fig. 6.3 : Radioactive decay of $^{128}_{53}\text{I}$.

Disintegration constant or decay constant (K)

Suppose a radioactive element A disintegrates into another substance B. Let the amount of nuclei of A in the beginning (i.e., at $t = 0$ time) be N_0 . Now as the time passes, element A disintegrates and hence the amount of A goes on decreasing while that of B goes on increasing. Suppose that after t time (which may be in seconds, minutes, days, years etc.) the amount of A left undisintegrated is N i.e., $(N_0 - N)$ is the amount of A that gets disintegrated into B after time t . Thus :



At $t = 0$ time, amounts of A and B = N_0

After t time, amounts of A and B = N

(Undisintegrated) (Disintegrated)

Now if a small amount, dN of A gets disintegrated into B in a small time dt , then the rate of disintegration (i.e., rate of decrease) of A into B is equal to $-dN/dt$ which is proportional to the amount of A left undisintegrated (N), i.e.,

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

(K is a constant of proportionality which is called disintegration or decay constant).

$$\text{or} \quad -\frac{dN}{N} = K \cdot dt$$

In equation (i) negative sign shows that the amount of A is decreasing with time. Now if 1 second, minute etc, then equation (i) becomes

$$-\frac{dN}{N} = K$$

Equation (ii) shows that disintegration constant (K) can be defined as the fraction of the

amount of the radioactive substance ($= \frac{dN}{N}$) which disintegrates in unit time. K is constant for a particular radioactive element; i.e., different elements have different values of K . The magnitude of K is not changed with the change of temperature, concentration, pressure and other physical factors.

Integrating equation (i) over limits N_0 (lower limit) and N (higher limit) (for left hand side) and 0 and t (for right hand side), we get :

$$\int_{N_0}^N \frac{dN}{N} = - \int_0^t K dt$$

$$\ln \frac{N}{N_0} = -Kt$$

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

Equation (iii) can also be written as :

$$2.303 \log_{10} \frac{N}{N_0} = -Kt \quad \text{or} \quad -2.303 \log_{10} \frac{N}{N_0} = Kt \quad \text{or} \quad 2.303 \log_{10} \frac{N_0}{N} = Kt$$

$$\text{or } t = \frac{2.303}{K} \log_{10} \frac{N_0}{N}$$

$$\text{or } t = \frac{2.303}{K} \log_{10} \frac{\text{Amount of the radioactive substance before its decay}}{\text{Amount of the radioactive substance after its decay for time } t}$$

$$\text{or } t = \frac{2.303}{K} \log_{10} \frac{\text{Amount of the substance in the beginning}}{\text{Amount of the substance left undisintegrated after time } t}$$

Equation (v) is the same as is obtained for a first order reaction. Hence, rate of a radioactive disintegration is a first order reaction. This equation shows that the complete disintegration of a radioactive substance takes place in infinite time.

Another definition of disintegration constant

We have seen that $N = N_0 e^{-Kt}$

Now put $K = \frac{1}{t}$ in the above equation to get :

$$N = N_0 e^{-\frac{1}{t} t} = N_0 e^{-1}$$

$$\text{or } N = \frac{N_0}{e} = \frac{N_0}{2.718} \quad (\because e = 2.718)$$

$$\text{or } N = 0.37 N_0 = 37\% \text{ of } N_0$$

$$\frac{1}{2.718} = 0.37$$

(vi)

Equation (vi) shows that the *disintegration constant (K)* can also be defined as the reciprocal of that time in which the amount of a radioactive substance reduces to 37% of its initial amount.

To find out an expression for half-life period: Relation between half-life period ($t_{0.5}$ or $t_{1/2}$) and disintegration constant (K)

It is evident from the definition of half-life period that an expression for half-life period can be obtained by putting $t = t_{0.5}$ and $N = N_0 / 2$ either in equation (A) or in equation (B).

$$N = N_0 e^{-Kt} \quad \dots(A)$$

On putting $N = N_0 / 2$ and $t = t_{0.5}$ in this equation, we get:

$$\frac{N_0}{2} = N_0 e^{-K \cdot t_{0.5}}$$

$$\text{or } \frac{1}{2} = e^{-K \cdot t_{0.5}} \quad \text{or} \quad \ln \left(\frac{1}{2} \right) = \ln [e^{-K \cdot t_{0.5}}] = -K \cdot t_{0.5}$$

$$\text{or } 2.303 \log_{10} \left(\frac{1}{2} \right) = -K \cdot t_{0.5} \quad \text{or} \quad -2.303 \log_{10} \frac{1}{2} = K \cdot t_{0.5} = 2.303 \log 2 = ?$$

$$\text{or } \frac{2.303 \log_{10} 2}{K} = t_{0.5} \quad \text{or } t_{0.5} = \frac{2.303 \times 0.301}{K}$$

$$\text{or } t_{0.5} = \frac{0.6932}{K}$$

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

On putting $t = t_{0.5}$ and $N = N_0/2$, we get :

$$t_{0.5} = \frac{2.303}{K} \log_{10} \frac{2N_0}{N_0} = \frac{2.303}{K} \log 2$$

$$\text{or } t_{0.5} = \frac{2.303 \times 0.301}{K} \quad \text{or } t_{0.5} = \frac{0.6932}{K}$$

Equations (vii) and (viii) are the same and give us a relation between half-life period ($t_{0.5}$) and disintegration constant (K) of a radioactive substance. Each of these equations shows that it depends only on the magnitude of K and not on the weight or the number of the atoms of the radioactive substance or any other factor. $t_{0.5}$ is inversely proportional to K . $t_{0.5}$ for different substances is different, i.e., half-life is fixed for a particular substance.

To find out an expression showing the relation between t and $t_{0.5}$

We have already shown that :

$$t = \frac{2.303}{K} \log_{10} \frac{N_0}{N} \quad \text{and} \quad t_{0.5} = \frac{0.6932}{K}$$

When K is eliminated from the above two equations, we get:

$$\frac{2.303}{t} \log_{10} \frac{N_0}{N} = \frac{0.6932}{t_{0.5}} \quad \text{or} \quad \frac{2.303 \times t_{0.5}}{0.6932} \log_{10} \frac{N_0}{N} = t$$

$$\text{or } t = \frac{2.303 \times t_{0.5}}{0.6932} \log_{10} \frac{N_0}{N}$$

This equation gives us a relation between t and $t_{0.5}$.

Average life period (t_{av})

The disintegration of a radioactive substance goes on indefinitely and the total period for complete disintegration of any radioactive sample is infinity which is meaningless. Therefore, new term viz. average life period has been introduced. Average life period (t_{av}) of a radioactive substance is the reciprocal of its disintegration constant (K), i.e.

$$t_{av} = \frac{1}{K}$$

Relation between t_{av} and $t_{0.5}$

$$\text{We know that } t_{av} = \frac{1}{K}$$

$$\text{We also know that } t_{0.5} = \frac{0.6932}{K} \Rightarrow \text{or } \frac{1}{K} = \frac{t_{0.5}}{0.6932} = t_{0.5} \times 1.44$$

$$\text{or } t_{av} = \frac{1}{K} = t_{0.5} \times 1.44$$

Equation (ii) gives us a relation between t_{av} and $t_{0.5}$ of a given radioactive material. This equation shows that the value of $t_{0.5}$ of a radioactive element is smaller than t_{av} and t_{av} is directly proportional to $t_{0.5}$.

Example 6.3. The half-life of radon is 3.8 days. After how many days will one twentieth of the radon sample be left over?

(I.I.T 1981, MLNR 1977)

Solution. Here the amount of radon left undisintegrated = $\frac{1}{20}$ th of its initial amount

or

$$N = \frac{1}{20} \times N_0 \quad \text{or} \quad \frac{N_0}{N} = 20$$

Using the equation viz. $t = \frac{2.303 \times t_{0.5}}{0.693} \times \log \frac{N_0}{N}$, we get

$$\begin{aligned} t &= \frac{2.303 \times 3.8}{0.693} \times \log 20 = \frac{2.303 \times 3.8}{0.693} \times \log (10 \times 2) \\ &= \frac{2.303 \times 3.8}{0.693} [\log 10 + \log 2] \end{aligned}$$

$$\begin{aligned} &= \frac{2.303 \times 3.8}{0.693} [1 + 0.301] \\ &= 16.42 \text{ days} \end{aligned} \quad (\because \log 2 = 0.301)$$

Example 6.4. Half-life period of $^{125}_{53}\text{I}$ is 60 days. What percentage of the original radioactivity would be present after 180 days? (Roorkee Entrance 1980)

Solution. Here the original amount of $^{125}_{53}\text{I}$ isotope (N_0) = 100 and N is to be found out. We know that :

$$N = N_0 \left(\frac{1}{2}\right)^n = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}} \quad (\because t = n \times t_{0.5})$$

$$\text{or } N = 100 \times \left(\frac{1}{2}\right)^{\frac{180}{60}} \quad \text{or } N = 100 \times \left(\frac{1}{2}\right)^3 = 12.5\%$$

\therefore % of the original radioactivity present after 180 days = 12.5%

Example 6.5. Half life of ^{226}Ra is 1580 years. How many grams will be left undisintegrated from 1.0 g. of the isotope after 4740 years.

Solution. We know that the amount of the isotope left undisintegrated = $N = N_0 \left(\frac{1}{2}\right)^n = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}}$

$$\left(\frac{1}{2}\right)^{t/t_{0.5}} \quad (\because t = n \times t_{0.5})$$

Here $N_0 = 1\text{ g}$, $t = 4740 \text{ yrs}$, $t_{0.5} = 1580 \text{ yrs}$

$$\therefore N = 1 \times \left(\frac{1}{2}\right)^{4740/1580} = \left(\frac{1}{2}\right)^3 = \frac{1}{8} = 0.125$$

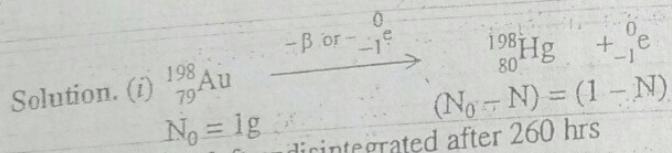
Thus the amount of Ra left undisintegrated after 4740 yrs = 0.125 g.

Example 6.6. Half-life of ^{210}Po is 140 days. Calculate the number of days after which $\frac{1}{4}$ g of ^{210}Po will be left undisintegrated from 1g of the isotope.

Solution. Here $N = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}}$

$$\text{or } \frac{1}{4} \times 1 = 1 \times \left(\frac{1}{2}\right)^{t/140} \quad \text{or } \frac{t}{140} = 2 \quad \text{or } t = 280 \text{ days}$$

Example 6.7. One gram of $^{198}_{79}\text{Au}$ ($t_{0.5} = 65 \text{ hrs}$) decays by β -emission to produce stable mercury. Answer the following - (i) Write the nuclear reaction for the process. (iii) How much mercury will be present after 260 hrs? (Roorkee Entrance 1984)



(ii) Amount Au left undisintegrated after 260 hrs

$$= N = N_0 \times \left(\frac{1}{2}\right)^{t/t_{0.5}} = 1 \times \left(\frac{1}{2}\right)^{260/65} = 1 \times \left(\frac{1}{2}\right)^4 = \frac{1}{16}$$
 $\therefore \text{Amount of Hg obtained} = (N_0 - N)\text{g} = 1 - \frac{1}{16} = \frac{15}{16} \text{g}$

Example 6.8. Radioactivity is a first order process. Radioactive carbon in a wood sample decays with a half life of 5770 years. What is the rate constant (in yrs^{-1}) for the decay? What fraction would remain after 11540 years? (I.I.T. 1988)

Solution. $t_{0.5} = 5770 \text{ yrs}, t = 11540 \text{ yrs.}$

(i) Rate constant, K is given by :

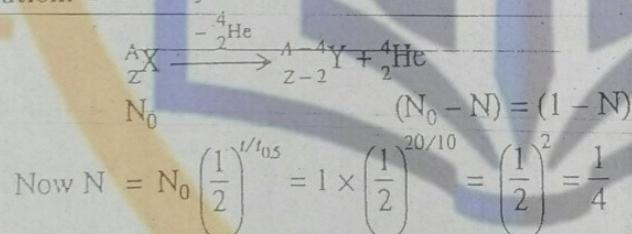
$$K = \frac{0.6932}{t_{0.5}} = \frac{0.6932}{5770 \text{ yrs.}} = 1.2 \times 10^{-4} \text{ yrs}^{-1}$$

$$(ii) N = N_0 \left(\frac{1}{2}\right)^n = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}} \quad \text{or} \quad N = 1 \times \left(\frac{1}{2}\right)^{11540/5770} = \left(\frac{1}{2}\right)^2 = \frac{1}{4}$$

Thus the fraction of the radioactive carbon that is left undisintegrated after 11540 yrs is 25% of the initial amount of carbon.

Example 6.9. A certain radioisotope A_ZX (half life = 10 days) decays to give ${}^{A-4}_{Z-2}Y$. If an atom of A_ZX is kept in a sealed vessel, how much helium will accumulate in 20 days? Express result in cm^3 at STP. (Roorkee Entrance 1990)

Solution. The decay can be shown as :



$$\therefore \text{Amount of } {}^4_2\text{He produced} = N_0 - N = 1 - \frac{1}{4} = \frac{3}{4}$$

$$\therefore \text{Volume of } \frac{3}{4} \text{ g atom of } {}^4_2\text{He at STP} = \frac{3}{4} \times 22400 \text{ cm}^3 = 16800 \text{ cm}^3$$

Example 6.10. A radioactive nuclide decays to form a stable nuclide. Its half-life time is 3 min. What fraction of 1 gm sample of the nuclide will remain radioactive after 9 min. (Roorkee 1990)

Solution. We know that :

$$N = N_0 \left(\frac{1}{2}\right)^n \quad \text{or} \quad N = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}} \quad (\because t = n \times t_{0.5})$$
 $= N_0 \left(\frac{1}{2}\right)^{9/3} = N_0 \left(\frac{1}{2}\right)^3 = 1 \times \left(\frac{1}{2}\right)^3 \quad \text{or} \quad N = \frac{1}{8}$

Thus $\frac{1}{8}$ gram of the sample will remain undisintegrated or radioactive.

Example 6.11. In a sample of radioactive substance, there are 10^6 radioactive nuclei

half-life period. W
Solution. W

Example 6.
of the pure radi
Solution. (

Amount re
t =
(ii) Initial
Amou

Radioactive e
Let a rad
form the prod

Successiv

No. of at

Disinteg

Half-life

The stag
B is equal to
the sample r

Rate of

or - d

On con

Now si

Supp
isotopes

Radioactivity

half-life period is 20 seconds. How many nuclei will be left after 10 seconds?

Solution. We know that

$$N = N_0 \left(\frac{1}{2}\right)^n = N_0 \left(\frac{1}{2}\right)^{\nu t_{0.5}} \quad (\because t = n \times t_{0.5})$$

$$= 10^6 \times \left(\frac{1}{2}\right)^{10/20} = 10^6 \times \left(\frac{1}{2}\right)^{1/2} \text{ or } N = 10^6 \times 0.707$$

Example 6.12. The half-life period of radium is 1590 yrs. After how many years will one gram of the pure radium (i) reduce to one centigram (ii) lose one centigram.

Solution. (i) Initial amount = 1 gm.

Amount remained undisintegrated = 1 centigram = $\frac{1}{100}$ gram = .01 gm

$$\therefore t = \frac{2.303 \times t_{0.5}}{0.693} \log \frac{N_0}{N} = \frac{2.303 \times 1590}{0.693} \times \log \frac{1}{0.01}$$

$$= \frac{2.303 \times 1590}{0.693} \log 100 = \frac{2.303 \times 1590 \times 2}{0.693} = 10567.8 \text{ yrs}$$

(ii) Initial amount = 1 gram

Amount that remained undisintegrated = $1 - 0.01 = 0.99$ gram

$$\therefore t = \frac{2.303 \times 1590}{0.693} \log \frac{1}{0.99} = 23.03 \text{ yrs}$$

Radioactive equilibrium : Law of successive disintegration

Let a radioactive substance A disintegrate to form a product B which further disintegrates to form the product C. Thus

Successive disintegration : A \longrightarrow B \longrightarrow C

No. of atoms :	N_A	N_B	N_C
----------------	-------	-------	-------

Disintegration constant :	K_A	K_B	K_C
---------------------------	-------	-------	-------

Half-life period :	$(t_{0.5})_A$	$(t_{0.5})_B$	$(t_{0.5})_C$
--------------------	---------------	---------------	---------------

The stage at which the rate of decay of A is equal to the rate of decay of B, the rate of decay of B is equal to that of C and so on is called radioactive equilibrium. At this stage the amount of B in the sample remains constant.

Rate of decay of A = Rate of decay of B = Rate of decay of C

$$\text{or } -\frac{dN_A}{dt} = -\frac{dN_B}{dt} = -\frac{dN_C}{dt} \text{ or } K_A N_A = K_B N_B = K_C N_C$$

On considering the equilibrium A \rightarrow B, we get:

$$\therefore K_A N_A = K_B N_B \text{ or } \frac{N_A}{N_B} = \frac{K_B}{K_A}$$

Now since $\frac{K_B}{K_A} = \frac{(t_{0.5})_A}{(t_{0.5})_B}$, we can also write

$$\boxed{\frac{N_A}{N_B} = \frac{K_B}{K_A} = \frac{(t_{0.5})_A}{(t_{0.5})_B}}$$

Suppose a radioactive sample contains two isotopes namely A and B. If the percentage of these isotopes present in the sample is $x\%$ and $y\%$ respectively, then:

$$\text{No. of moles of A isotope} = \frac{(t_{0.5})_A}{K_B} = \frac{K_B}{K_A}$$

$$\text{No. of moles of B isotope} = \frac{(t_{0.5})_B}{K_A} = \frac{K_A}{K_B}$$

or $\frac{x/\text{mass number}}{\text{mass number}} \text{ of A isotope} = \frac{(t_{0.5})_A}{K_B} = \frac{K_B}{K_A}$

or $\frac{x}{\text{Mass number of A isotope}} \times \frac{\text{Mass number of B isotope}}{y} = \frac{(t_{0.5})_A}{(t_{0.5})_B} = \frac{K_B}{K_A}$

Comparison between radioactive equilibrium and chemical equilibrium

A chemical equilibrium is reversible, since its direction can be changed by making a change in temperature, pressure or concentration of the species involved in the reaction. On the other hand, radioactive equilibrium is irreversible and hence its direction cannot be changed by making a change in temperature, pressure etc.

Example 6.13. A radioactive sample contains 15.8% ^{238}U and $5.3 \times 10^{-6}\%$ ^{226}Ra . If half-life of ^{226}Ra is 1590 years, what is the decay constant of ^{238}U ?

Solution. We know that

$$\frac{\text{No. of moles of U-238 } (N_{238})}{\text{No. of moles of Ra-226 } (N_{226})} = \frac{15.80/238}{5.3 \times 10^{-6}/226}$$

$$\text{or } \frac{N_{238}}{N_{226}} = \frac{15.80}{238} \times \frac{226}{5.3 \times 10^{-6}} = 2.83 \times 10^6$$

Again we know that:

$$\frac{N_{238}}{N_{226}} = \frac{(t_{0.5})_{238}}{(t_{0.5})_{226}} \quad \text{or} \quad 2.83 \times 10^6 = \frac{(t_{0.5})_{238}}{1590}$$

$$(t_{0.5})_{238} = 2.83 \times 10^6 \times 1590 = 4.4997 \times 10^9 \text{ years}$$

$$\text{Now } K_{238} = \frac{0.693}{(t_{0.5})_{238}} = \frac{0.693}{4.4997 \times 10^9 \text{ years}}$$

$$\text{or } K_{238} = 1.54 \times 10^{-10} \text{ years}^{-1}$$

Activity of a radioactive substance ($-\frac{dN}{dt}$ or A)

Activity of a radioactive substance is defined as the number of disintegrations which the substance undergoes (per second). Thus the unit of activity is disintegrations per second (dps). The activity is denoted by $-\frac{dN}{dt}$ or A which, as we have already seen, is equal to KN, i.e.,

Activity of a radioactive substance (A) or the number of disintegrations undergone by the substance in one second = $KN = \frac{0.693}{t_{0.5}} \times N$

In the above equation K = disintegration constant of the radioactive substance, N = number of atoms or nuclei of the substance left undisintegrated and $t_{0.5}$ = half-life of the substance.

Calculation of N

Suppose we have x grams of a radioactive element whose mass number is B. The number of atoms (N) present in x grams of this element is given by:

Thus activity (A) of x grams of an element is given by :

$$N = \frac{\text{Avogadro's number} \times \text{Mass of the element}}{\text{Mass number of the element}}$$

$$\text{Activity (A)} = K \times \frac{\text{Avogadro's number} \times \text{Mass of the element}}{\text{Mass number of the element}} \quad \text{s}^{-1}$$

$$\text{or } A = K \times \frac{6.022 \times 10^{23} \times x}{B} \quad \text{s}^{-1}$$

Radioactivity

$$A = \text{dis} / \text{sec}$$

$$\text{or } A = \frac{0.693}{t_{0.5}} \times \frac{6.022 \times 10^{23} \times x}{B} \text{ s}^{-1}$$

The above equation gives us the number of disintegrations that x g of the substance undergoes in one second. If the number of disintegrations undergone by x g of the substance in t time is to be found out, the following relation is used.

No. of disintegrations undergone by x g of the substance in t time

$$= KNt = \frac{0.693}{t_{0.5}} \times \frac{(6.022 \times 10^{23}) \times \text{mass}}{\text{mass number}} \times t = \frac{0.693}{t_{0.5}} \times \frac{(6.022 \times 10^{23}) \times x}{B} \times t$$

We have already shown that:

$$t = \frac{2.303}{K} \log_{10} \frac{\text{Amount of the radioactive substance in the beginning}}{\text{Amount of the radioactive substance left undisintegrated after time } t}$$

Now since the activity shown by a radioactive substance is directly proportional to its amount, the above equation can also be written as :

$$t = \frac{2.303}{K} \log_{10} \frac{\text{Activity shown by the radioactive substance in the beginning}}{\text{Activity shown by the radioactive substance after time } t}$$

$$\text{or } t = \frac{2.303}{K} \log_{10} \frac{A_0}{A} \quad \dots(ii)$$

Equation (ii) can also be written as equation (iii) or equation (iv)

$$A = A_0 e^{-kt} \quad \dots(iii)$$

$$A = A_0 \left(\frac{1}{2}\right)^n \quad \dots(iv)$$

In equation (iv) n is the number of half-lives ($t_{0.5}$) of which the total time (t) is composed, i.e.

$$t = n \times t_{0.5} \quad \text{or} \quad n = (t / t_{0.5})$$

Example 6.14. Half-life of radium (atomic mass 226) is 1580 yrs. Show that 1 g of radium gives 3.70×10^{10} disintegrations per second.

Solution. We know that the activity (A) of a radioactive substance is given by:

$$\begin{aligned} A &= KN = \frac{0.693}{(t_{0.5})} \times N \\ &= \frac{0.693}{1580 \times 365 \times 24 \times 60 \times 60 \text{ s}} \times \frac{\text{Avogadro's number} \times 1 \text{ gram}}{\text{Mass number}} \\ &= \frac{0.693 \times 6.022 \times 10^{23} \times 1}{1580 \times 365 \times 24 \times 60 \times 60 \times 226} \text{ dis. s}^{-1} \end{aligned}$$

$$\text{or } A = 3.70 \times 10^{10} \text{ dis. s}^{-1}$$

Example 6.15. The half-life of the nuclide Rn^{220} is 54.5 s. What mass of this nucleus is equivalent to 1 millicurie (mci)?

Solution. Activity of $Rn^{220} = 1 \text{ mci} = 3.7 \times 10^7 \text{ dis s}^{-1}$

Let the mass of $Rn^{220} = x$ gram

$$\therefore 3.7 \times 10^7 = \frac{0.693}{54.5} \times \frac{6.022 \times 10^{23} \times x}{220}$$

$$\therefore x = \frac{3.7 \times 10^7 \times 54.5 \times 220}{0.693 \times 6.022 \times 10^{23}} \text{ g} = 1.06 \times 10^{-12} \text{ g} = 1.06 \times 10^{-15} \text{ kg}$$

Example 6.16. Calculate the alpha activity in terms of disintegrations per minute (dpm) of 10^{-3} g. sample of Pu^{239} . Given that $t_{0.5} = 24,300$ yrs and $1 \text{ yr} = 3.15 \times 10^7 \text{ s}$

Solution. Activity of Pu^{239} is given by:

$$A = KN = \frac{0.693}{t_{0.5}} \times \frac{6.022 \times 10^{23} \times \text{mass of } Pu^{239}}{\text{Mass number}}$$

$$= \frac{0.693 \times 60}{24300 \times 3.15 \times 10^7 \text{ m}} \times \frac{6.022 \times 10^{23} \times 10^{-3}}{239} = 1.43 \times 10^8 \text{ dis. m}^{-1}$$

Example 6.17. U^{235} yields 4770 disintegrations $\text{min}^{-1} \text{ mg}^{-1}$. Calculate its decay constant and half-life (1 year = $3.15 \times 10^7 \text{ s}$).

Solution. We know that

$$A = K \times N \quad \text{or} \quad A = K \times \frac{(6.022 \times 10^{23}) \times \text{mass}}{\text{Mass number}}$$

$$\text{or} \quad 4770 \text{ d.m}^{-1} \text{ mg}^{-1} = K \times \frac{(6.022 \times 10^{23} \text{ g}) \times 10^{-3} \text{ g}}{235}$$

$$\text{or} \quad \frac{4770}{60} \text{ d.s}^{-1} \text{ mg}^{-1} = K \times \frac{(6.022 \times 10^{23}) \times 10^{-3}}{235} \quad \therefore K = \frac{4770 \times 235 \text{ s}^{-1}}{60 \times 6.022 \times 10^{23} \times 10^{-3}}$$

$$= \frac{4770 \times 235 \times (3.15 \times 10^7)}{60 \times 6.022 \times 10^{23} \times 10^{-3}} \text{ yr}^{-1} = 9.78 \times 10^{-10} \text{ yr}^{-1}$$

$$\therefore t_{0.5} = \frac{0.693}{K} = \frac{0.693}{9.78 \times 10^{-10} \text{ yr}^{-1}}$$

$$= \frac{0.693}{9.78} \times 10^{10} \text{ yr} = \frac{69.3}{9.78} \times 10^8 \text{ yr} \quad \text{or} \quad t_{0.5} = 7.08 \times 10^8 \text{ y}$$

Example 6.18. The activity of a sample of titanium is decreased by 5.5% over a period of one year. What is the half-life of titanium?

Solution. We know that

$$t = \frac{2.303}{K} \log \frac{A_0}{A} \quad 1y = \frac{2.303}{K} \log \frac{100}{100 - 5.5}$$

$$\text{or} \quad 1y = \frac{2.303}{K} \log \frac{100}{94.5} \quad \text{or} \quad K = \frac{2.303}{1y} \log \frac{100}{94.5} = 0.0566 \text{ y}^{-1}$$

Again we know that

$$t_{0.5} = \frac{0.693}{K} = \frac{0.693}{0.0566 \text{ y}^{-1}} \quad \text{or} \quad t_{0.5} = 12.24 \text{ y}$$

Example 6.19. Calculate the weight of ^{14}C (half-life = 5720 yrs) atoms which give 3.7 dpm disintegrations per second.

(Roorkee 1998)

Solution. If the weight of ^{14}C be x gram, then:

$$3.70 \times 10^7 \text{ s}^{-1} = \frac{0.693}{5720 \times 365 \times 24 \times 60 \times 60 \text{ s}} \times \frac{(6.022 \times 10^{23}) \times x}{14}$$

$$\text{or} \quad 3.70 \times 10^7 \text{ s}^{-1} = 3.83 \times 10^{-12} \times 6.022 \times 10^{23} \times \frac{x}{14} \text{ s}^{-1}$$

$$\therefore x = \frac{14 \times 3.70 \times 10^7}{3.83 \times 10^{-12} \times 6.022 \times 10^{23}}$$

$$g = 0.224 \times 10^{-3} \text{ g}$$

Example 6.20. Half-life of Co^{60} is 5.27 yrs. Find out the alpha activity (dpm) of a 2.0 g sample of the isotope.

$$\text{Solution. Activity (A)} = KN = \frac{0.693}{t_{0.5}} \times \frac{\text{Avogadro's number} \times \text{mass}}{\text{mass number}}$$

$$= \frac{0.693}{5.27 \times 365 \times 24 \times 60 \text{ m}} \times \frac{(6.022 \times 10^{23}) \times 2}{60}$$

$$= 5.028 \times 10^{15} \text{ dpm}$$

Example 6.21. A sample of a radioactive isotope showed 7620 counts per minute at one time and 3640 counts per minute after 10 hours. Find the half-life of the isotope.

Solution. We know that

$$= 86.254 \times 0.9031 \text{ yrs}$$

Example 6.26. The radioactive decay rate of a radioactive element found to be 10^3 disintegrations per second at a certain time. If the half-life of the element is one second, find the rate after 1 second and after 3 seconds. (I.I.T.)

Solution. We know that

$$(i) \quad N = N_0 \left(\frac{1}{2}\right)^n = N_0 \times \left(\frac{1}{2}\right)^{\frac{t-t_0}{T_{1/2}}} = 10^3 \times \left(\frac{1}{2}\right)^{1/1} = 10^3 \times \frac{1}{2} = 500$$

$$(ii) N = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}} = 10^3 \times \left(\frac{1}{2}\right)^{3/1} = 10^3 \times \frac{1}{8} = 125$$

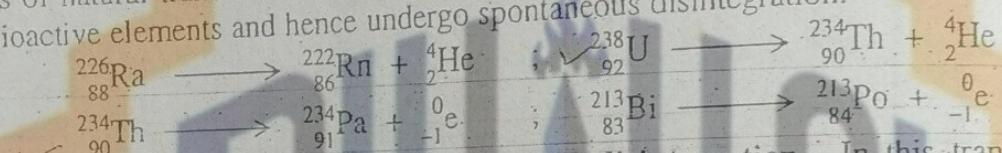
Transmutation or disintegration of elements

Transmutation or disintegration of elements

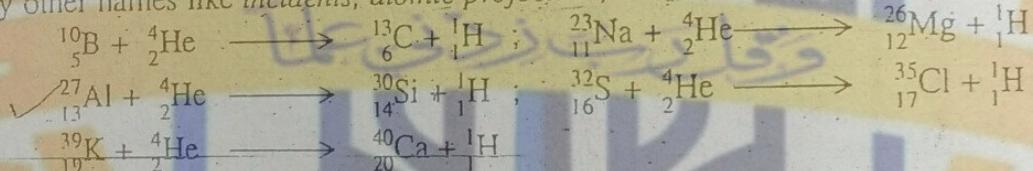
Transmutation of an element is a process in which the element is converted into another element. This process may be of the following two types.

Spontaneous transmutation or disintegration. In this transmutation, a ra-

(i) Natural or spontaneous transmutation or disintegration. In this transmutation, an active element is spontaneously converted into another element by emitting α , β or γ -rays. Examples of natural transmutation are given below. In these examples ^{226}Ra , ^{238}U , ^{234}Th and ^{213}Bi radioactive elements undergo spontaneous disintegration.

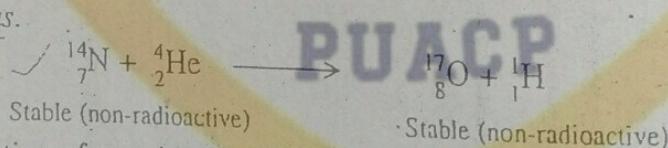


(ii) Artificial transmutation or artificial disintegration. In this transmutation, a (non-radioactive) element is converted into another stable element by bombarding it with bombarding particles like α -particles, protons, deuterons etc. The bombarding particles are called many other names like *incidents, atomic projectiles, bullets* etc. Examples are

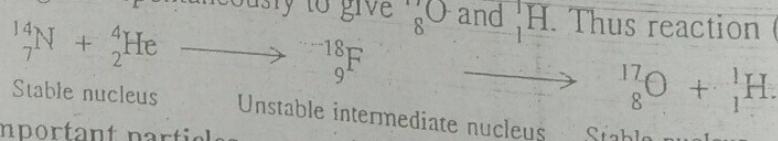


Discovery of artificial transmutation

It was for the first time in 1919 when Rutherford showed that when nitrogen atom $^{14}_7\text{N}$ (which is a stable element) is bombarded by energised α -particles, it is converted into $^{17}_8\text{O}$ atom and proton (^1_1H) is emitted. $^{17}_8\text{O}$ is also a stable element. $^{14}_7\text{N}$ nucleus is called target nucleus while $^{17}_8\text{O}$ is called recoil nucleus.



Explanation of reaction (i). Rutherford proved by experiments that in reaction (i) α -particle captured by $^{14}_{7}\text{N}$ nucleus and unstable intermediate nucleus namely $^{18}_{9}\text{F}$ is formed. $^{18}_{9}\text{F}$, being unstable, disintegrates spontaneously to give $^{17}_{8}\text{O}$.



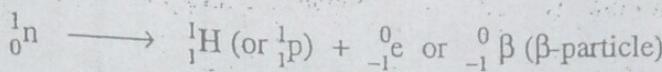
Some important particles

Before we study nuclear reactions, it is essential for us to know the symbol, mass number, charge (atomic number) etc. of some particles which we shall be using again and again during discussion. The following are important particles:

(i) Alpha particle [${}^4\text{He}$ or ${}^4\text{H}_2$]

neutrons. Thus its symbol is ${}_{+2}^4\text{He}$ or ${}_{+2}^4\text{He}$, showing that its mass number (A) is 4 and charges (atomic number) on it are +2, i.e., $A = 4 = 2p + 2n$ and $Z = 2$.

(ii) Beta particle $[{}_{-1}^0\beta \text{ or } {}_{-1}^0e]$. It is an electron and hence is represented by the symbol ${}_{-1}^0\beta$ or ${}_{-1}^0e$. Its mass number (A) = 0 and charges or atomic number = -1. The nucleus of an atom does not contain a β -particle or an electron as such. It is produced when a neutron (${}_{0}^1n$) is converted into a proton (${}_{1}^1H$ or ${}_{1}^1p$).



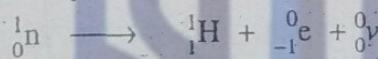
(iii) γ -ray $[{}_{0}^0\gamma]$. It is an electromagnetic radiation of very short wave length. Its mass number and charges (atomic number) on it both are zero. Thus γ -ray is neutral and massless ray and hence is represented as ${}_{0}^0\gamma$.

(iv) Deuteron $[{}_{+1}^2H \text{ or } {}_{+1}^2H \text{ or } {}_{+1}^2D \text{ or } {}_{+1}^2D]$. It is the nucleus of heavy hydrogen atom called deuterium. Its mass number (A) = 2 and atomic number (Z) = 1.

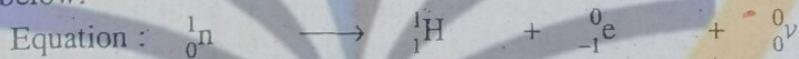
(v) Triton $[{}_{+1}^3H \text{ or } {}_{+1}^3H \text{ or } {}_{+1}^3T \text{ or } {}_{+1}^3T]$. It is the nucleus of heavy hydrogen atom called tritium. Its mass number (A) = 3 and atomic number (Z) = 1.

(vi) Neutrino $[{}_{0}^0\nu]$. It is a nuclear particle having no mass and charge. Thus its mass number and atomic number both are equal to zero. The mass of this particle is equal to zero. Actual mass of this particle is 0.00002 with respect to O - 16 scale.

It was assumed by Pauli that this particle is emitted when a neutron (${}_{0}^1n$) is converted into a proton (${}_{1}^1H$) and a β -particle (${}_{-1}^0e$).

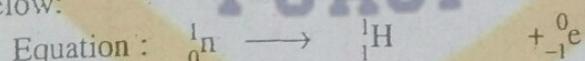


The above equation is balanced in so far as angular momentum values of different particles is concerned, as shown below:



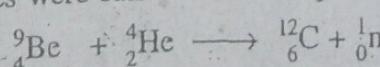
$$\text{Angular momentum values : } +\frac{1}{2} \cdot \frac{h}{2\pi} + \frac{1}{2} \cdot \frac{h}{2\pi} - \frac{1}{2} \cdot \frac{h}{2\pi} + \frac{1}{2} \cdot \frac{h}{2\pi}$$

If ${}_{0}^0\nu$ is supposed to be emitted in the above reaction, angular momentum values are not balanced as shown below:



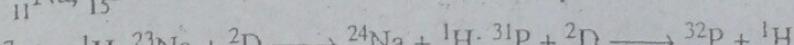
$$\text{Angular momentum values : } +\frac{1}{2} \cdot \frac{h}{2\pi} + \frac{1}{2} \cdot \frac{h}{2\pi} - \frac{1}{2} \cdot \frac{h}{2\pi}$$

(vii) Neutron (${}_{0}^1n$). In 1931 Chadwick showed that when beryllium nucleus, ${}_{+4}^9\text{Be}$ is bombarded by α -particles (${}_{+2}^4\text{He}$), penetrating rays are obtained. He studied the characteristics of these rays and suggested that these rays are composed of *neutral particles* whose mass is equal to that of H-atom (i.e., equal to 1). These particles were called *neutrons* by him and denoted as ${}_{0}^1n$.

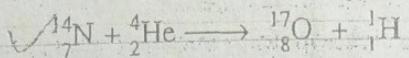


Neutrons can also be obtained by many other nuclear reactions.

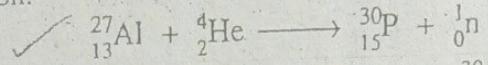
(viii) Proton (${}_{+1}^1H$ or ${}_{+1}^1H$ or ${}_{+1}^1p$). It is the nucleus of ordinary hydrogen atom. Its mass number is 1 and charge equal to +1. This particle is present in the nucleus of the atom of all elements. Its presence in the nucleus was realised by its production in the nuclear reaction in which lighter elements like ${}_{+3}^{11}\text{Li}$, ${}_{+11}^{23}\text{Na}$, ${}_{+15}^{31}\text{P}$ etc. are bombarded by deuteron (${}_{+1}^2D$).



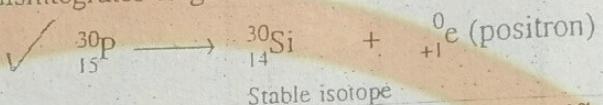
and in Rutherford's artificial transmutation reaction (1919) in which he bombarded ^{14}N nucleus with α -particles



(ix) Positron. (${}_{+1}^0\text{e}$). It is a counterpart of an electron which has $+1$ charge and negligible mass (Actual mass = 0.0005486 amu). Thus it is a positive electron. This particle was discovered by Curie and her husband (name-Frederick Joliot) in 1934. They bombarded Al-27 isotope (non-radioactive isotope) with α -particles so that it was converted into radioactive P-30 isotope with emission of a neutron.



Being radioactive, P-30 disintegrates to give stable ${}^{30}_{14}\text{Si}$ isotope and positron (${}_{+1}^0\text{e}$).



Positron has also been obtained in many nuclear reactions. (See "artificial radioactivity")

Some important projectiles and projectile accelerators

α -particle (${}^4_2\text{He}$ or ${}^4_4\text{He}$), proton (${}_{+1}^1\text{H}$ or ${}^1_1\text{H}$), deuteron (${}^2_1\text{H}$ or ${}^2_2\text{H}$), neutron (${}^1_0\text{n}$) etc. are important fundamental projectiles which are generally used in the transmutation of different elements. Since α -particles have positive charge equal to $+2$, they are repelled by the nucleus when they hit the positively-charged nucleus and hence do not prove to be good projectiles. It has been seen that hardly one α -particle in a million may hit the nucleus. Protons and deuterons will have less positive charge ($+1$) than an α -particle (positive charge = $+2$) are better projectiles than α -particle. Neutrons (${}^1_0\text{n}$) are the most effective projectiles, since they do not contain any charge.

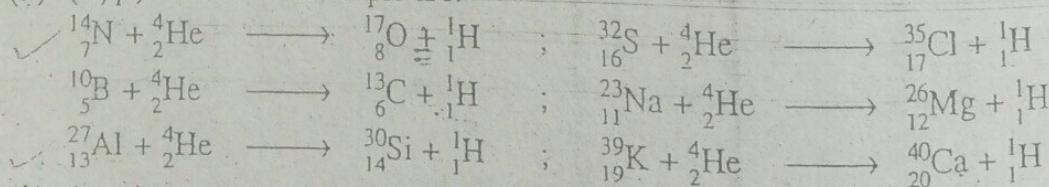
The positively-charged α -particles, protons and deuterons can be made to act as more effective projectiles, if their velocity is accelerated. For this purpose, several instruments have been developed. These instruments are called projectile accelerators. Some such instruments are cyclotron (made by E.O. Lawrence at the university of California, U.S.A), Van de Graaf generator, betatron, electron and proton synchrotron etc. In cyclotron the projectile particles are made to follow a spiral path under the combined high frequency a.c. voltage of the order of up to 2×10^4 volts. The particles finally leave the instrument with a velocity of about 40,000 Km per second.

Artificial transmutation reactions induced by different bombarding projectiles

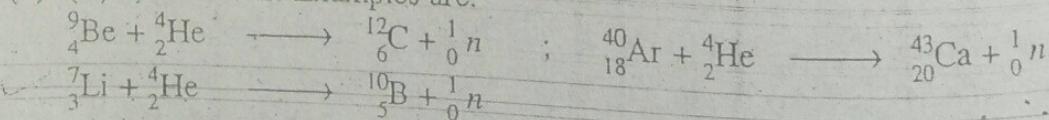
Artificial transmutation reactions induced by different bombarding particles may be of the following types:

1. Artificial transmutation reactions induced by α -particles (${}^4_2\text{He}$). These reactions may be of the following types:

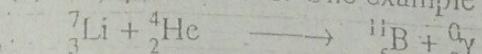
(a) (α, p) reactions. Examples are:



(b) (α, n) reactions. Examples are:



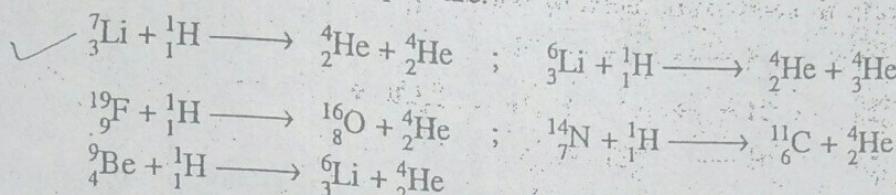
(c) (α, γ) reactions. One example of such reactions is given below:



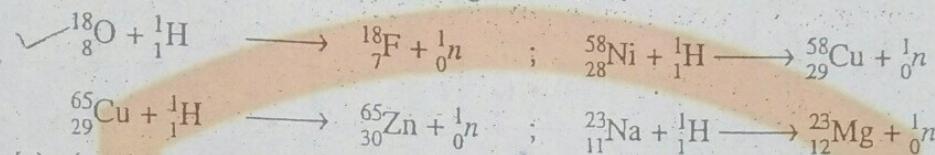
Radioactivity

2. Artificial transmutation reactions induced by protons (1H). These reactions may be of the following types:

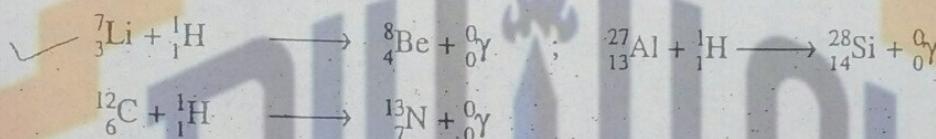
(a) (p, α) reactions. Examples are:



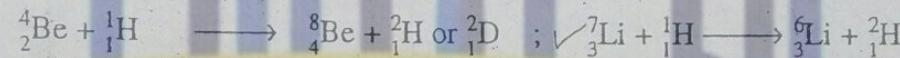
(b) (p, n) reactions. Examples are given below:



(c) (p, γ) reactions. Examples are given below:

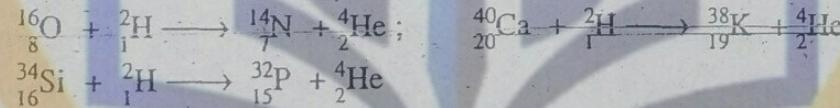


(d) (p, D) reactions. Examples are:



3. Artificial transmutation reactions induced by deuterons (2H or 2D). These reactions may be of the following types:

(a) (D, α) reactions: ${}_{3}^6Li + {}_{1}^2H \longrightarrow {}_{2}^4He + {}_{2}^4He$ (D, 2 α type)

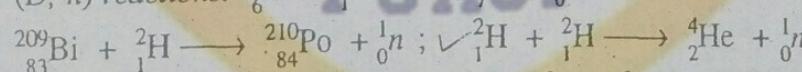


(b) (D, p) reactions: ${}_{15}^{31}P + {}_{1}^2H \longrightarrow {}_{15}^{32}P + {}_1^1H$

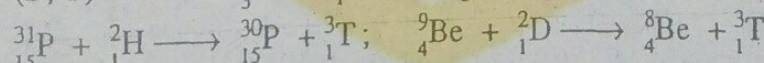


$\checkmark {}_3^6Li + {}_{1}^2H \longrightarrow {}_3^7Li + {}_1^1H$

(c) (D, n) reactions: ${}_{6}^{12}C + {}_{1}^2H \longrightarrow {}_{7}^{13}N + {}_0^1n$

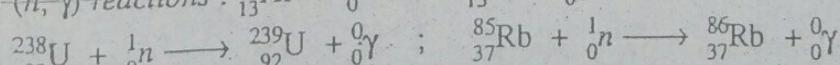


(d) (D, T) reactions: ${}_{3}^7Li + {}_{1}^2H \longrightarrow {}_3^6Li + {}_{1}^3H \text{ or } {}_{1}^3T$

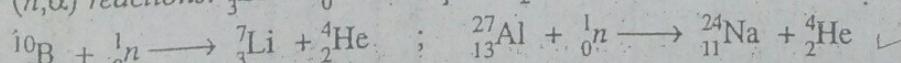


4. Artificial transmutation reactions induced by neutrons (1n). Examples are:

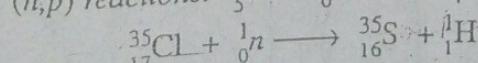
(a) (n, γ) reactions: ${}_{13}^{27}Al + {}_0^1n \longrightarrow {}_{13}^{28}Al + {}_0^0\gamma$



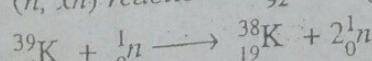
(b) (n, α) reactions: ${}_{3}^6Li + {}_0^1n \longrightarrow {}_1^3H + {}_2^4He$



(c) (n, p) reactions: ${}_{5}^{11}B + {}_0^1n \longrightarrow {}_{4}^{11}Be + {}_1^1H$

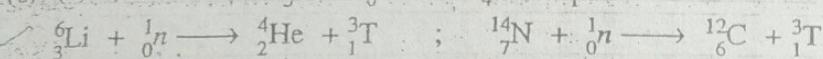
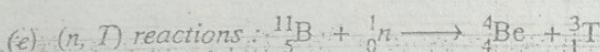


(d) (n, xn) reactions: ${}_{92}^{235}U + {}_0^1n \longrightarrow {}_{56}^{139}Ba + {}_{36}^{94}Kr + 3 {}_0^1n$

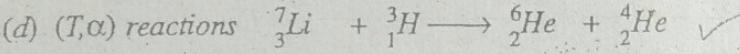
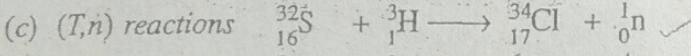
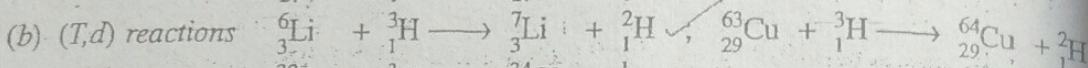
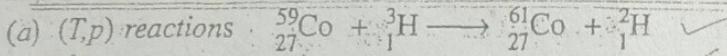


Thus the bond length of Li_2 is 1.5 Å. Example 6.21
 (a) ${}_{14}^7\text{Li}$
 (b) ${}_{10}^3\text{Li}$
 (c) ${}_{15}^5\text{Li}$
 (d) ${}_{17}^{35}\text{Li}$

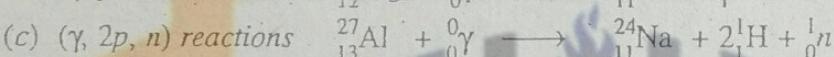
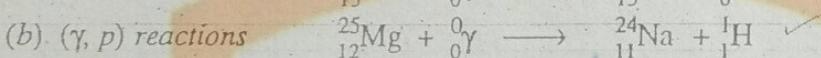
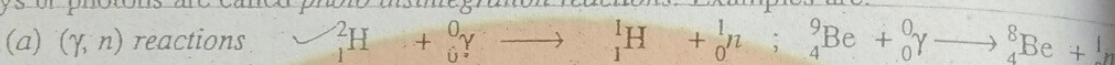
Solution.



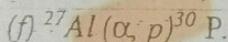
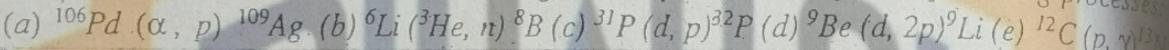
5. Artificial transmutation reactions induced by tritons (${}^3\text{H}$ or ${}^3\text{T}$). Examples are:



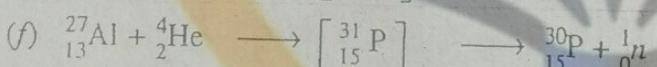
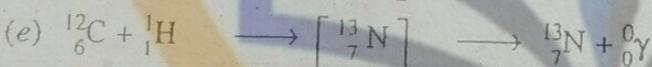
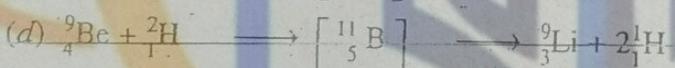
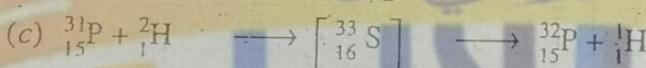
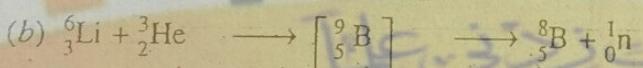
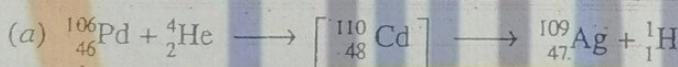
6. Artificial transmutation reactions induced by γ -rays (${}^0\gamma$). Nuclear reactions induced by γ -rays or photons are called *photo disintegration reactions*. Examples are:



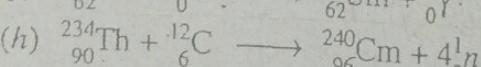
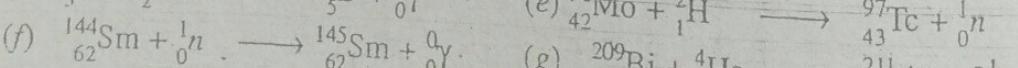
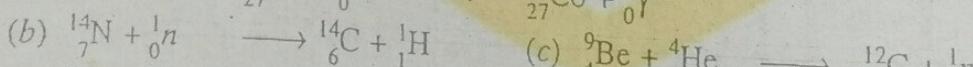
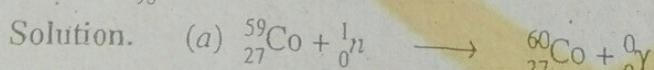
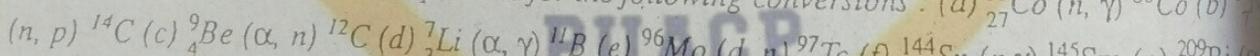
Example 6.27. State the reactions including the compound nuclei for the following processes:



Solution. We have:

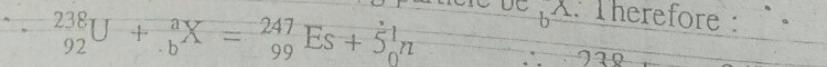


Example 6.28. Construct equations for the following conversions : (a) ${}^{59}_{27}\text{Co} (n, \gamma) {}^{60}_{27}\text{Co}$ (b) ${}^{14}_7\text{N} (n, p) {}^{14}_6\text{C}$



Example 6.29. The nuclide ${}^{247}_{99}\text{Es}$ can be obtained by bombardment of ${}^{238}_{92}\text{U}$ in a reaction that emits five neutrons. Identify the bombarding particle.

Solution. Let the bombarding particle be ${}^a_b\text{X}$. Therefore :



$$\text{or } a = (247 + 5) - 238 = 14;$$

$$92 + b = 99$$

$$\therefore b = 99 - 92 = 7$$

Application

Some

1. Di

reactions h

neutrons,

has been

in

the

reaction

is

the

reaction

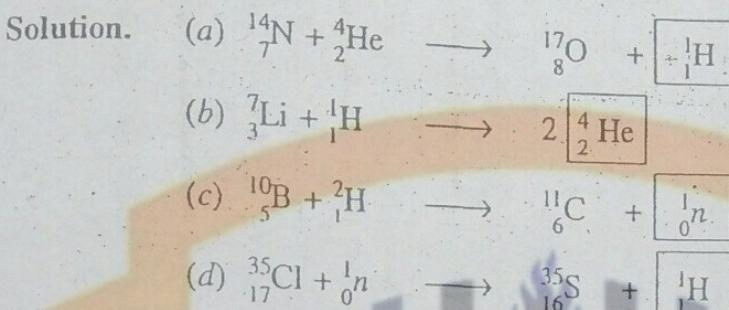
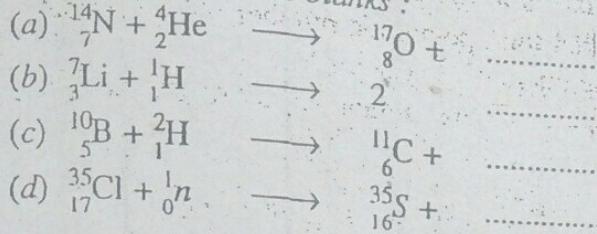
is

the

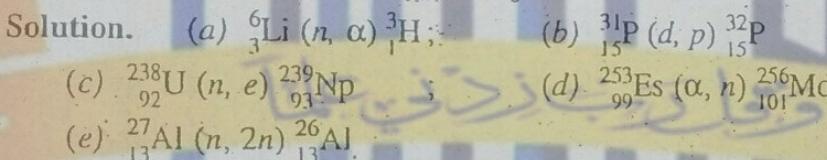
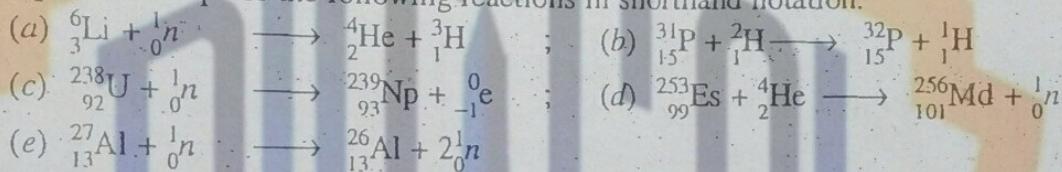
reaction

Thus the bombarding particle is ^{14}N .

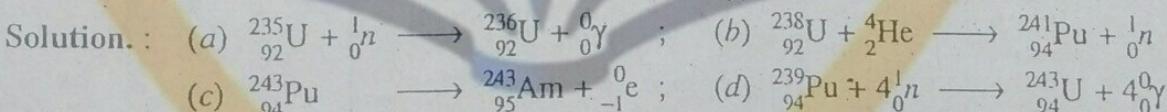
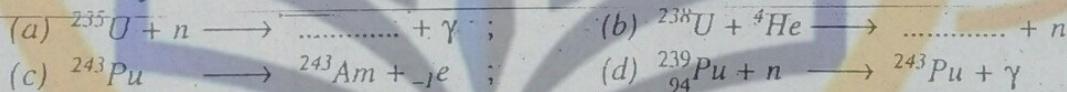
Example 6.30. Fill in the blanks:



Example 6.31. Express the following reactions in shorthand notation.



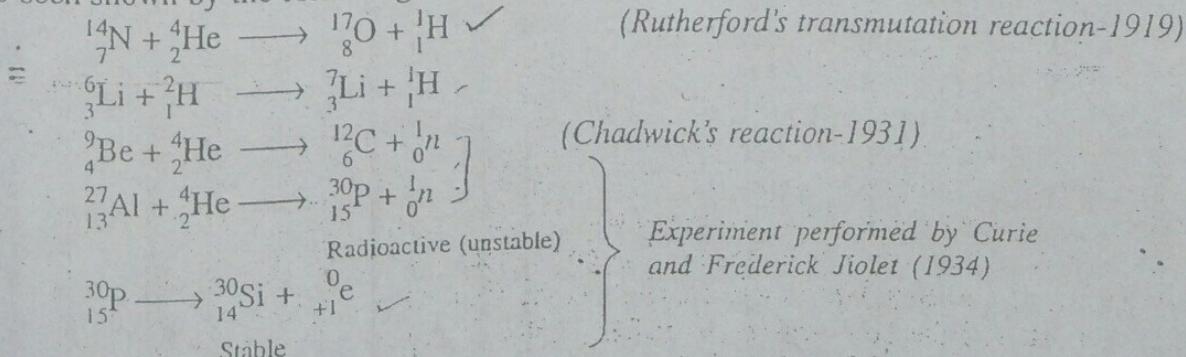
Example 6.32. Complete the following reactions, giving the mass number and atomic number wherever necessary.



Applications of artificial transmutation reactions (artificial radioactivity)

Some of the applications of artificial transmutation reactions are discussed below:

1. **Discovery of new fundamental particles and their uses.** The study of transmutation reactions has enabled us to discover new fundamental particles like α -particles, protons, deuterons, neutrons, tritons, γ -rays, positrons etc. The discovery of protons (${}_1^1\text{H}$), neutrons (${}_0^1n$) and positron (${}_{+1}^0e$) has been shown by the following nuclear reactions:

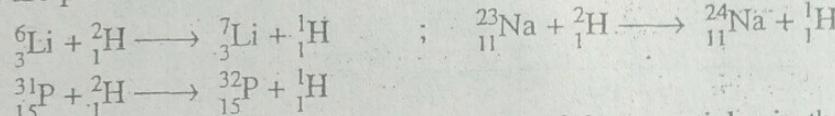


The discovery of these particles has added to our knowledge of the composition of the nucleus. For example:

(a) The scattering of α -particles seen by Rutherford in his α -particle scattering experiment

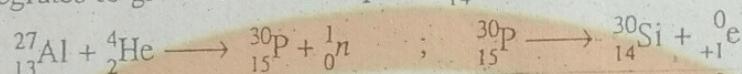
* ~~deflected~~ proved the existence of positively charged nucleus at the centre of the atom of all elements. The extent of deflection of α -particles has established that the atomic number of an element is numerically equal to the nuclear charge carried by the nucleus.

(b) When lighter elements like ${}^6\text{Li}$, ${}^{23}\text{Na}$, ${}^{31}\text{P}$ etc. are bombarded by means of deuterons (${}^2\text{H}$) protons (${}^1\text{H}$) are produced.



The production of protons confirms the presence of these particles in the nucleus.

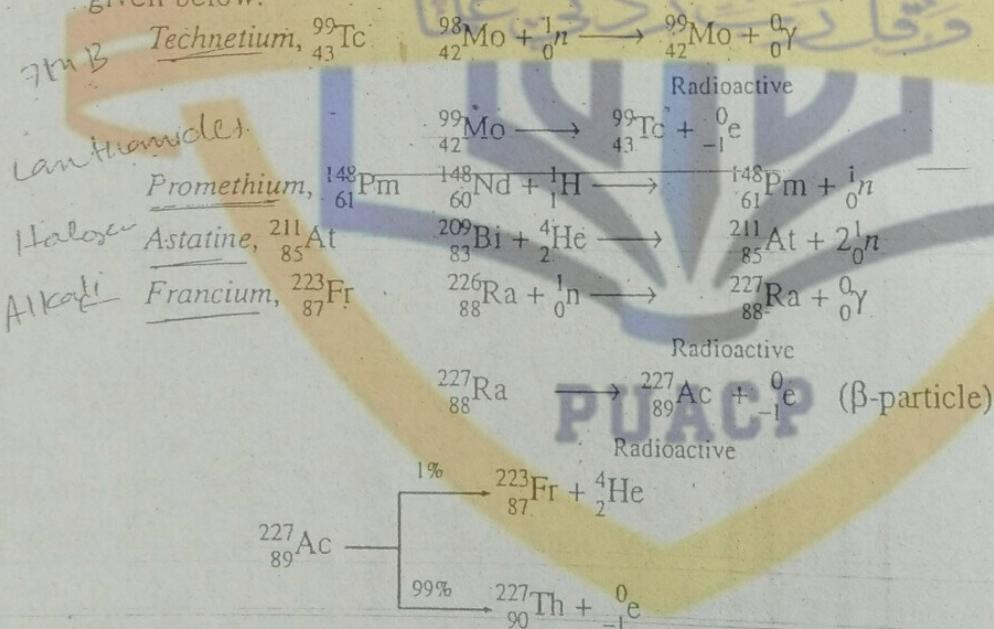
(c) The bombardment of ${}^{27}\text{Al}$ isotope by α -particles produces ${}^{30}\text{P}$ which is radioactive and hence disintegrates to give a stable isotope of ${}^{30}\text{Si}$ with the emission of positrons (${}_{+1}^0\text{e}$).



The production of positrons in this way reveals the presence of these particles in the nucleus.

2. Preparation of isotopes of various elements. Examples showing the use of artificial transmutation reactions for the preparation of isotopes of elements are given below:

(a) Preparation of missing elements. When Mendeleef arranged the elements in the form of a periodic table (Mendeleef periodic table), he left four gaps in it. These gaps were left for the elements with atomic numbers 43, 61, 85 and 87, since these elements were not known at the time. He called these elements as missing elements. After a few years, radioactive isotopes of these elements were synthesised by using artificial transmutation reactions and were characterised. These elements were named as technetium, $\text{Tc}(Z = 43)$, promethium, $\text{Pm}(Z = 61)$, astatine, $\text{At}(Z = 85)$ and francium, $\text{Fr}(Z = 87)$ respectively. The synthesis of these elements is given below:



The missing elements whose preparation is given above have been identified and have been given proper place in the periodic table. ${}_{87}\text{Fr}$ has been placed along with alkali metals in group I, ${}_{43}\text{Tc}$ has been placed in group VII B under ${}_{25}\text{Mn}$ (transition elements), ${}_{85}\text{At}$ has been put in group VIIA along with halogens and ${}_{61}\text{Pm}$ has been placed along with lanthanides.

(b) Preparation of trans-uranic elements. Thirteen elements with atomic numbers 93 to 105 are called trans-uranic elements, since these elements come after ${}_{92}\text{U}$ in actinide series. By changing the target element and the bombarding projectiles, various isotopes of these elements have been obtained in sub-microgram quantities (10^{-5} g to 10^{-6} g) by artificial transmutation reactions and have been characterised. The synthesis of these elements is shown below:

Target element	Bombarding projectile	Product
$^{238}_{92}\text{U}$	+ ^1H	$^{239}_{93}\text{Np} (\text{Neptunium}) + 2^1n$
$^{239}_{92}\text{U}$	+ ^2He	$^{240}_{94}\text{Pu} (\text{Plutonium}) + 2^1n$
$^{239}_{94}\text{Pu}$	+ ^2He	$^{241}_{95}\text{Am} (\text{Americium}) + ^1\text{H} + 1^1n$
$^{239}_{94}\text{Pu}$	+ ^2He	$^{240}_{96}\text{Cm} (\text{Curium}) + 3^1n$
$^{244}_{96}\text{Cm}$	+ ^2He	$^{245}_{97}\text{Bk} (\text{Berkelium}) + ^1\text{H} + 2^1n$
$^{238}_{92}\text{U}$	+ ^{12}C	$^{245}_{98}\text{Cf} (\text{Californium}) + 5^1n$
$^{238}_{92}\text{U}$	+ ^{14}N	$^{247}_{99}\text{Es} (\text{Einsteinium}) + 5^1n$
$^{238}_{92}\text{U}$	+ ^{16}O	$^{250}_{100}\text{Fm} (\text{Fermium}) + 4^1n$
$\rightarrow 253_{99}\text{Es}$	+ ^2He	$^{256}_{101}\text{Md} (\text{Mendelevium}) + 1^1n$
$\rightarrow 246_{95}\text{Cm}$	+ ^{13}C	$^{251}_{102}\text{No} (\text{Nobelium}) + 8^1n$
$\rightarrow 252_{98}\text{Cf}$	+ ^{10}B	$^{257}_{103}\text{Lw} (\text{Lawrencium}) + 5^1n$
$\rightarrow 242_{92}\text{Pu}$	+ ^{12}Ne	$^{260}_{104}\text{Ku} (\text{Kurchatovium}) + 4^1n$
$\rightarrow 249_{98}\text{Cf}$	+ ^{15}N	$^{266}_{105}\text{Ha} (\text{Hahnium}) + 4^1n$

(c) Preparation of radioactive and non-radioactive isotopes: Discovery of isotopes. Artificial transmutation reactions have been used to prepare many radioactive isotopes (e.g. Na-24, Co-60, C(Z = 43), promethium-30, P-32 etc.) which have been used as radioactive tracers in various processes met with in medical field, agriculture, industry, analytical chemistry etc. The preparation of some radioactive isotopes are given below. These are the examples of induced radioactivity.

Non-radioactive (stable) isotope	Bombarding projectile	Radioactive (unstable) isotope
$^{23}_{11}\text{Na}$	+ ^1H	$^{24}_{12}\text{Na} + ^1\text{H}$
$^{27}_{13}\text{Al}$	+ 1n	$^{24}_{13}\text{Na} + ^2\text{He}$
$^{59}_{27}\text{Co}$	+ 1n	$^{60}_{27}\text{Co}$
$^{27}_{13}\text{Al}$	+ ^2He	$^{36}_{15}\text{P} + ^1n$
$^{32}_{16}\text{S}$	+ 1n	$^{33}_{15}\text{P} + ^1\text{H}$
$^{14}_{7}\text{N}$	+ 1n	$^{14}_{6}\text{C} + ^1\text{H}$
$^{10}_{5}\text{B}$	+ ^2He	$^{13}_{7}\text{N} + ^1n$

Transmutation reactions have also been used to convert stable isotope of an element into stable isotope of another element. For example :

Stable isotope (Non-radioactive isotope)	Bombarding projectile	Stable isotope (Non-radioactive isotope)
$=^{14}_{7}\text{N}$	+ ^2He	$^{17}_{8}\text{O} + ^1\text{H}$
$^{10}_{5}\text{B}$	+ ^2He	$^{13}_{6}\text{C} + ^1\text{H}$
$^{23}_{11}\text{Na}$	+ ^2He	$^{26}_{12}\text{Mg} + ^1\text{H}$
$^{27}_{13}\text{Al}$	+ ^2He	$^{30}_{14}\text{Si} + ^1\text{H}$
$^{32}_{16}\text{S}$	+ ^2He	$^{35}_{17}\text{Cl} + ^1\text{H}$
$^{39}_{19}\text{K}$	+ ^2He	$^{40}_{20}\text{Ca} + ^1\text{H}$

3. Release of atomic energy in nuclear fission and nuclear fusion reactions. A large amount of energy (called atomic energy or nuclear energy) is released in nuclear fission and nuclear fusion

processes. This energy has been put to peaceful uses like the production of electricity or it can be used for the destructive purposes of making an atom bomb.

Natural and artificial radioactive series

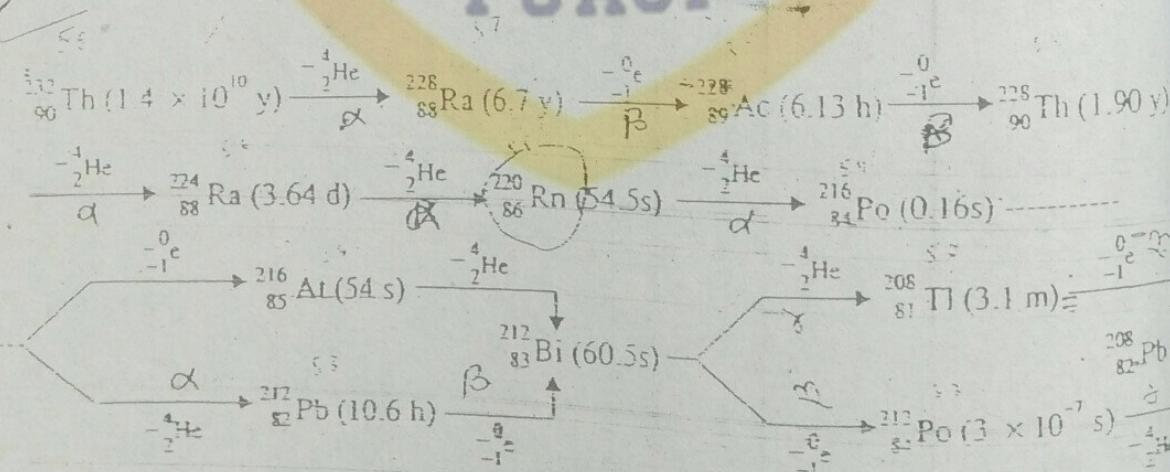
The isotopes of naturally occurring heavy elements like $^{235}_{92}\text{Th}$, $^{235}_{92}\text{U}$, $^{238}_{92}\text{U}$ etc. are unstable hence are constantly emitting α and β particles and giving rise to the formation of new radioactive elements. Being radioactive, these new elements spontaneously disintegrate and give a series of elements until a stable (i.e., non-radioactive) element (usually lead) is obtained. The series of elements thus obtained by the successive disintegration of the new radioactive elements is known as radioactive series. The series obtained by the emission of α and β particles from $^{232}_{90}\text{Th}$, $^{238}_{92}\text{U}$ and $^{235}_{92}\text{U}$ are called natural radioactive series. Obviously there are three natural radioactive series. In addition to the natural radioactive series, there is another series which has been obtained by emission of α and β particles from the artificially prepared $^{237}_{93}\text{Np}$ isotope. This series is called artificial radioactive series or neptunium-237 or $(4n+1)$ series.

Natural radioactive series

As already said, the series obtained by the emission of various α and β particles from $^{232}_{90}\text{Th}$, $^{238}_{92}\text{U}$ and $^{235}_{92}\text{U}$ are called natural radioactive series. Obviously these series are of three types as shown below.

(i) Thorium-232 or $4n$ series ($^{232}_{90}\text{Th} \rightarrow ^{208}_{82}\text{Pb}$). This series starts from $^{232}_{90}\text{Th}$ (parent element) and ends at $^{208}_{82}\text{Pb}$ (end element) which is a stable element. The parent element viz. $^{232}_{90}\text{Th}$ decays into $^{228}_{88}\text{Ra}$ by emitting a α -particle. $^{228}_{88}\text{Ra}$ emits a β -particle to form $^{228}_{89}\text{Ac}$ which again emits a β -particle to become $^{228}_{90}\text{Th}$. This disintegration process goes on proceeding continuously until stable end product viz. $^{208}_{82}\text{Pb}$ is obtained (See Table 6.3). The mass number of different members of this series is equal to $4n$ where n is a whole number whose value is different for different members of the series. The value of n for the parent element ($^{232}_{90}\text{Th}$) and end element ($^{208}_{82}\text{Pb}$) is $232/4 = 58$ and $208/4 = 52$ respectively. If the mass number of different members is divided by 4, the remainder obtained is equal to zero. Number of α and β particles emitted in the conversion of Th to Pb can be calculated with the help of the equations $232 - 4x = 208$ and $90 - 2x + y = 82$. These equations give x (number of α -particles) = 6 and y (number of β -particles) = 4. Half-life period of each member is given in bracket (y = years, d = days, h = hours, m = minutes and s = seconds).

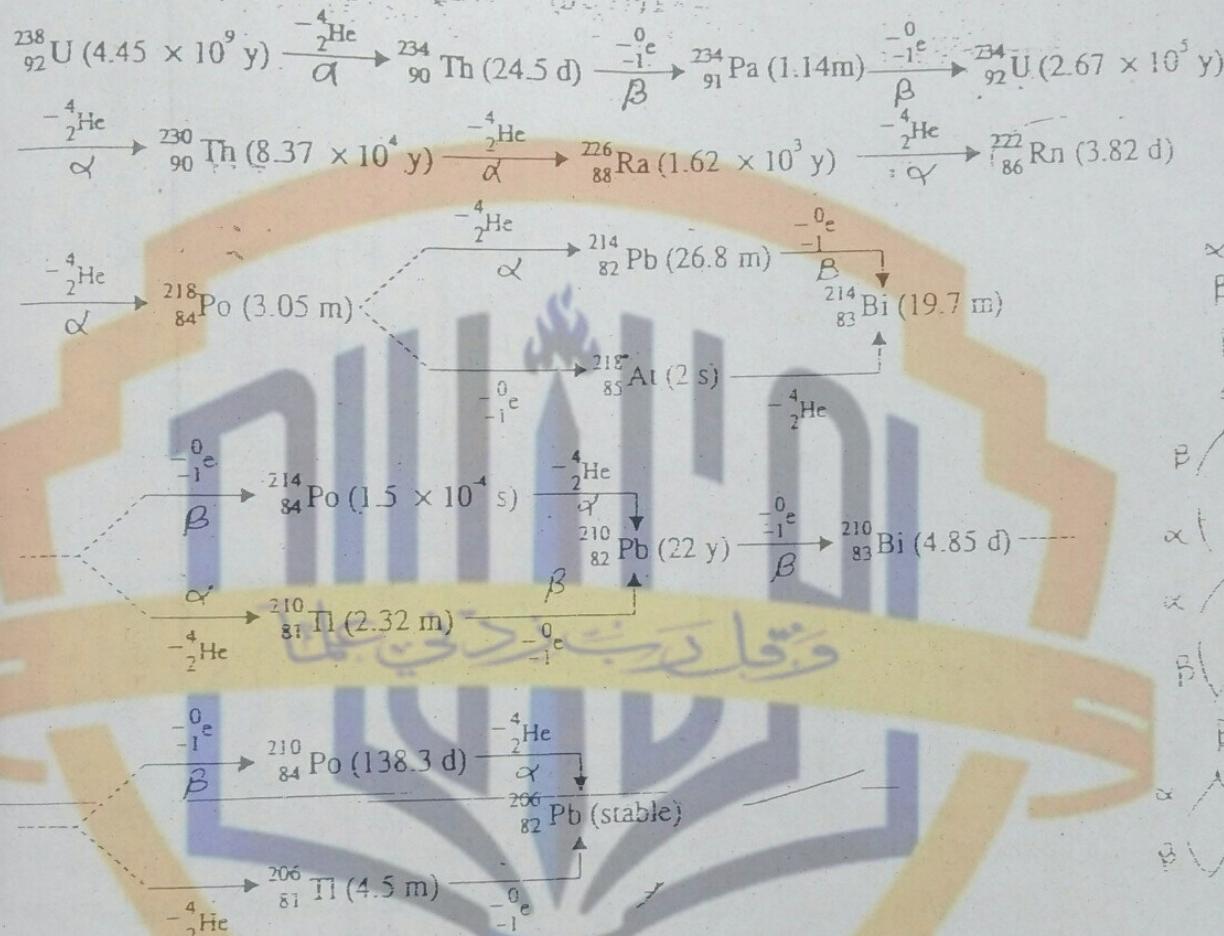
Table 6.3: Thorium-232 or $4n$ series (natural radioactive series $^{232}_{90}\text{Th} \rightarrow ^{208}_{82}\text{Pb}$ series)



(ii) Uranium-238 or $(4n+2)$ series ($^{238}_{92}\text{U} \rightarrow ^{208}_{82}\text{Pb}$). This series has $^{238}_{92}\text{U}$ as its parent element and $^{208}_{82}\text{Pb}$ as its final (stable) product (See Table 6.4). The mass number of different members is $(4n+2)$ which on being divided by 4, gives 2 as the remainder. This means that the value of n for $^{238}_{92}\text{U}$ and

is equal to $\frac{238 - 2}{4} = 59$ and $\frac{206 - 2}{4} = 51$ respectively. The number of α and β particles emitted by $^{238}_{92}\text{U}$ to form $^{206}_{82}\text{Pb}$ can be calculated by the equations $238 - 4x = 206$ and $92 - 2x + y = 82$. These equations give x (i.e., number of α -particles) = 8 and y (i.e., number of β -particles) = 6.

Table 6.4: Uranium-238 or $(4n+2)$ series (Natural radioactive series) [$^{238}_{92}\text{U} - ^{206}_{82}\text{Pb}$ series]

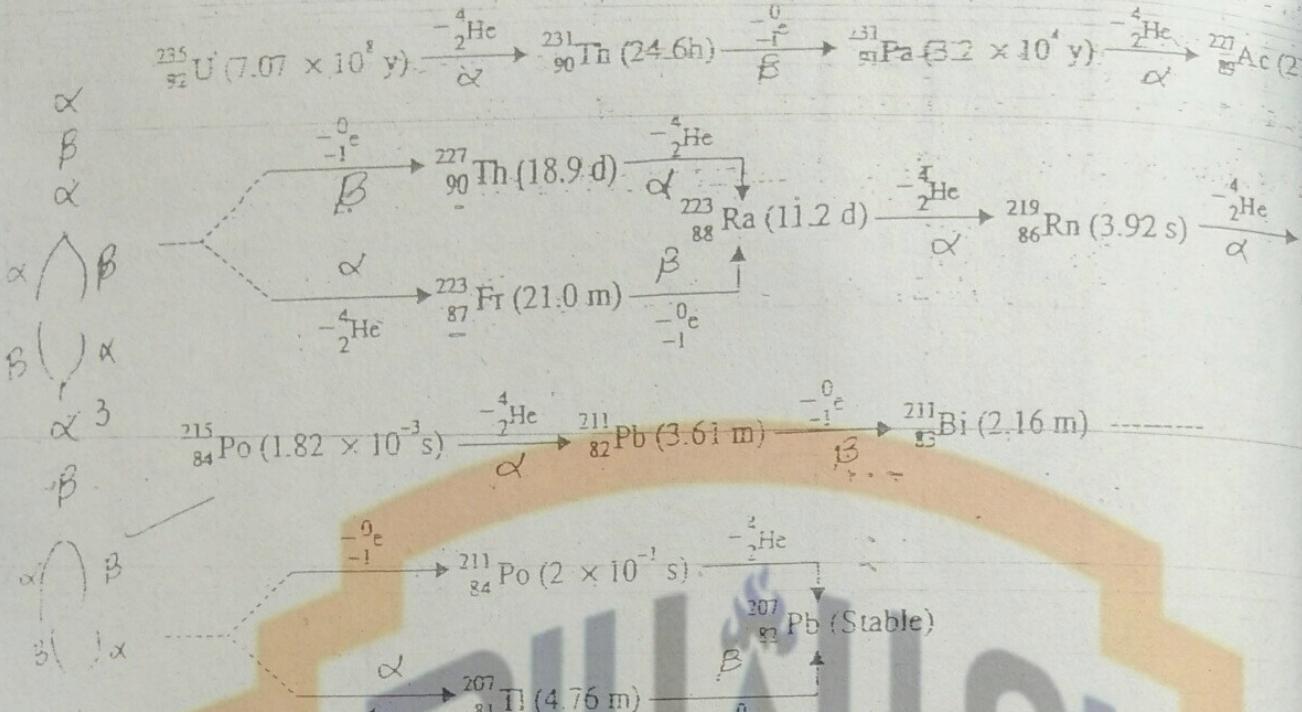


(iii) Uranium-235 or $(4n + 3)$ series [$^{235}_{92}\text{U} - ^{207}_{82}\text{Pb}$ series]. This series starts with $^{235}_{92}\text{U}$ and ends at $^{207}_{82}\text{Pb}$ which is a stable element. If the mass number of each member of this series is divided by 4, then 3 is obtained as a remainder. This means that the value of n for $^{235}_{92}\text{U}$ and $^{207}_{82}\text{Pb}$ is equal to $\frac{235 - 3}{4} = 58$ and $\frac{207 - 3}{4} = 51$ respectively. The number of α and β particles emitted in the series can be calculated by using the equations $235 - 4x = 207$ and $92 - 2x + y = 82$. On solving, we get $x = 7$ and $y = 4$, where x and y are the number of α and β particles. (See table 6.5).

Similarities between the natural radioactive series

- In all the three natural radioactive series, sometimes a product is formed which disintegrates in a branching way by emitting one α and one β particle and thus produces two elements. These two elements are then converted into a common element when one of them emits a α -particle and the other emits a β -particle.
- In all the series an element with atomic number 86 ($_{86}\text{Rn}$) is produced. This element has the properties of an inert gas and is called emanation.
- The end product obtained in each series is a stable isotope of lead which may be $^{208}_{82}\text{Pb}$, $^{206}_{82}\text{Pb}$ or $^{207}_{82}\text{Pb}$.

Table 6.5: Uranium -235 or ($4n+3$) series (Natural radioactive series) $[^{235}_{92}\text{U} \rightarrow ^{209}_{82}\text{Pb}$ series]

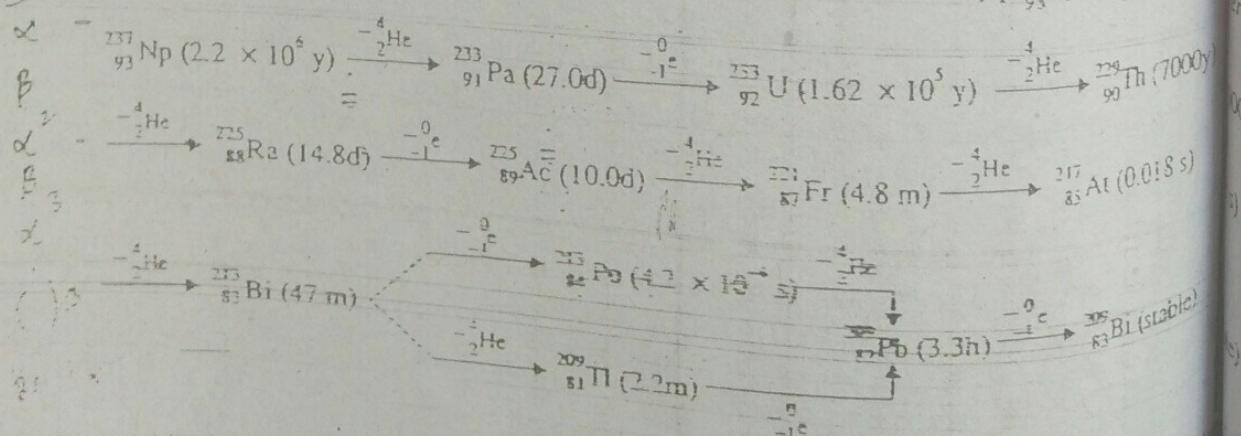


Neptunium-237 or ($4n+1$) series ($^{237}_{93}\text{Np} \rightarrow ^{209}_{83}\text{Bi}$ Series) : Artificial radioactive series

This series was discovered after the discovery of trans-uranic elements. The possibility of existence of this series was suggested by A.S. Russell in 1923 and later on it was discovered by Turner in 1940. The members of this series do not occur in nature. As a matter of fact, all members have been obtained by artificial methods in the laboratory.

This series starts with $^{237}_{93}\text{Np}$ (parent element : longest lived element) and ends at $^{209}_{83}\text{Bi}$ (end element which is a stable element). The parent element viz. $^{237}_{93}\text{Np}$ decays into $^{233}_{91}\text{Pa}$ by emitting an α -particle, emits a β -particle to form $^{231}_{92}\text{U}$ and so on until a stable end product viz. $^{209}_{83}\text{Bi}$ is obtained (See Table 6.6). The mass number of different members of this series is equal to $(4n+1)$ which shows that if the mass number is divided by 4, the remainder obtained is equal to 1. Mass number equal to $(4n+1)$ also means that the value of n for $^{237}_{93}\text{Np}$ and $^{209}_{83}\text{Bi}$ is equal to $\frac{237-1}{4}=59$ and $\frac{209-1}{4}=52$ respectively. The members of this series are not found in nature, since the half-life period of its longest-lived member viz. $^{237}_{93}\text{Np}$ ($= 2.2 \times 10^6$ years) is much less than the age of the earth ($= 5 \times 10^9$ years). The number of α and β particles emitted in the transmutation of $^{237}_{93}\text{Np}$ to $^{209}_{83}\text{Bi}$ can be calculated with the help of the equations $237 - 4x = 209$ and $93 + y = 83$, which give $x = 7$ and $y = 4$ where x and y denote the number of α - and β -particles.

Table 6.6: Neptunium or ($4n+1$) series (Artificial radioactive series) $[^{237}_{93}\text{Np} \rightarrow ^{209}_{83}\text{Bi}$ series]



Summary

Summary of all the four radioactive series is given below:

Series	Parent element of the series	End element of the series	No. of particles emitted		Value of n for the parent element of the series	Value of n for the end element of the series
			α	β		
(A) Natural radioactive series						
(i) Thorium-232 or $4n$ series [$^{232}_{90}\text{Th} - ^{208}_{82}\text{Pb}$ series]	$^{232}_{90}\text{Th}$	$^{208}_{82}\text{Pb}$	6	4	$\frac{232}{4} = 58$ [$^{232}_{90}\text{Th}$]	$\frac{208}{4} = 52$ [$^{208}_{82}\text{Pb}$]
(ii) Uranium-238 or $(4n + 2)$ series [$^{238}_{92}\text{U} - ^{206}_{82}\text{Pb}$ series]	$^{238}_{92}\text{U}$	$^{206}_{82}\text{Pb}$	8	6	$\frac{238 - 2}{4} = 59$ [$^{238}_{92}\text{U}$]	$\frac{206 - 2}{4} = 51$ [$^{206}_{82}\text{Pb}$]
(iii) Uranium-235 or $(4n + 3)$ series [$^{235}_{92}\text{U} - ^{207}_{82}\text{Pb}$ series]	$^{235}_{92}\text{U}$	$^{207}_{82}\text{Pb}$	7	4	$\frac{235 - 3}{4} = 58$ [$^{235}_{92}\text{U}$]	$\frac{207 - 3}{4} = 51$ [$^{207}_{82}\text{Pb}$]
(B) Artificial radioactive series : Neptunium-237 or $(4n + 1)$ series [$^{237}_{93}\text{Np} - ^{209}_{83}\text{Bi}$ series]	$^{237}_{93}\text{Np}$	$^{209}_{83}\text{Bi}$	7	4	$\frac{237 - 1}{4} = 59$ [$^{237}_{93}\text{Np}$]	$\frac{209 - 1}{4} = 52$ [$^{209}_{83}\text{Bi}$]

Use of radioactive series: Discovery of isotopes and isobars

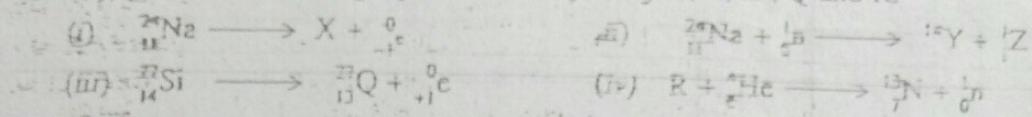
For the first time, it was during the study of radioactive series that the existence of isotopes and isobars was realised. Thus radioactive series became a source of the discovery of isotopes and isobars. In 1919, Thomson showed that it is not only radioactive elements that give isotopes; non-radioactive elements (stable isotopes) also exist as isotopes.

University Questions

1. **Ques:** Define radioactivity. **Ans:** (Devi Ahilya, 1992; Meerut 93; Osmania, 93)
2. **Ques:** Compare α , β and γ rays in terms of mass, charge and penetrating power. **Ans:** (Rohilkhand, 90)
3. **Ques:** What is group displacement law? How does it throw light on the idea of radioactive isotopes? **Ans:** (M.S. Baroda 91, Osmania 93, Meerut 95)
4. **Ques:** Explain what is meant by "Radioactive Equilibrium"? How does it differ from chemical equilibrium? **Ans:** (Bombay 90, Osmania 93, Meerut 97)
5. **Ques:** Write a note on:
 - (a) Artificial transmutation (b) Health hazards of radiations
 - (i) Artificial radioactivity (give examples)
 - (b) Transmutation of Elements
 - (ii) Atomic fission
 - (iii) Decay series (give examples)
 - (iv) Carbon dating**Ans:** (Bahuguna, 92) (Agra, 92) (Meerut M.Sc., 94) (Agra, 92) (Meerut, 92) (Delhi, 92)
6. **Ques:** What is meant by average life period of a radioactive element and how is it related with half-life period of that element? **Ans:** (Meerut M.Sc., 94)
7. **Ques:** State and explain the law of radioactive disintegration. What do you understand by the half-life period of a radioactive element? **Ans:** (Meerut, 97)

✓ 7. Prove that half-life period of a radioactive element is given by $0.693/k$ where K is the decay constant.

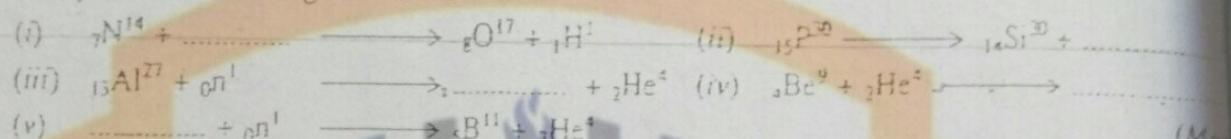
8. Complete the following equations and identify X, Y, Z, Q and R.



9. The amount of C-14 in a piece of wood is found to be one-sixth of its amount in a fresh piece. Calculate the age of the wood. (Bahan)

10. At radioactive equilibrium the ratio between atoms of the two radioactive elements A and B is to be 3.1×10^9 . If the half-life period of element A is 2×10^9 years, what is the half-life period of element B? (Meerut)

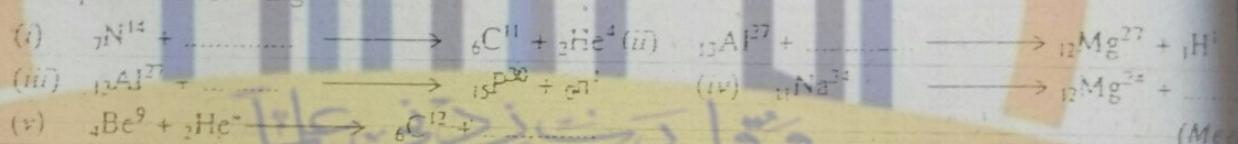
11. Complete the following nuclear reactions:



12. The radioactivity of a radioactive isotope falls to 12.5% in 90 days. Calculate the half-life period and disintegration constant of the radio isotope. (Meerut)

13. The half-life period of a radioactive element is 1600 years. Calculate the disintegration constant. (Meerut)

14. Complete the following:



15. How does the number of protons in a nucleus change when an α and then a β particle is emitted from the nucleus? (Meerut)

16. What is artificial transmutation? Give the nuclear reactions induced by neutron, proton and α -particle. (Osmania)

17. Ac- 227 has a half-life of 220 yrs with respect to radioactive decay. The decay follows two parallel paths, one leading to ^{227}Th and the other to ^{223}Fr . The percentage yields of these daughter nuclides are 20 and 98.0 respectively. What are the decay constants (λ) for each of the separate paths? (I.I.T.)

H

PUACP

Tl₈₁ Pb₈₂ Bi Po At Fr Ra Ac

Th Pa U Np

$$\text{or } 1 \text{ amu} = 0.166 \times 10^{-26} \text{ kg}$$

Now we know that the relation between mass and energy corresponding to this mass is given by Einstein's mass-energy relationship viz. $E = mc^2$ where E = energy in joules, m = mass in kg and c = velocity of light in m.s^{-1} ($= 2.998 \times 10^8 \text{ m.s}^{-1}$).

Since $1 \text{ amu} = 0.166 \times 10^{-26} \text{ kg}$, then energy corresponding to 1 amu is the energy corresponding to $0.166 \times 10^{-26} \text{ kg}$. Thus

$$\begin{aligned} \text{Energy}(E) \text{ corresponding to } 1 \text{ amu} &= (0.166 \times 10^{-26} \text{ kg}) \times (2.998 \times 10^8 \text{ m.s}^{-1})^2 \\ &= 0.166 \times 10^{-26} \times 8.9880 \times 10^{16} \text{ kg.m}^2 \text{s}^{-2} \end{aligned}$$

$$\text{or } 1 \text{ amu} = 1.4920 \times 10^{-10} \text{ J} \quad (\because \text{kg.m}^2 \text{s}^{-2} = \text{J})$$

Now we know that $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$

$$1 \text{ amu} = \frac{1.4920 \times 10^{-10}}{1.602 \times 10^{-19} \text{ eV}} \text{ eV} = 0.9313 \times 10^9 \text{ eV}$$

$$= \frac{0.9313 \times 10^9}{10^6} \text{ MeV} \quad (\because 1 \text{ MeV} = 10^6 \text{ eV})$$

$$= 0.9313 \times 10^3 \text{ MeV} = 931.3 \text{ MeV}$$

$$\text{i.e., } 1 \text{ amu} = 931.3 \text{ MeV}$$

For the sake of convenience, in our calculations we shall be using the relation:

$$1 \text{ amu} = 931.50 \text{ MeV}$$

Mass Defect (ΔM)

Since the nucleus of an atom contains protons and neutrons and the mass of electrons (which are present in different shells outside the nucleus) is negligible, almost the entire mass of the atom is concentrated in the nucleus. If the mass of the electrons is also considered, then it has been found that the actual mass (M) of an atom as determined by mass spectrograph (i.e., atomic mass of the atom or atom) is always less than the sum of the masses (M') of all protons, all neutrons and all electrons present in the atom i.e., $M < M'$. The difference in masses viz. $(M' - M)$ is called mass defect, mass loss, packing loss, mass deficit or mass decrement (ΔM). Thus:

$$\text{Mass defect} = (\text{Masses of all protons} + \text{masses of all neutrons} + \text{masses of all electrons}) - \text{Actual atomic mass of the atom}$$

$$\text{or } \Delta M = M' - M.$$

When nucleons (i.e., neutrons and protons) combine to form the nucleus of an atom, mass equal to $(M' - M)$ is lost.

Let us calculate the mass defect for an isotope namely ${}^A_Z X$ in which A is its mass number and Z is its atomic number (nuclear charge). We know that since $Z = p = e$, $A = n + p$ and $n = A - Z$. Atom of the given isotope contains Z protons, Z electrons and $(A - Z)$ neutrons. Now if the mass of one proton, one electron and one neutron is m_p , m_e and m_n respectively, then Sum of the masses of Z protons, Z electrons and $(A - Z)$ neutrons (M') = $Zm_p + Zm_e + (A - Z)m_n$

$$\text{or } M' = Z(m_p + m_e) + (A - Z)m_n \quad (i)$$

We know that $(m_p + m_e)$ is the sum of the mass of one proton and mass of one electron. Again now that since, ${}^1 H$ has one proton and one electron but has no neutron, the mass of H-atom is sum of mass of one proton and mass of one electron, i.e.,

$$\text{Mass of H-atom } (m_H) = (m_p + m_e) \quad (ii)$$

the help of equation (ii), equation (i) reduces to:

$$M' = Zm_H + (A - Z)m_n \quad (iii)$$

Now if the actual atomic mass of ${}^A_Z X$ isotope as determined by mass spectrograph is M , then mass defect (ΔM) of this isotope will be given by:

$$\text{Mass defect } (\Delta M) = M' - M$$

$$\text{or } \Delta M = [Zm_p + Zm_n + (A - Z)m_e] - M \quad \text{or } \Delta M = [Z(m_p + m_n) - (A - Z)m_n] - M$$

$$\text{or } \Delta M = [Zm_H - (A - Z)m_n] - M$$

Some important values and relations

- (i) Mass of one proton (m_p) = 1.007277 amu
- (ii) Mass of one neutron (m_n) = 1.008665 amu
- (iii) Mass of one electron (m_e) = 0.0005486 amu
- (iv) Mass of a helium nucleus, ${}^4\text{He}$ = 4.0026 amu
- (v) Mass of a deuterium nucleus, ${}^2\text{H}$ = 2.01471 amu

$$\text{(vi) Mass of one H-atom } {}^1\text{H} (m_H) = \text{Mass of one proton} + \text{Mass of one electron}$$

$$= 1.0072770 + 0.0005486 = 1.0078256 \text{ amu}$$

$$\text{(vii) Avogadro's number} = 6.022 \times 10^{23}$$

$$\text{(viii) } 1 \text{ amu} = 0.166 \times 10^{-26} \text{ kg}$$

$$\text{(ix) velocity of light (c)} = 3.0 \times 10^{10} \text{ cm.s}^{-1} = \frac{3.0 \times 10^{10}}{100} \text{ m.s}^{-1} = 3.0 \times 10^8 \text{ ms}^{-1}$$

$$\text{(x) } J = \text{kg m}^2 \text{s}^{-2}$$

$$\text{(xi) } 1 \text{ amu} = 1.4920 \times 10^{-10} \text{ J} = 931.5 \text{ MeV}$$

$$\text{(xii) } 1 \text{ eV} = 10^{-6} \text{ MeV} = 23.06 \text{ Kcal} = 1.602 \times 10^{-19} \text{ J} = 1.6021 \times 10^{-12} \text{ erg}$$

$$\text{(xiii) } 1 \text{ MeV} = 1.602 \times 10^{-16} \text{ J}$$

Example 8.8. Calculate the mass defect of oxygen atom, ${}^{16}\text{O}$ which has a mass of 15.99491 amu.

Given that mass of a neutron = 1.008665 amu, mass of a proton = 1.007277 amu and mass of an electron = 0.0005486 amu.

Solution. ${}^{16}\text{O}$ contains 8 protons, 8 neutrons and 8 electrons. Thus

$$\text{mass of 8 protons} = 8 \times 1.007277 = 8.058216 \text{ amu}$$

$$\text{mass of 8 neutrons} = 8 \times 1.008665 = 8.069320 \text{ amu}$$

$$\text{mass of 8 electrons} = 8 \times 0.0005486 = 0.004388 \text{ amu}$$

$$M' = 8.058216 + 8.069320 + 0.004388 = 16.131924 \text{ amu}$$

$$M = 15.994910 \text{ amu} \text{ (given)}$$

$$\text{Mass defect } (\Delta M) = 16.131924 - 15.994910 = 0.137014 \text{ amu}$$

Example 8.9. Calculate the mass defect in helium atom, ${}^4\text{He}$ which has a mass of 4.0026 amu.

Given that mass of a neutron 1.008665 amu and mass of one H-atom = 1.007825 amu.

Solution. ${}^4\text{He}$ contains 2 protons, 2 electrons and 2 neutrons.

$$M' = \text{mass of 2 protons} + \text{mass of 2 electrons} + \text{mass of 2 neutrons}$$

$$= 2 \times (\text{mass of one proton} + \text{mass of one electron}) + \text{mass of 2 neutrons}$$

$$= 2 \times \text{mass of a H-atom} + \text{mass of 2 neutrons}$$

$$= (2 \times 1.007825 + 2 \times 1.008665) \text{ amu} = (2.01560 + 2.017330) \text{ amu} = 4.032980 \text{ amu}$$

$$M = 4.002600 \text{ amu} \text{ (given)}$$

$$\therefore \Delta M = (4.032980 - 4.002600) \text{ amu} = 0.030380 \text{ amu}$$

Example 8.10. An element with mass number 15 and isotopic mass 15.00486 amu has mass defect of 0.124043 amu. If mass of a proton and a neutron is 1.008145 amu and 1.008986 amu respectively, find out the atomic number of the element. Mass of the electron can be neglected.

Solution. Let the element be represented as ${}^{15}\text{X}$. Obviously the nucleus of the atom of the element has a protons and $(15 - a)$ neutrons.

$$\text{Now, } M' = \text{Mass of } a \text{ protons} + \text{Mass of } (15 - a) \text{ neutrons}$$

$$= [a \times 1.008145 + (15 - a) \times 1.008986] \text{ amu}$$

$$M = 15.00486 \text{ amu} \text{ (given)}$$

$$\therefore \text{Mass of defect } (\Delta M) = M' - M$$

$$\text{or } 0.124043 = 1.008145 a + 1.008986 \times (15 - a) - 15.00486$$

On solving this equation we get $a = 7$

✓ Binding energy of a nucleus or nuclear binding energy (B) and its calculation

We have said above (see *Mass Defect*) that when nucleons (i.e., neutrons and protons) together to form the nucleus of an atom, some mass is lost. The mass lost is called mass defect. The mass is lost in the process of combination of nucleons to form the nucleus, since it is converted into energy, i.e., when protons and neutrons combine together to form the nucleus, it is transformed into energy which is released in the process. The energy released in this process is called **binding energy of the nucleus or nuclear binding energy (B)**. Thus the energy released in the combination of protons and neutrons to form the nucleus is called **binding energy of the nucleus**.

It should be evident from the above discussion that when a nucleus is broken up into its constituent neutrons and protons, energy is needed and this energy is equal to the binding energy of the nucleus.

If the mass lost in the formation of a nucleus by the combination of neutrons and protons is ΔM amu (i.e., if the mass defect is ΔM amu), then the energy into which this lost mass is converted is equal to $(\Delta M \times 931.5)$ MeV, since, as we have already shown that 1 amu = 931.5 MeV.

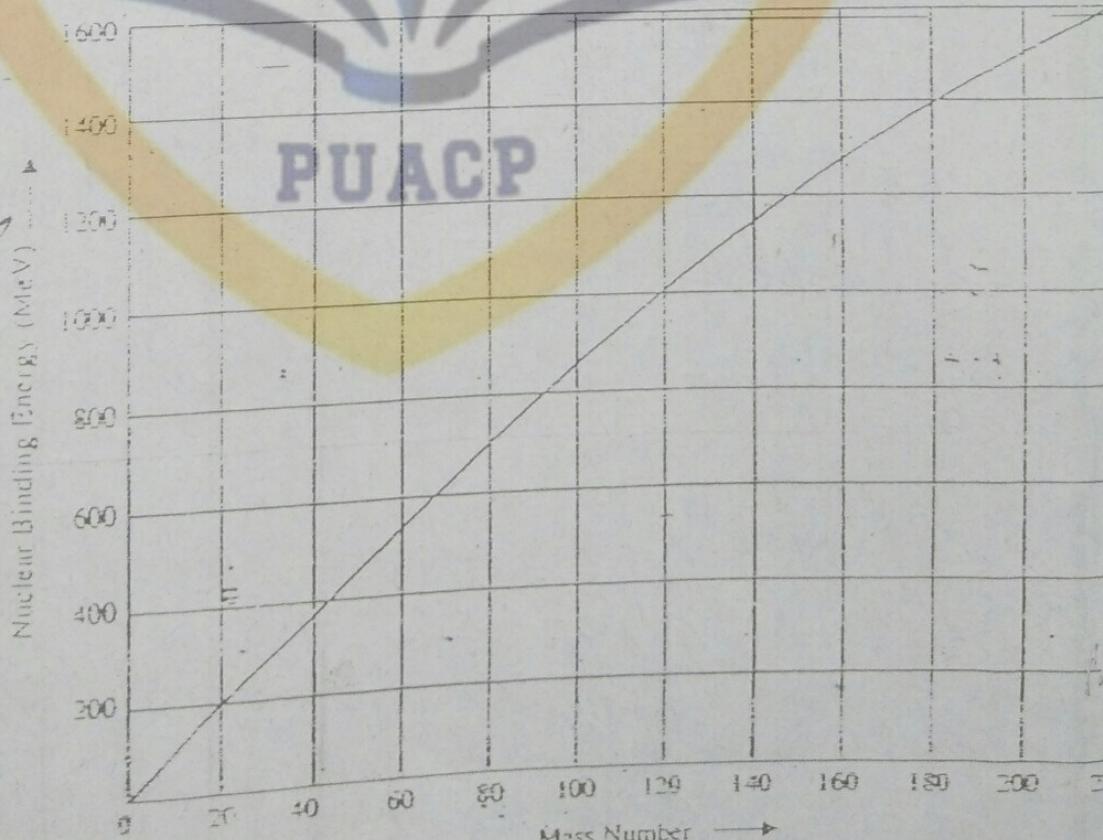
Thus, we find that when the mass defect (i.e., the mass lost) is equal to ΔM amu, the energy released in the formation of a nucleus by the combination of neutrons and protons is equal to $\Delta M \times 931.5$ MeV. This is the binding energy (B) of the nucleus, i.e.,

$$\text{Binding energy of the nucleus (B)} = \text{Mass defect, } \Delta M \text{ (in amu)} \times 931.5 \text{ MeV}$$

The above relation shows that if the mass defect is 1 amu, then binding energy is equal to $931.5 \text{ MeV} = 931.5 \text{ MeV}$.

Variation of the nuclear binding energy with mass number and its relation with the nuclear mass defect

The study of the variation of the nuclear binding energy with mass numbers of isotopes can be made from the plot shown in Fig. 8.3.



This plot is a graph between the nuclear binding energy (in MeV) of a number of isotopes and their corresponding mass number. This graph shows that as the mass number of the isotopes increases, the magnitude of the nuclear binding energy also increases. However, for the isotopes having high mass numbers, the increase in the magnitude of nuclear binding energy is small.

In case of two or more isotopes having the same mass numbers, the nucleus of the isotope having higher value of B is more stable than the nucleus of the isotope having lower value of B.

The stability of the nuclei of the isotopes having different mass numbers is generally compared with the help of the value of their binding energies per nucleon (\bar{B}).

Binding energy per nucleon (\bar{B})

As the name suggests, the binding energy of a nucleus (B) divided by the sum of the protons (p) and neutrons (n) (i.e., nucleons) present in the nucleus is called binding energy per nucleon (\bar{B}). Thus \bar{B} is given by

$$\text{Binding energy per nucleon } (\bar{B}) = \frac{\text{Binding energy of the nucleons } (B)}{\text{No. of nucleons in the nucleus}}$$

or

$$\bar{B} = \frac{\text{Mass defect } (\Delta M) \times 931.5}{\text{No. of nucleons in the nucleus}} \text{ MeV}$$

or

$$\bar{B} = \frac{\Delta M \times 931.5}{p + n} \text{ MeV} = \frac{\Delta M \times 931.5}{A} \text{ MeV}$$

Here A is the mass number which is equal to $(p + n)$.

Variation of binding energy per nucleon (\bar{B}) with mass number (A) and its relation with nuclear stability

How the magnitude of \bar{B} varies with the mass numbers (A) of the isotopes can be studied with the help of the plot shown in Fig. 8.4.

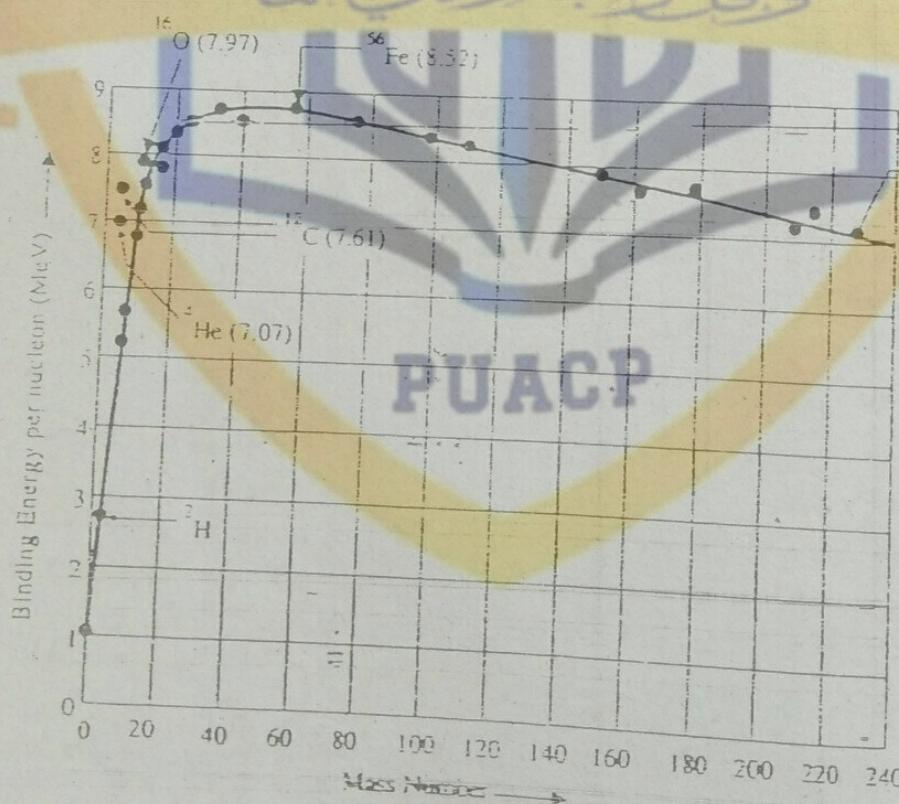
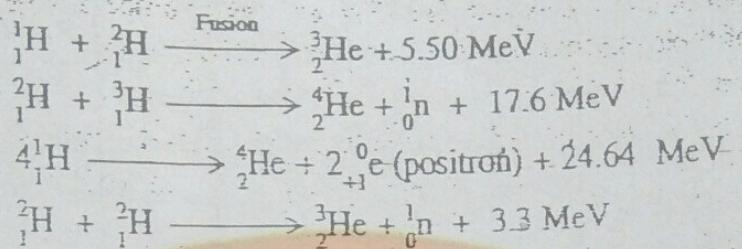


Fig. 8.4 : Variation of binding energy per nucleon (in MeV) with mass number of different nuclei.

This plot is a graph between the binding energy per nucleon (in MeV) of a number of isotopes and their corresponding mass numbers. This plot is called binding energy curve. Binding energy per nucleon is a measure of the stability of the nucleus. Greater is the magnitude of binding energy per nucleon, greater is the stability attained by the nucleus or greater is the force holding the

nucleons together in the nucleus. The largest values of \bar{B} are the characteristics of the most stable nuclei. From the binding energy curve the following points may be noted.

(i) \bar{B} values of the nuclei having very low mass numbers (i.e., lighter nuclei like 1H , 2H , etc.) are very small and hence these nuclei are unstable. Being unstable they combine together to give heavy nuclei and a huge amount of energy is also liberated. Examples of nuclear reactions are given below:

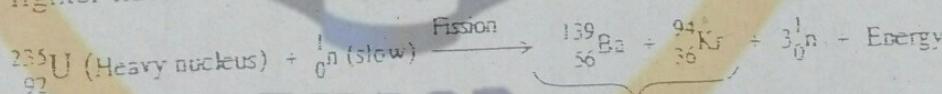


(ii) The nuclei whose mass numbers are multiples of 4 or multiples of helium nucleus which have equal number of protons and neutrons (i.e., light nuclei like 4He , ${}^{12}O$, ${}^{16}O$, ${}^{20}Ne$, ${}^{28}Si$) show a rapid increase in their \bar{B} values. 8Be is an exception. It splits into two alpha particles (${}^8Be \rightarrow 2 {}^4He$). \bar{B} values for the above said light nuclei are high (${}^4He = 7.0747 \text{ MeV}$, ${}^{12}O = 7.61833 \text{ MeV}$, ${}^{16}O = 7.976 \text{ MeV}$) and hence these nuclei are stable. It may also be concluded that helium nucleus has quite stable structure and this is the reason why α -particles are emitted by many radioactive elements.

(iii) At mass number 56, the value of \bar{B} becomes maximum ($= 8.52 \text{ MeV}$). This maximum value is for ${}^{56}Fe$ isotope. This value shows that the nucleus of iron is exceptionally stable, hence iron is found in large abundance in nature.

(iv) The plot for the nuclei having mass numbers in the range 60–80 is almost flat, means that the values of \bar{B} for the above nuclei do not change very much.

(v) As the mass number increases beyond 80, the values of \bar{B} start decreasing, i.e., the nuclei having mass numbers greater than 80 (e.g., heavy nuclei like ${}^{235}U$) have low values of \bar{B} , hence these nuclei are unstable. Their unstable nature is evident from the fact that when a nucleus ($\bar{B} = 7.1 \text{ MeV}$) (heavy nucleus) is bombarded by slow-moving neutrons, it undergoes fission into lighter nuclei viz. ${}^{139}Ba$ and ${}^{94}Kr$ and a large amount of energy is released.



PUACP

Lighter nuclei

Example 8.11. Calculate the binding energy per nucleon in helium atom (4He) which has mass of 4.00260 amu. Mass of 1 neutron = 1.008665 amu and mass of one H-atom = 1.007825 amu. Express the result in Joules as well.

Solution. We know that 4He atom contains 2 protons, 2 electrons and $4 - 2 = 2$ neutrons.

$$\begin{aligned} \text{Mass of 2 protons + 2 electrons} &= 2 \times (\text{mass of 1 proton} + \text{mass of 1 electron}) \\ &= 2 \times \text{mass of one H-atom} = 2 \times 1.007825 \text{ amu.} \end{aligned}$$

$$\therefore \text{Mass of 2 protons + 2 electrons + 2 neutrons}$$

$$\begin{aligned} &= 2 \times 1.007825 + 2 \times 1.008665 = 2.015650 + 2.017330 \\ &= 4.032980 \text{ amu} \end{aligned}$$

$$\text{Thus } M' = 4.032980 \text{ amu} ; M = 4.00260 \text{ amu (given)}$$

$$\therefore \text{Mass defect } (\Delta M) = M' - M = 4.032980 - 4.002600 = 0.030380 \text{ amu}$$

$$\text{Since } 1 \text{ amu} = 931.5 \text{ MeV. } 0.030380 \text{ amu} = 0.030380 \times 931.5 \text{ MeV} = 28.298 \text{ MeV}$$

$$\text{Thus binding energy of helium nucleus (B) = } 28.298 \text{ MeV}$$

$$\begin{aligned}\text{Binding energy per nucleon } (\bar{B}) &= \frac{28.298}{4} = 7.0745 \text{ MeV} \\ &= 7.0745 \times 10^6 \text{ eV} = 7.0745 \times 10^6 \times 1.602 \times 10^{-19} \text{ J} \\ &= 11.33 \times 10^{-13} \text{ J}\end{aligned}$$

Example 8.12. The observed mass of $^{56}_{26}\text{Fe}$ is 55.9375 amu. Using the masses of one proton and one neutron as 1.00732 amu and 1.00866 amu respectively; calculate the binding energy per nucleon in MeV and in Joules. Also calculate the energy evolved when one mole of $^{56}_{26}\text{Fe}$ atoms are formed from protons and neutrons. Neglect the mass of electrons.

Solution. The nucleus of $^{56}_{26}\text{Fe}$ contains 26 protons and $56 - 26 = 30$ neutrons.

Mass of 26 protons + mass of 30 neutrons (M')

$$\begin{aligned}&= 26 \times 1.00732 + 30 \times 1.00866 \\ &= 26.19032 + 30.2698 = 56.45012 \text{ amu}\end{aligned}$$

Now $M = 55.9375 \text{ amu}$ (given)

$$\text{Mass defect } (\Delta M) = M' - M = 56.45012 - 55.9375 = 0.51262 \text{ amu}$$

$$\text{Binding energy } (B) = \Delta M \times 931.5 \text{ MeV} = 0.51262 \times 931.5 \text{ MeV} = 477.50553 \text{ MeV}$$

$$\text{Binding energy per nucleon } (\bar{B}) = \frac{477.50553}{56} \text{ MeV} = 8.5268844 \text{ MeV}$$

$$= 8.5268844 \times 1.602 \times 10^{-19} \text{ J} = 1.3660068 \times 10^{-42} \text{ J}$$

Energy released when one mole of $^{56}_{26}\text{Fe}$ atoms are formed from protons and neutrons

$$= [56 \times 8.5268844 \times \text{Avogadro's number}] \text{ MeV}$$

$$= 56 \times 8.5268844 \times 6.022 \times 10^{23} \text{ MeV}$$

$$= 2875.5382 \times 10^{23} \text{ MeV.}$$

Nuclear shell model: Magic numbers

This model was proposed by Maria Mayer, Eugene Wigner and Hans Jensen in 1950 who earned them noble prize in 1963.

According to this model:

1. Each nucleon moves in its orbit within the nucleus, independently of all other nucleons. It is for this reason that this model is also known as *Independent particle model* or *single particle model*.

2. Each nucleon is acted upon by an average field produced by the action of other nucleons.

3. The neutrons as well as protons pair amongst themselves (i.e., a neutron forms a pair with another neutron and similarly a proton forms a pair with another proton) in the nucleus and these paired nucleons are packed into separate shells (called *nuclear shells*) within the nucleus. A nuclear shell which contains a specific number of neutrons and/or protons in it is called a *filled shell* and this filled shell is more stable than other shells. These specific numbers are 2, 8, 20, 28, 50, 82 and 126 which are called *Magic numbers*. These magic numbers indicate that the nucleons exist in pairs in the nucleus. The nuclei having either protons or neutrons or both equal to the magic numbers given above are called *Magic nuclei* and these nuclei are very stable. Being stable, these nuclei are also called *stable nuclei*. The greater stability associated with these nuclei is confirmed by the following facts:

(i) These nuclei are found in greater abundance in nature as compared to other isotopic forms of the same element.

(ii) These nuclei cannot capture a neutron because the nuclear shells in their respective nuclei are already filled with nucleons and hence cannot contain an extra neutron. The nuclei having the magic number (i.e., *Magic nuclei*) have been classified into the following two groups:

(a) Nuclei in which only protons or neutrons are magic numbers. Such nuclei are called *single magic number nuclei*. Examples of such nuclei are $^{17}_8\text{O}$ ($p = 8, n = 17 - 8 = 9$), $^{56}_{26}\text{Fe}$ ($p = 26, n = 56 - 26 = 30$), $^{207}_{82}\text{Pb}$ ($p = 82, n = 207 - 82 = 125$) and $^{209}_{83}\text{Bi}$ ($p = 83, n = 209 - 83 = 126$).

(b) Nuclei in which protons and neutrons both are magic numbers. Such nuclei are called *doubly magic nuclei*.

double magic number nuclei. Examples are ^4_2He ($p = 2, n = 2$), $^{16}_8\text{O}$ ($p = 8, n = 8$) = 20, $n = 20$), $^{208}_{82}\text{Pb}$ ($p = 82, n = 126$).

When a nuclide contains protons or neutrons or both equal to any of the magic numbers say that this nuclide has closed or filled shell. Such a nuclide gives a number of stable isotopes, e.g. $^{50}_{28}\text{Sn}$ ($p = 50$ which is a magic number) has ten stable isotopes having the numbers equal to H-2, H-14, H-15, H-16, H-17, H-18, H-20, H-22 and H-24. $^{40}_{20}\text{Ca}$ ($p = 20$ which is a magic number) has six stable isotopes. The maximum number of stable isotopes (isotones are those which have the same number of neutrons) occur for those nuclei which have $n = 50$ or 80 numbers are also magic numbers. The nuclei having 6, 14, 28 or 40 protons or neutrons are more stable than those nuclei which have protons or neutrons or both equal to magic numbers namely 2, 8, 14, 28 and 40 are called semi-magic numbers. The nuclei having protons or neutrons other than magic numbers or semi-magic numbers are comparatively less stable. This model has successfully explained the nuclear stability, spin, magnetic moment etc. The nuclides ^2_1H , ^6_3Li , $^{10}_5\text{B}$ and $^{14}_7\text{N}$ are not covered under the scheme of this model.

UNIVERSITY QUESTIONS

Binding energy, binding energy curve and stability of the nucleus

- What is meant by binding energy per nucleon? How does it vary with atomic number of the nucleus? Discuss the importance of binding energy curve in the release of nuclear energy. (Rohilkhand 90; Meerut M.Sc. 91)
- Discuss the various theories given for the stability of the nucleus. (M.Sc. Baroda 90; Lucknow 91)
- Establish relation between the binding energy, mass nucleus and mass defect of the nucleus. (M.Sc. Baroda 91; Allahabad 91; Berhampur 91; Kurukshetra 91)
- How is nuclear stability related to packing fraction and binding energy. Explain. (Osmania 93; E.C.D. Allahabad 93)
- Discuss the stability of nucleus under the following heads (a) Binding energy per nucleon (b) N/Z ratio and (c) Odd-even rule. (Lucknow 91)

Numerical problems

- Calculate the mass defect and binding energy of $^2_1\text{He}^4$. Given that mass of $^2_1\text{He}^4$ = 4.00390 amu, mass of proton = 1.00758 amu, mass of neutron = 1.00893 and mass of electron = 0.0005486 amu. (Allahabad 93)
- Calculate the mass defect and binding energy per nucleon of $^{12}_6\text{C}^{12}$ which has isotopic mass of 12.0 amu. Given that mass of neutron = 1.008671 amu, mass of hydrogen = 1.00787 amu, 1 amu = 931.5 MeV. (Osmania 93; Delhi 93)
- Calculate the binding energy per nucleon in $^{35}_{17}\text{Cl}^{35}$ nucleus. Given that mass of $^{35}_{17}\text{Cl}^{35}$ = 34.9800 amu, mass of $^1_1\text{H}^1$ = 1.007825 amu, mass of $^{17}\text{Cl}^{35}$ = 34.9800 amu, 1 amu = 931.5 MeV. (Delhi 93)
- The atomic mass of a nucleus is 6.017 amu. Calculate its total binding energy (Mass of ^1_1H = 1.007825 amu, mass of ^1_0n = 1.008665 amu). (Kurukshetra 91) (Ans.: 2875)
- Calculate the binding energy of a deuteron nucleus, given that mass of neutron = 1.008665 amu, mass of proton = 1.007825 amu and mass of deuteron nucleus = 2.014103 amu. (Meerut M.Sc. 91)
- Calculate the relative atomic mass of an element which consists of the following isotopes with indicated relative abundance. (Guru Nanak Dev 93)

Isotope	Isotopic mass	Natural abundance
1	28.0	92.0
2	29.0	5.0
3	30.0	3.0

- Calculate the mass defect and binding energy in MeV for the isotope $^{35}_{17}\text{Cl}^{35}$. Given that 1 amu = 931.5 MeV, mass of electron = 0.0005486 amu, mass of proton = 0.007277 amu and mass of neutron = 1.008665 amu. (Delhi 93)

120