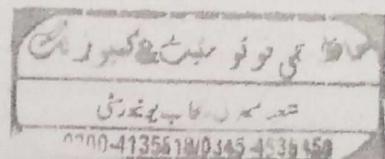


02-01-2011

MSc II

جیز راہ

6



Radioactivity

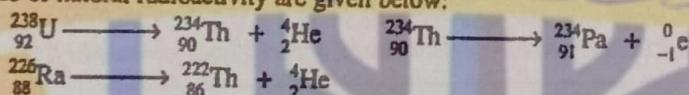
Radioactivity or natural radioactivity

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*.

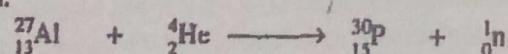
Types of radioactivity

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 Iren Curie and her husband, Frederick Jiolet (1934). They showed that when ${}^{27}_{13}\text{Al}$ isotope which is non-radioactive is bombarded with α -particles, it is converted into ${}^{30}_{15}\text{P}$ isotope (a radioactive isotope) with the emission of a neutron.

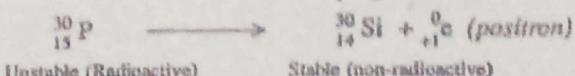


Stable (Non-radioactive)

Unstable (Radioactive)

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

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 ($^{0}_{+1}\text{e}$)



More examples showing artificial radioactivity are given below:

- (i) $^{10}_{5}\text{B} + ^{4}_{2}\text{He} \longrightarrow ^{13}_{7}\text{N} + ^{1}_{0}\text{n}$ (neutron)
- Non-radioactive Radioactive
- $^{13}_{7}\text{N} \longrightarrow ^{13}_{6}\text{C} + ^{0}_{+1}\text{e}$ (positron)
- Radiative
- (ii) $^{11}_{5}\text{B} + ^{4}_{2}\text{He} \longrightarrow ^{14}_{6}\text{C} + ^{1}_{1}\text{H}$ (proton)
- $^{14}_{6}\text{C} \longrightarrow ^{14}_{7}\text{N} + ^{0}_{-1}\text{e}$ (β -particle)
- (iii) $^{12}_{6}\text{C} + ^{1}_{1}\text{H} \longrightarrow ^{13}_{7}\text{N}$
- $^{13}_{7}\text{N} \longrightarrow ^{13}_{6}\text{C} + ^{0}_{+1}\text{e}$ (positron)
- (iv) $^{14}_{7}\text{N} + ^{4}_{2}\text{He} \longrightarrow ^{17}_{9}\text{F} + ^{1}_{0}\text{n}$ (neutron)
- $^{17}_{9}\text{F} \longrightarrow ^{17}_{8}\text{O} + ^{0}_{+1}\text{e}$ (positron)
- (v) $^{23}_{11}\text{Na} + ^{2}_{1}\text{H} \longrightarrow ^{24}_{11}\text{Na} + ^{1}_{1}\text{H}$ (proton)
- $^{24}_{11}\text{Na} \longrightarrow ^{24}_{12}\text{Mg} + ^{0}_{+1}\text{e}$ (positron)
- (vi) $^{23}_{11}\text{Na} + ^{4}_{2}\text{He} \longrightarrow ^{26}_{13}\text{Al} + ^{1}_{0}\text{n}$ (neutron)
- $^{26}_{13}\text{Al} \longrightarrow ^{26}_{12}\text{Mg} + ^{0}_{+1}\text{e}$
- (vii) $^{27}_{13}\text{Al} + ^{1}_{0}\text{n} \longrightarrow ^{24}_{11}\text{Na} + ^{4}_{2}\text{He}$
- $^{24}_{11}\text{Na} \longrightarrow ^{24}_{12}\text{Mg} + ^{0}_{+1}\text{e}$
- (viii) $^{24}_{12}\text{Mg} + ^{4}_{2}\text{He} \longrightarrow ^{27}_{14}\text{Si} + ^{1}_{0}\text{n}$
- $^{27}_{14}\text{Si} \longrightarrow ^{27}_{13}\text{Al} + ^{0}_{+1}\text{e}$

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 10^6 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 $1\text{c} / 1\text{r} = 3.7 \times 10^{10} / 10^6$ or $1\text{c} = 3.7 \times 10^4\text{r}$

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.

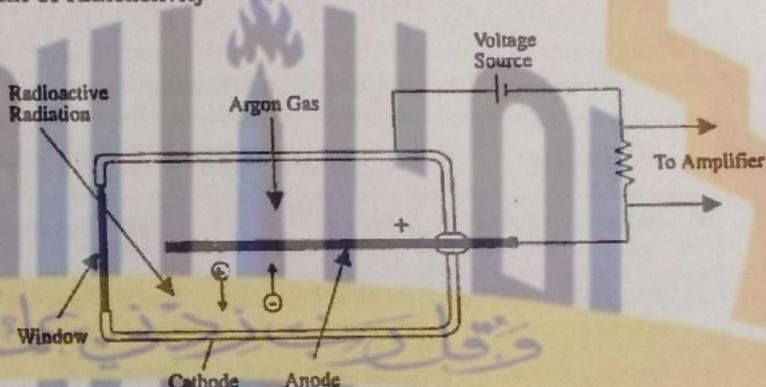


Fig. 6.1 : Geiger-Muller counter used for the detection and measurement of radioactivity of a substance.

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 using a slit. Now they passed the beam of invisible rays coming from radium between the parallel positive and negative plates of a strong electric field and found that the beam splitted into three different rays which are : (i) *Alpha* (α) rays which are deflected towards the negative plate (ii) *Beta* (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 equal to +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 $4 \text{ amu} = 4 \times 0.166 \times 10^{-26} \text{ kg}$.

(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.

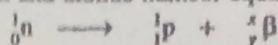
The mass of a β -particle is equal to $\frac{1}{1840} \text{ amu} = 0.0005482 \text{ amu} = 0.0005482 \times 0.166 \times 10^{-26} \text{ kg}$.

Since the mass in amu is so small ($= 0.0005482 \text{ amu}$) that the mass of a β -particle is taken to be equal

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 :

When the nucleus of the atom of a radioactive element loses a β -particle, one of the neutrons (${}_{0}^1n$) present in the nucleus of the atom is changed into a proton (${}_{+1}^1p$ or ${}_{-1}^0e$) 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 (${}_{+2}^4He$ or ${}_{-2}^4He$)	β -rays (${}_{-1}^0\beta$ or ${}_{-1}^0e$)	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 ($m = 0$)

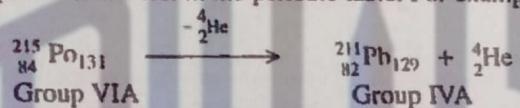
(c) When an atom of an element loses an electron, a cation of the same element is formed and hence the composition of the nucleus of the parent element remains the same. On the other hand, when the nucleus of an element loses a β -particle a new neutral element (called daughter element) is obtained. 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 ${}^4_2\text{He}$ 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 :

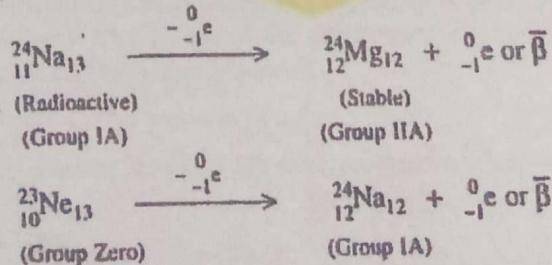


Explanation. We know that a helium nucleus (${}^4_2\text{He}$) has mass number equal to 4 and atomic number equal to 2. Thus this nucleus contains 2 protons and $4 - 2 = 2$ neutrons (${}^4_2\text{He}_2$). Thus the above nuclear reaction can be written as

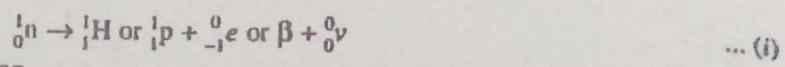


The presence of two protons and two neutrons in helium nucleus implies that when the nucleus of ${}_{84}^{215}\text{Po}_{131}$ loses an α -particle, 2 protons and 2 neutrons are lost by it, i.e., the number of protons (or atomic number) in the daughter element becomes $84 - 2 = 82$ and the number of 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.

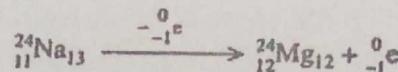
(ii) Emission of a beta particle, β or ${}^0_{-1}\text{e}$. We know that a β -particle is an electron which has mass number equal to zero and its charge or atomic number is -1. Thus it is represented as ${}^0_{-1}\text{e}$ or β . When a radioactive element emits one ${}^0_{-1}\text{e}$ (or β -particle), 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 is increased 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 :



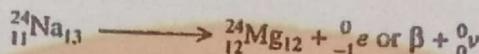
Explanation. We know that nucleus does not contain ${}_{-1}^0 e$ (β -particle) as such. Then how is β -particle produced in the nuclear reactions like those as given above? In order to explain its production, it is assumed that one of the neutrons (${}_{-1}^0 n$) present in the parent element is converted 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.,



Thus in the nuclear reaction,



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 ${}_{12}^{24} Mg_{12}$ and hence the above reaction should be written as :

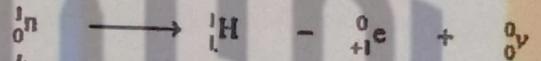


The discussion made above shows that since mass number of the parent element and of the daughter element are the same, these two elements are isobars to each other. Thus we can say that the emission of one or more β -particles (or ${}_{-1}^0 e$) by a radioactive element produces its isobar(s).

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 :



Angular momentum values : $+ \frac{h}{4\pi}$

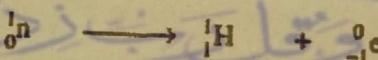
$+ \frac{h}{4\pi}$

$- \frac{h}{4\pi}$

$+ \frac{h}{4\pi}$

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 :

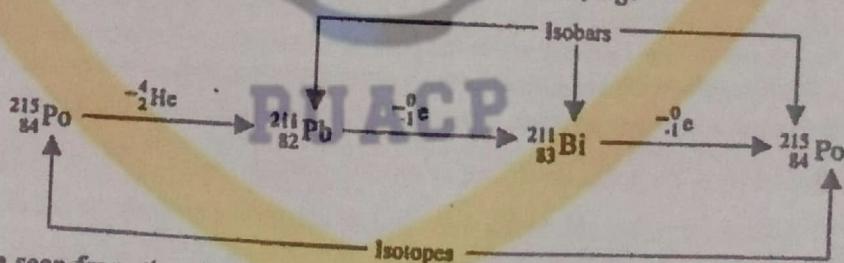


Angular momentum values : $+ \frac{h}{4\pi}$

$+ \frac{h}{4\pi}$

$- \frac{h}{4\pi}$

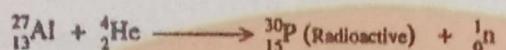
Formation of isotopes and isobars. When a radioactive element emits one α -particle (${}_{+2}^4 He$) and two β -particles (${}_{-1}^0 e$), the daughter element has the same atomic number as the parent element and hence these two elements are isotopes to each other. Thus the combined emission of one α -particle and two β -particles produces an isotope of the parent element, e.g.



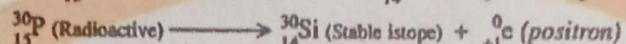
It may be seen from the above nuclear reactions that the emission of one or more β -particles (${}_{-1}^0 e$) by a radioactive element produces its isobar(s).

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

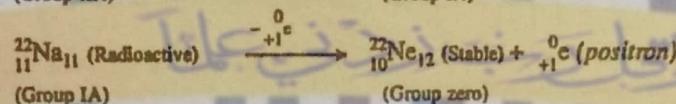
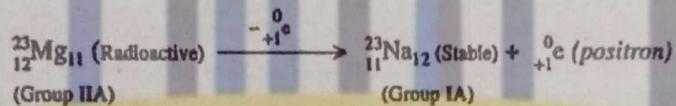
i.e., a positron has mass number equal to zero (its actual mass $\approx 0.0005486 \text{ amu}$) and its charge or atomic number is +1. Thus positron is represented as ${}_{+1}^0 e$. This particle was discovered by Irene Curie and her husband (name-Frederick Joliot) in 1934. They bombarded ${}_{13}^{27}\text{Al}$ nuclide (non-radioactive isotope) with α -particles so that it was converted into radioactive ${}_{15}^{30}\text{P}$ isotope with the emission of a neutron (${}_0^1 n$).



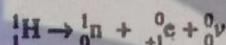
Being radioactive ${}_{15}^{30}\text{P}$ disintegrates to give stable ${}_{14}^{30}\text{Si}$ isotope and a positron (${}_{+1}^0 e$)



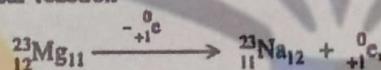
It is evident from the above nuclear reaction that when a radioactive element emits a positron, the mass number of the daughter element remains the same (since the mass number of ${}_{+1}^0 e$ is zero) but its atomic number is decreased by one unit (since the charge or atomic number of ${}_{+1}^0 e$ 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:



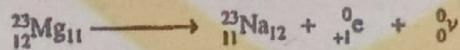
Explanation: How is the positron produced in a nuclear reaction has been explained by assuming that one of the protons (${}_1^1 p$ or ${}_1^1 H$) present in the nucleus of the parent element is converted into a neutron (${}_0^1 n$) and in this process one positron (${}_{+1}^0 e$) and one neutrino (${}_{0}^0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



Thus in the nuclear reaction

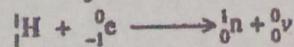


one of the 12 protons is converted into a neutron and hence the daughter element has $12 - 1 = 11$ protons and $11 + 1 = 12$ neutrons and in this process one positron (${}_{+1}^0 e$) and one neutrino (${}_{0}^0 \nu$) are also produced. Thus the daughter element is ${}_{11}^{23}\text{Na}_{12}$ and hence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

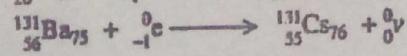
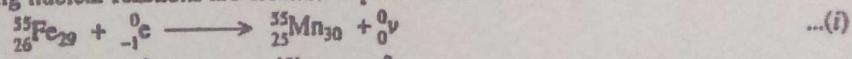


Since the mass number of the parent element and the daughter element are the same, these two elements are isobars to each other. Thus, we see that the emission of one or more positrons (${}_{+1}^0 e$) by a radioactive element produces its isobar(s).

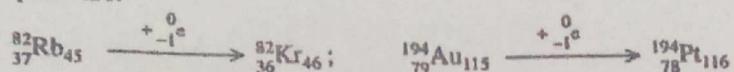
(iv) **Addition of an electron: Electron - capture process.** In this process an electron from the K or L shell is captured by a proton of the nucleus and this proton is converted into a neutron. In this process a neutrino (${}_{0}^0 \nu$) is also produced.



The following nuclear reactions are electron-capture reactions.



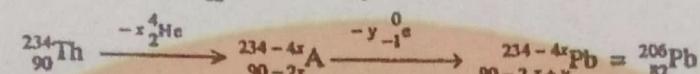
In reaction (i), one of the 26 protons captures an electron and is converted into a neutron and in this process one neutrino is also produced. Thus the number of protons (i.e. atomic number) of the daughter element is decreased by one unit and the number of neutrons is increased by one unit. Consequently 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 :

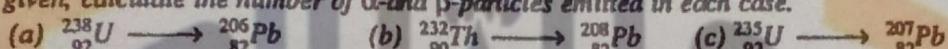


$$\text{Thus } 234 - 4x = 206 \text{ or } x = 7 \text{ and } 90 - 2x + y = 82$$

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

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 a 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:

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

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 $= N_0 - \frac{1}{2} N_0 = \frac{1}{2} N_0$

- (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 the 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 as such 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 the 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 undecomposed will be one-sixteenth of its initial amount [i.e., $\frac{1}{16}N_0 = \left(\frac{1}{2}\right)^4 N_0$]. Thus the 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 the substance that remains undisintegrated will be equal to $\left(\frac{1}{2}\right)^n N_0$ and hence the amount of the 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 or t time ($t = n \times t_{0.5}$)

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

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

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

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 in one half-life ($1 \times t_{0.5}$) the number of atoms that remain undisintegrated would be equal to $\frac{1}{2}N_0$ = $\frac{1}{2} \times 24 = 12$ and the number of atoms that undergo disintegration would be equal to $N_0 - \frac{1}{2}N_0 = 24 - \frac{24}{2} = 24 - 12 = 12$. 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 the number of atoms undergone disintegration in the subsequent half-lives can also be found out (See Fig. 6.2).

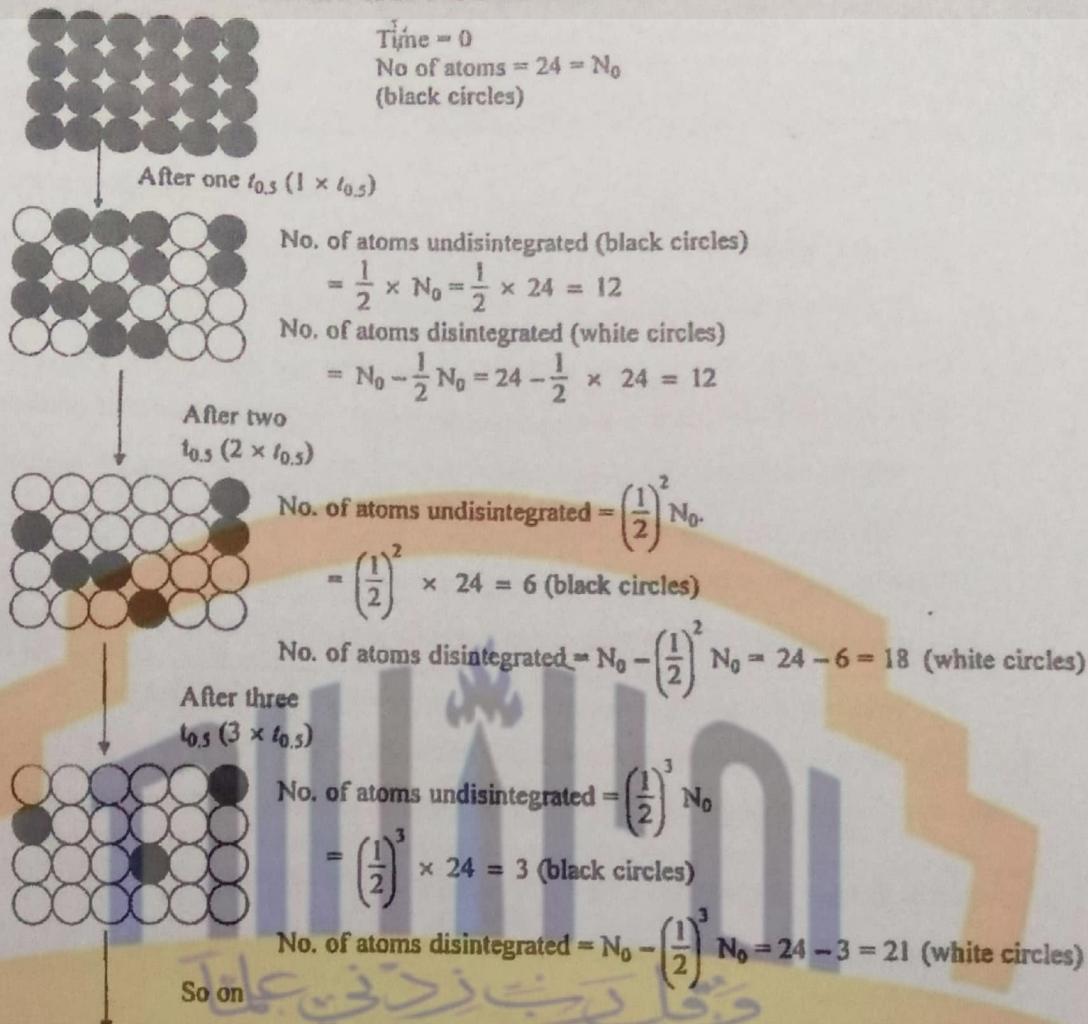


Fig. 6.2: To calculate the number of atoms of a radioactive substance left undisintegrated or disintegrated in n half-lives.

(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.

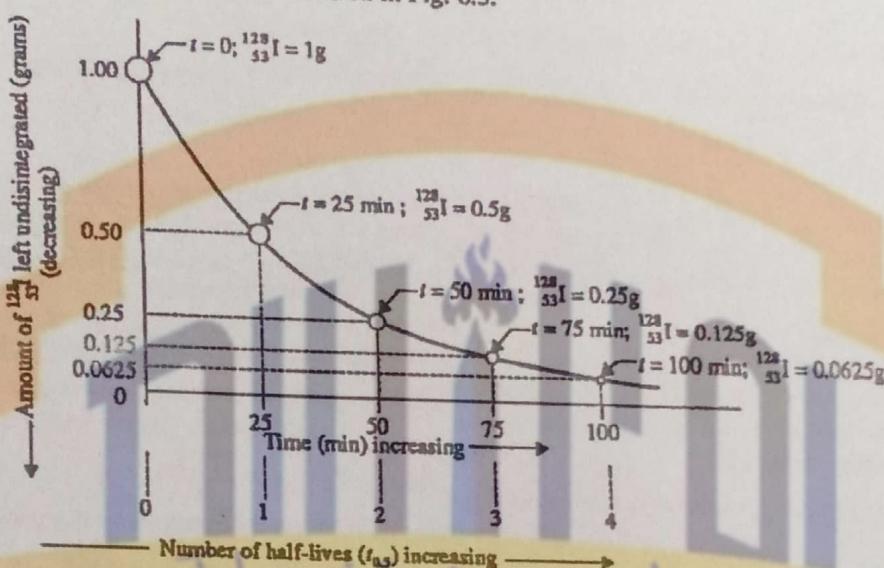


Fig. 6.3 : Radioactive decay of $^{128}_{53}\text{I}$

Disintegration constant or decay constant (K)

Suppose a radioactive element A disintegrates into another substance B. Let the amount or the number of nuclei of A in the beginning (i.e., at $t = 0$ time) be N_0 . Now as the time passes, the 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 =	A Disintegration → B N_0 0
After t time, amounts of A and B =	N $(N_0 - N)$ (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.,

$$-\frac{dN}{dt} \propto N \quad \text{or} \quad -\frac{dN}{dt} = KN \quad (\text{K is a constant of proportionality which is called disintegration or decay constant}).$$

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

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

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

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

amount of the radioactive substance $\left(\frac{dN}{N} \right)$ 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. K is expressed in time⁻¹ units (i.e., in s⁻¹, min⁻¹, hrs⁻¹; days⁻¹, yrs⁻¹).

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 :

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

$$\ln \frac{N}{N_0} = -Kt \quad (iii)$$

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

Equation (iii) can also be written as :

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

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

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

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

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 :

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

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

$$\text{or } N = 0.37 N_0 = 37\% \text{ of } N_0. \quad (vi)$$

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).

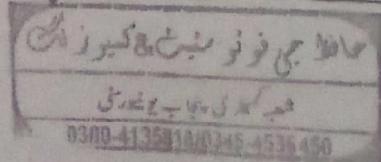
$$N = N_0 e^{-Kt} \quad \dots(A)$$

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

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

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

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



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

$$\text{or } t_{0.5} = \frac{0.6932}{K} \quad \dots (\text{vii})$$

$$t = \frac{2.303}{K} \log_{10} \frac{N_0}{N} \quad \dots (\text{B})$$

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

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

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

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 $t_{0.5}$ 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 equation, we get:

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

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

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, a 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 $t_{0.5}$

$$\text{We know that } t_{av} = \frac{1}{K} \quad (\text{i})$$

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

$$\text{or } t_{av} = \frac{1}{K} = t_{0.5} \times 1.44 \quad (\text{ii})$$

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 a radon sample be left over? (I.I.T 1981, MLNR 1976)

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

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

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

$$\begin{aligned} t &= \frac{2.303 \times 3.8}{0.693} \times \log 20 = \frac{2.303 \times 3.8}{0.693} \times \log (10 \times 2) \\ &= \frac{2.303 \times 3.8}{0.693} [\log 10 + \log 2] \\ &= \frac{2.303 \times 3.8}{0.693} [1 + 0.301] \quad (\because \log 2 = 0.301) \\ &= 16.42 \text{ days} \end{aligned}$$

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 :

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

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

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

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

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

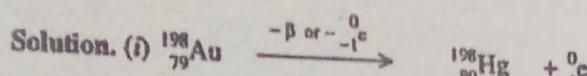
Thus the amount of Ra left undisintegrated after 4740 yrs = 0.125 g.

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

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

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)



$$N_0 = 1 \text{ g} \quad (N_0 - N) = (1 - N)$$

(ii) Amount Au left undisintegrated after 260 hrs

$$N = N_0 \times \left(\frac{1}{2}\right)^{t/t_{1/2}} = 1 \times \left(\frac{1}{2}\right)^{260/65} = 1 \times \left(\frac{1}{2}\right)^4 = \frac{1}{16}$$

$$\therefore \text{Amount of Hg obtained} = (N_0 - N) \text{ g} = 1 - \frac{1}{16} = \frac{15}{16} \text{ g}$$

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 yr^{-1}) for the decay? What fraction would remain after 11540 years? (I.I.T. 1984)

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

(i) Rate constant, K is given by :

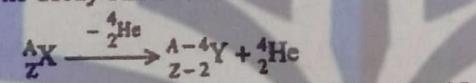
$$K = \frac{0.6932}{t_{0.5}} = \frac{0.6932}{5770 \text{ yrs.}} = 1.2 \times 10^{-4} \text{ yrs}^{-1}$$

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

Thus the fraction of the radioactive carbon that is left undisintegrated after 11540 yrs = $\frac{1}{4} = 25\%$ of the initial amount of carbon.

Example 6.9. A certain radioisotope ${}^A_Z\text{X}$ (half life = 10 days) decays to give ${}^{A-4}_{Z-2}\text{Y}$. If 1.0 g atom of ${}^A_Z\text{X}$ is kept in a sealed vessel, how much helium will accumulate in 20 days? Express the result in cm^3 at STP. (Roorkee Entrance 1987)

Solution. The decay can be shown as :



$$N_0 \quad (N_0 - N) = (1 - N)$$

$$\text{Now } N = N_0 \left(\frac{1}{2}\right)^{t/t_{1/2}} = 1 \times \left(\frac{1}{2}\right)^{20/10} = \left(\frac{1}{2}\right)^2 = \frac{1}{4}$$

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

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

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 1982)

Solution We know that :

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

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

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. Its

CELL # 0321-9432968/ 0345-4536450
half-life period is 20 seconds. How many nuclei will be left after 10 seconds?

Solution. We know that

$$\begin{aligned} N &= N_0 \left(\frac{1}{2}\right)^n = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}} \quad (\because t = n \times t_{0.5}) \\ &= 10^6 \times \left(\frac{1}{2}\right)^{10/20} = 10^6 \times \left(\frac{1}{2}\right)^{1/2} \text{ or } N = 10^6 \times 0.707 \end{aligned}$$

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.

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

$$\begin{aligned} \therefore t &= \frac{2.303 \times t_{0.5}}{0.693} \log \frac{N_0}{N} = \frac{2.303 \times 1590}{0.693} \times \log \frac{1}{0.01} \\ &= \frac{2.303 \times 1590}{0.693} \log 100 = \frac{2.303 \times 1590 \times 2}{0.693} = 10567.8 \text{ yrs} \end{aligned}$$

(ii) Initial amount = 1 gram

$$\text{Amount that remained undisintegrated} = 1 - 0.01 = 0.99 \text{ gram}$$

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

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:

$$K_A N_A = K_B N_B \text{ or } \frac{N_A}{N_B} = \frac{K_B}{K_A} \quad (i)$$

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

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

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:

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

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

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, a 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

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

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:

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

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

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

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 = $KN = \frac{0.693}{t_{0.5}} \times N$... (i)

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 :

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

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

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

$$\text{CELL \# 0321-9432968/0345-4536450}$$

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

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)

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

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

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 Rn²²⁰ is 54.5 s. What mass of this nucleus is equivalent to 1 millicurie (mci)?

Solution. Activity of Rn²²⁰ = 1 mci = 3.7×10^7 dis s⁻¹

Let the mass of Rn²²⁰ = 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 Pu²³⁹. Given that $t_{0.5} = 24,300$ yrs and 1 yr = 3.15×10^7 s

Solution. Activity of Pu²³⁹ is given by:

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

Advanced Inorganic Chemistry — Vol. I

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

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

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

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

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

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

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

$$= \frac{0.693}{9.78} \times 10^{10} \text{ yr} = \frac{69.3}{9.78} \times 10^9 \text{ yr} \quad \text{or} \quad t_{0.5} = 7.08 \times 10^8 \text{ y}$$

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

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

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

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 3.7×10^{10} disintegrations per second.

(Roorkee 1986)

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

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

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

$$\therefore x = \frac{14 \times 3.70 \times 10^7}{3.83 \times 10^{-12} \times 6.022 \times 10^{23}} \text{ g} = 0.224 \times 10^{-3} \text{ g}$$

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 an activity of 8640 counts per minute at one time and 7620 counts per minute after 1 hr. Calculate the disintegration constant?

Solution. We know that

CELL # 0321-9432968 / 0345-4536450

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

$$= \frac{2.303}{1 \times 60 \text{ min}} \times \log_{10} \frac{8640}{7620} = 0.0383 \times \log 1.19 \text{ min}^{-1} = 2.09 \times 10^{-3} \text{ min}^{-1}$$

Example 6.22. The rate of decay of Co^{60} changes from an initial value of 3112 dpm to 980 dpm in 42 days. Compute the value of half-life of Co^{60} .

Solution. We know that

$$t = \frac{2.303}{K} \log_{10} \frac{A_0}{A} \quad \text{or} \quad t = \frac{2.303 \times (t_{0.5})}{0.693} \log_{10} \frac{A_0}{A} \quad \left[\because K = \frac{0.693}{t_{0.5}} \right]$$

$$42 \text{ d} = \frac{2.303 \times (t_{0.5})}{0.693} \log_{10} \frac{3112}{980} = \frac{2.303 \times t_{0.5}}{0.693} \times 0.5018$$

$$\therefore t_{0.5} = \frac{42 \times 0.693}{2.303 \times 0.5018} \text{ d} = \frac{29.106}{1.1556} = 25.18 \text{ d}$$

Example 6.23. A count rate-meter is used to measure the activity of a given sample. At one time the meter shows 4750 counts min^{-1} . Five minutes later it shows 2700 counts min^{-1} . Find the decay constant and half-life of the sample. (Roorkee 86, MLNR 85)

Solution. (i) We know that

$$t = \frac{2.303}{K} \log_{10} \frac{A_0}{A} \quad \text{or} \quad 5 = \frac{2.303}{K} \log_{10} \frac{4750}{2700}$$

$$\text{or} \quad K = \frac{2.303}{5} \log \frac{4750}{2700} = 0.4606 \times \log 1.759 \quad \text{or} \quad K = 0.4606 \times 0.2455 = 0.1130 \text{ min}^{-1}$$

$$(ii) t_{0.5} = \frac{0.6932}{K} = \frac{0.6932}{0.1130 \text{ min}^{-1}} = 6.1345 \text{ min.}$$

Example 6.24. The activity of a radioactive isotope falls to 12.5% in 90 days. Compute the half-life and decay constant of the isotope. (MLNR 1986)

Solution. We know that

$$t = \frac{2.303}{K} \log_{10} \frac{A_0}{A}$$

$$\text{or} \quad K = \frac{2.303}{t} \log_{10} \frac{A_0}{A} = \frac{2.303}{90 \text{ d}} \log_{10} \frac{100}{12.5}$$

$$= 0.0255 \times \log_{10}(2)^3 = 0.0255 \times 3 \times \log 2$$

$$= 0.0255 \times 3 \times 0.301 = 0.02312 \text{ d}^{-1}$$

$$\text{Now } t_{0.5} = \frac{0.693}{k} = \frac{0.693}{0.0231} \text{ d} = 30.10 \text{ d}$$

Example 6.25. The activity of a radioactive substance falls to 87.5% of its initial value after 5 yrs. Compute the half-life period of the substance. After what time the activity will fall by 87.5% ($\log 87.5 = 1.9420$ and $\log 12.5 = 1.0969$)

Solution. We know that

$$K = \frac{2.303}{t} \log \frac{A_0}{A} = \frac{2.303}{5 \text{ yrs}} \times \log \frac{100}{87.5}$$

$$= 0.4606 \times [\log 100 - \log 87.5] \text{ yrs}^{-1} = 0.4606 \times [2 - 1.9420] \text{ yrs}^{-1}$$

$$= 0.4606 \times 0.0580 \text{ yrs}^{-1} = 0.02671 \text{ yrs}^{-1}$$

$$\therefore t_{0.5} = \frac{0.693}{0.026} = 26.65 \text{ yrs}$$

Now let the time after which the activity falls by 87.5% be t , then

$$t = \frac{2.303}{K} \log \frac{A_0}{A} = \frac{2.303}{0.0267} \log \frac{100}{(100 - 87.5)} = \frac{2.303}{0.0267} \times \log \frac{100}{12.5} \text{ yrs}$$

$$= 86.254 \times [\log 100 - \log 12.5] \text{ yrs} = 86.254 \times [2 - 1.0969] \text{ yrs}$$

$$= 86.254 \times 0.9031 \text{ yrs.} = 77.89 \text{ yrs}$$

Example 6.26. The radioactive decay rate of a radioactive element is found to be 10^3 disintegrations per second at a certain time. If the half-life of the element is one second, find the decay rate after 1 second and after 3 seconds. (I.I.T. 1983)

Solution. We know that

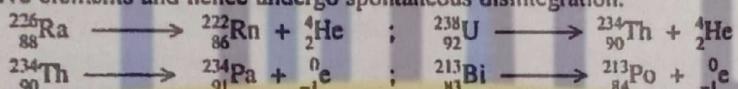
$$(i) N = N_0 \left(\frac{1}{2}\right)^n = N_0 \times \left(\frac{1}{2}\right)^{t/t_{1/2}} = 10^3 \times \left(\frac{1}{2}\right)^{1/1} = 10^3 \times \frac{1}{2} = 500$$

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

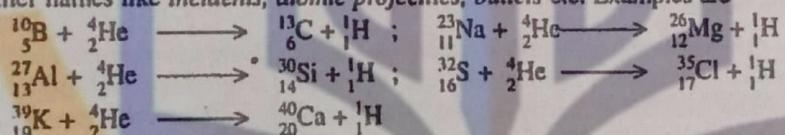
Transmutation or disintegration of elements

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.

(i) **Natural or spontaneous transmutation or disintegration.** In this transmutation, a *radioactive 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 are radioactive elements and hence undergo spontaneous disintegration.

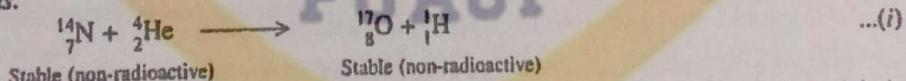


(ii) **Artificial transmutation or artificial disintegration.** In this transmutation, a *stable* (non-radioactive) element is converted into another *stable element* by bombarding it with bombarding particles like α -particles, protons, deuterons etc. The bombarding particles are called by many other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

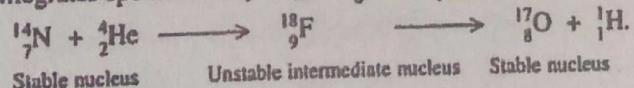


Discovery of artificial transmutation

It was for the first time in 1919 when Rutherford showed that when nitrogen atom ${}^7_7\text{N}$ (which is a stable element) is bombarded by energised α -particles, it is converted into ${}^8_8\text{O}$ atom and proton (${}^1_1\text{H}$) is emitted. ${}^8_8\text{O}$ is also a stable element. ${}^7_7\text{N}$ nucleus is called *target nucleus* while ${}^8_8\text{O}$ is called *recoil nucleus*.



Explanation of reaction (i). Rutherford proved by experiments that in reaction (i) α -particle is captured by ${}^7_7\text{N}$ nucleus and unstable intermediate nucleus namely ${}^{18}_9\text{F}$ is formed. ${}^{18}_9\text{F}$, being unstable, disintegrates spontaneously to give ${}^8_8\text{O}$ and ${}^1_1\text{H}$. Thus reaction (i) can be shown as:



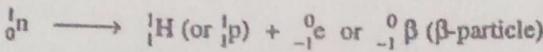
Some important particles

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 our discussion. The following are important particles.

(i) **Alpha particle** [${}^4_2\text{He}$ or ${}^4_2\text{He}$]. It is a helium nucleus which contains 2 protons and 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 ${}_{-1}^0\beta$ 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 ${}_1^1p$).



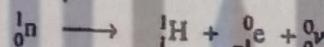
(iii) γ -ray ${}_{0}^0\gamma$. It is an electromagnetic radiation of very short wave length. Its mass number and charges (atomic number) on it both are zero. Thus γ -ray is neutral and massless ray and hence is represented as ${}_{0}^0\gamma$.

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

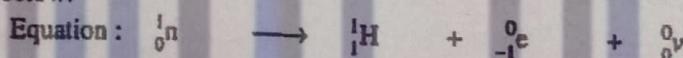
(v) Triton ${}_{+1}^3H$ or ${}_{+1}^3H$ or ${}_{+1}^3T$ or ${}_{+1}^3T$. It is the nucleus of heavy hydrogen atom called tritium. Its mass number (A) = 3 and atomic number (Z) = 1.

(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 (${}_{-1}^0e$).

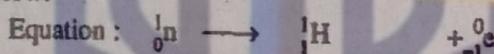


The above equation is balanced in so far as angular momentum values of different particles is concerned, as shown below:



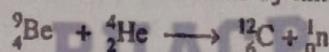
$$\text{Angular momentum values : } +\frac{1}{2} \cdot \frac{h}{2\pi} + +\frac{1}{2} \cdot \frac{h}{2\pi} - \frac{1}{2} \cdot \frac{h}{2\pi} + \frac{1}{2} \cdot \frac{h}{2\pi}$$

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



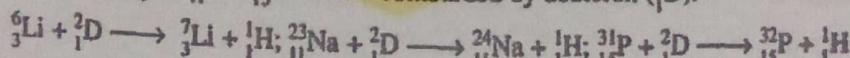
$$\text{Angular momentum values : } +\frac{1}{2} \cdot \frac{h}{2\pi} + \frac{1}{2} \cdot \frac{h}{2\pi} - \frac{1}{2} \cdot \frac{h}{2\pi}$$

(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 ${}_0^1n$.

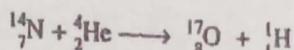


Neutrons can also be obtained by many other nuclear reactions.

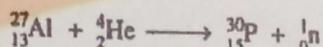
(viii) Proton (${}_{+1}^1H$ or ${}_{+1}^1H$ or ${}_{+1}^1p$). It is the nucleus of ordinary hydrogen atom. Its mass number is 1 and charge equal to +1. This particle is present in the nucleus of the atom of all elements. Its presence in the nucleus was realised by its production in the nuclear reaction in which lighter elements like ${}_{3}^6\text{Li}$, ${}_{11}^{23}\text{Na}$, ${}_{15}^{31}\text{P}$ etc. are bombarded by deuteron (${}_{+1}^2D$).



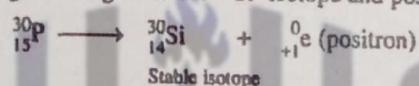
and in Rutherford's artificial transmutation reaction (1919) in which he bombarded $^{14}_7\text{N}$ nucleus by α -particles



(ix) Positron. (${}^0_{+1}\text{e}$). 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 Irene 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 the emission of a neutron.



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



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 ${}^4_2\text{He}$), proton (${}^1_1\text{H}$ or ${}^1_1\text{H}$), deuteron (${}^2_1\text{H}$ or ${}^2_1\text{H}$), 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 which 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.

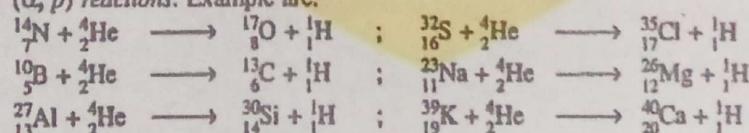
The positively-charged α -particles, protons and deuterons can be made to act as more effective projectiles, if their velocity is accelerated. For this purpose, several instruments have been developed. These instruments are called *projectile accelerators*. Some such instruments are *cyclotron* (made by E.O. Lawrence at the university of California, U.S.A), *Van de Graaf electrostatic 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 10^4 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

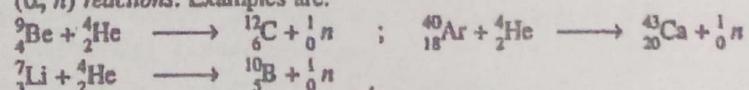
Artificial transmutation reactions induced by different bombarding particles may be of the following types:

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

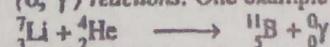
(a) (α, p) reactions. Examples are:



(b) (α, n) reactions. Examples are:

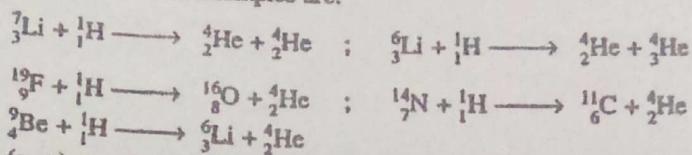


(c) (α, γ) reactions. One example of such reactions is given below:

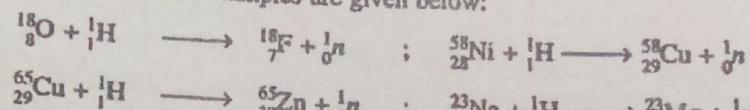


2. Artificial transmutation reactions induced by protons (1H). These reactions may be of the following types:

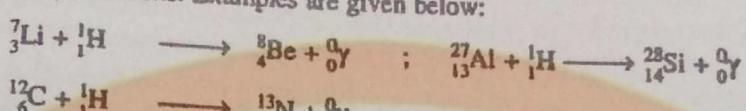
(a) (p, α) reactions. Examples are:



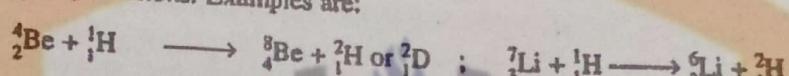
(b) (p, n) reactions. Examples are given below:



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

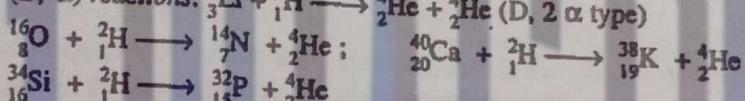


(d) (p, D) reactions. Examples are:

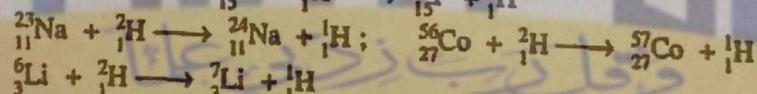


3. Artificial transmutation reactions induced by deuterons (2H or 2D). These reactions may be of the following types:

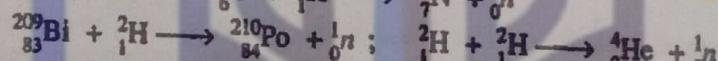
(a) (D, α) reactions: ${}^3_3Li + {}^2_1H \longrightarrow {}^4_2He + {}^4_2He$ (D, 2 α type)



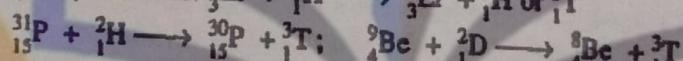
(b) (D, p) reactions: ${}_{15}^{31}P + {}^2_1H \longrightarrow {}_{15}^{32}P + {}^1_1H$



(c) (D, n) reactions: ${}_{12}^{12}C + {}^2_1H \longrightarrow {}_7^{13}N + {}_0^1n$

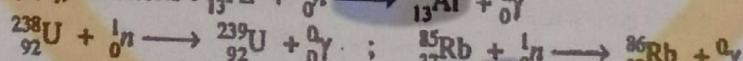


(d) (D, T) reactions: ${}^3_3Li + {}^2_1H \longrightarrow {}_3^6Li + {}_1^3H \text{ or } {}_1^3T$

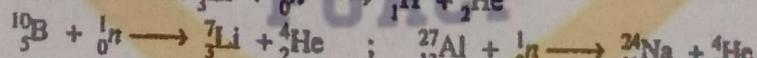


4. Artificial transmutation reactions induced by neutrons (${}_0^1n$). Examples are:

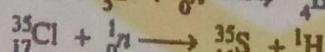
(a) (n, γ) reactions: ${}_{13}^{27}Al + {}_0^1n \longrightarrow {}_{13}^{28}Al + {}_0^0\gamma$



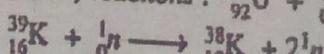
(b) (n, α) reactions: ${}^3_3Li + {}_0^1n \longrightarrow {}_1^3H + {}^4_2He$

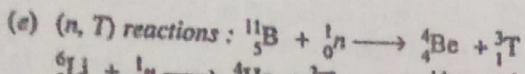


(c) (n, p) reactions: ${}_{11}^{23}B + {}_0^1n \longrightarrow {}_{11}^{21}Be + {}_1^1H$



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





5. Artificial transmutation reactions induced by tritons (3_1H or 3_1T). Examples are:

- (a) (T, p) reactions $^{59}_{27}\text{Co} + ^3_1\text{H} \rightarrow ^{61}_{27}\text{Co} + ^2_1\text{H}$
- (b) (T, d) reactions $^{6}_3\text{Li} + ^3_1\text{H} \rightarrow ^7_3\text{Li} + ^2_1\text{H}$; $^{63}_{29}\text{Cu} + ^3_1\text{H} \rightarrow ^{64}_{29}\text{Cu} + ^2_1\text{H}$
- (c) (T, n) reactions $^{32}_{16}\text{S} + ^3_1\text{H} \rightarrow ^{34}_{17}\text{Cl} + ^1_0n$
- (d) (T, α) reactions $^{7}_3\text{Li} + ^3_1\text{H} \rightarrow ^6_2\text{He} + ^4_2\text{He}$

6. Artificial transmutation reactions induced by γ -rays ($^0_0\gamma$). Nuclear reactions induced by γ -rays or photons are called *photo disintegration reactions*. Examples are:

- (a) (γ, n) reactions $^{2}_1\text{H} + ^0_0\gamma \rightarrow ^1_1\text{H} + ^1_0n$; $^{9}_4\text{Be} + ^0_0\gamma \rightarrow ^8_4\text{Be} + ^1_0n$
 $^{31}_{15}\text{P} + ^0_0\gamma \rightarrow ^{30}_{15}\text{P} + ^1_0n$
- (b) (γ, p) reactions $^{25}_{12}\text{Mg} + ^0_0\gamma \rightarrow ^{24}_{11}\text{Na} + ^1_1\text{H}$
- (c) ($\gamma, 2p, n$) reactions $^{27}_{13}\text{Al} + ^0_0\gamma \rightarrow ^{24}_{11}\text{Na} + 2^1_1\text{H} + ^1_0n$

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

- (a) $^{106}_{46}\text{Pd} (\alpha, p)$ $^{109}_{47}\text{Ag}$ (b) $^6_3\text{Li} (^3_1\text{He}, n)$ ^8_5B (c) $^{31}_{15}\text{P} (d, p)$ $^{32}_{15}\text{P}$ (d) $^9_4\text{Be} (d, 2p)$ ^9_3Li (e) $^{12}_6\text{C} (p, \gamma)$ $^{13}_{7}\text{N}$
- (f) $^{27}_{13}\text{Al} (\alpha, p)$ $^{30}_{15}\text{P}$.

Solution. We have:

- (a) $^{106}_{46}\text{Pd} + ^4_2\text{He} \rightarrow \left[^{110}_{48}\text{Cd} \right] \rightarrow ^{109}_{47}\text{Ag} + ^1_0n$
- (b) $^6_3\text{Li} + ^3_1\text{He} \rightarrow \left[^9_5\text{B} \right] \rightarrow ^8_5\text{B} + ^1_0n$
- (c) $^{31}_{15}\text{P} + ^2_1\text{H} \rightarrow \left[^{33}_{16}\text{S} \right] \rightarrow ^{32}_{15}\text{P} + ^1_0n$
- (d) $^9_4\text{Be} + ^2_1\text{H} \rightarrow \left[^{11}_5\text{B} \right] \rightarrow ^9_3\text{Li} + 2^1_1\text{H}$
- (e) $^{12}_6\text{C} + ^1_0n \rightarrow \left[^{13}_7\text{N} \right] \rightarrow ^{13}_7\text{N} + ^0_0\gamma$
- (f) $^{27}_{13}\text{Al} + ^4_2\text{He} \rightarrow \left[^{31}_{15}\text{P} \right] \rightarrow ^{30}_{15}\text{P} + ^1_0n$

- Example 6.28. Construct equations for the following conversions : (a) $^{59}_{27}\text{Co} (n, \gamma)$ $^{60}_{27}\text{Co}$ (b) $^{14}_7\text{N} (n, p)$ $^{14}_6\text{C}$ (c) $^9_4\text{Be} (\alpha, n)$ $^{12}_6\text{C}$ (d) $^7_3\text{Li} (\alpha, \gamma)$ $^{11}_5\text{B}$ (e) $^{96}_{42}\text{Mo} (d, n)$ $^{97}_{43}\text{Tc}$ (f) $^{144}_{62}\text{Sn} (n, \gamma)$ $^{145}_{62}\text{Sm}$ (g) $^{209}_{83}\text{Bi} (\alpha, 2n)$ $^{211}_{85}\text{At}$ (h) $^{232}_{90}\text{Th} (^{12}_6\text{C}, 4n)$ $^{240}_{96}\text{Cm}$.

Solution. (a) $^{59}_{27}\text{Co} + ^1_0n \rightarrow ^{60}_{27}\text{Co} + ^0_0\gamma$

- (b) $^{14}_7\text{N} + ^1_0n \rightarrow ^{14}_6\text{C} + ^1_0n$ (c) $^9_4\text{Be} + ^4_2\text{He} \rightarrow ^{12}_6\text{C} + ^1_0n$
- (d) $^7_3\text{Li} + ^4_2\text{He} \rightarrow ^{11}_5\text{B} + ^0_0\gamma$ (e) $^{96}_{42}\text{Mo} + ^2_1\text{H} \rightarrow ^{97}_{43}\text{Tc} + ^1_0n$
- (f) $^{144}_{62}\text{Sn} + ^1_0n \rightarrow ^{145}_{62}\text{Sm} + ^0_0\gamma$ (g) $^{209}_{83}\text{Bi} + ^4_2\text{He} \rightarrow ^{211}_{85}\text{At} + 2^1_0n$
- (h) $^{232}_{90}\text{Th} + ^{12}_6\text{C} \rightarrow ^{240}_{96}\text{Cm} + 4^1_0n$

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 b_X . Therefore :

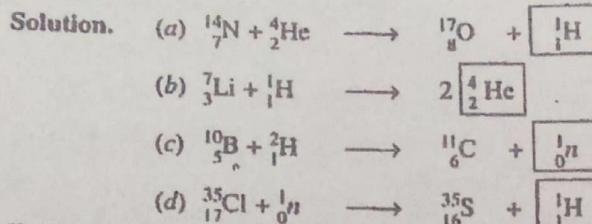
$$\frac{238}{92}\text{U} + {}^b_X = \frac{247}{99}\text{Es} + 5^1_0n \quad \therefore 238 + b = 247 + 5$$

$$\text{or } b = (247 + 5) - 238 = 14; \quad 92 + b = 99 \quad \therefore b = 99 - 92 = 7$$

Thus the bombarding particle is ${}_{7}^{14}\text{N}$.

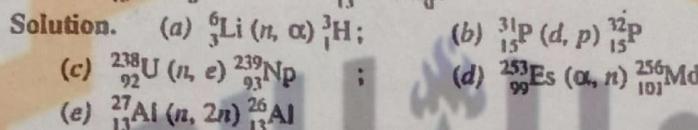
Example 6.30. Fill in the blanks :

- ${}_{7}^{14}\text{N} + {}_{2}^{4}\text{He} \longrightarrow {}_{8}^{17}\text{O} + \dots$
- ${}_{3}^{7}\text{Li} + {}_{1}^{1}\text{H} \longrightarrow 2 \quad \dots$
- ${}_{5}^{10}\text{B} + {}_{1}^{2}\text{H} \longrightarrow {}_{6}^{11}\text{C} + \dots$
- ${}_{17}^{35}\text{Cl} + {}_{0}^{1}\text{n} \longrightarrow {}_{16}^{35}\text{S} + \dots$



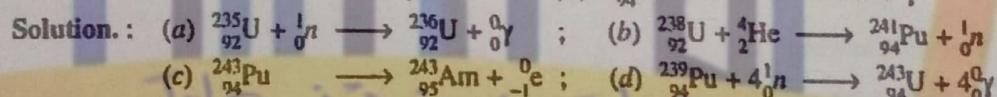
Example 6.31. Express the following reactions in shorthand notation.

- ${}_{3}^{6}\text{Li} + {}_{0}^{1}\text{n} \longrightarrow {}_{2}^{4}\text{He} + {}_{1}^{3}\text{H}$; (b) ${}_{15}^{31}\text{P} + {}_{1}^{2}\text{H} \longrightarrow {}_{15}^{32}\text{P} + {}_{1}^{1}\text{H}$
- ${}_{92}^{238}\text{U} + {}_{0}^{1}\text{n} \longrightarrow {}_{93}^{239}\text{Np} + {}_{-1}^{0}\text{e}$; (d) ${}_{99}^{253}\text{Es} + {}_{2}^{4}\text{He} \longrightarrow {}_{101}^{256}\text{Md} + {}_{0}^{1}\text{n}$
- ${}_{13}^{27}\text{Al} + {}_{0}^{1}\text{n} \longrightarrow {}_{13}^{26}\text{Al} + 2 {}_{0}^{1}\text{n}$



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

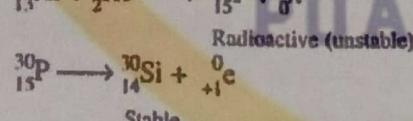
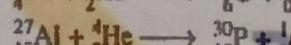
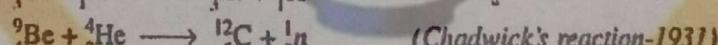
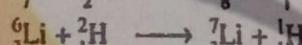
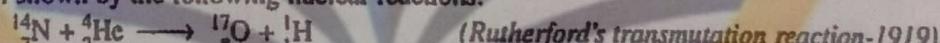
- ${}_{92}^{235}\text{U} + n \longrightarrow \dots + \gamma$; (b) ${}_{92}^{238}\text{U} + {}_{2}^{4}\text{He} \longrightarrow \dots + n$
- ${}_{94}^{243}\text{Pu} \longrightarrow {}_{95}^{243}\text{Am} + {}_{-1}^{0}\text{e}$; (d) ${}_{94}^{239}\text{Pu} + n \longrightarrow {}_{94}^{243}\text{Pu} + \gamma$



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 (${}_{0}^{1}\text{n}$) and positron (${}_{+1}^{0}\text{e}$) has been shown by the following nuclear reactions:

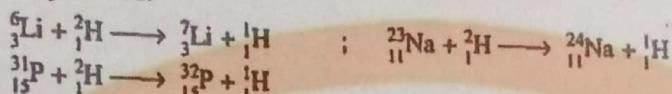


{ Experiment performed by Curie and Frederick Joliet (1934) }

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

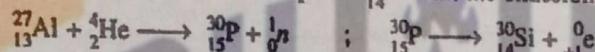
(a) The scattering of α -particles seen by Rutherford in his α -particle scattering experiment has proved the existence of positively charged nucleus at the centre of the atom of all elements. The extent of deflection of α -particles has established that the atomic number of an element is numerically 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.

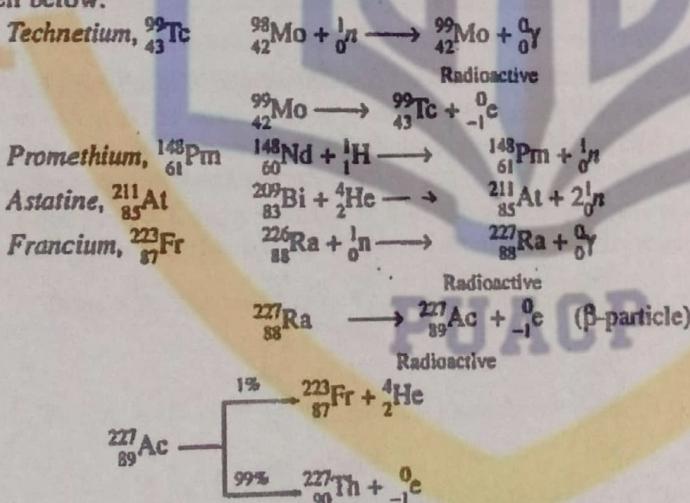
(c) The bombardment of ${}^{27}\text{Al}$ isotope by α -particles produces ${}^{30}\text{P}$ which is radioactive and hence disintegrates to give a stable isotope of ${}^{30}\text{Si}$ with the emission of positrons (${}_{+1}^0\text{e}$).



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 that 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 IA, ${}_{43}\text{Tc}$ 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
$^{238}_{92}\text{U}$	+ ^1_1H	→	$^{238}_{93}\text{Np} (\text{Neptunium}) + ^1_0n$
$^{239}_{92}\text{U}$	+ ^4_2He	→	$^{240}_{94}\text{Pu} (\text{Plutonium}) + ^1_0n$
$^{239}_{94}\text{Pu}$	+ ^4_2He	→	$^{241}_{95}\text{Am} (\text{Americium}) + ^1_1\text{H} + ^1_0n$
$^{239}_{94}\text{Pu}$	+ ^4_2He	→	$^{240}_{96}\text{Cm} (\text{Curium}) + ^3_0n$
$^{244}_{96}\text{Cm}$	+ ^4_2He	→	$^{245}_{97}\text{Bk} (\text{Berkelium}) + ^1_1\text{H} + ^2_1n$
$^{238}_{92}\text{U}$	+ $^{12}_6\text{C}$	→	$^{245}_{98}\text{Cf} (\text{Californium}) + ^5_1n$
$^{238}_{92}\text{U}$	+ $^{14}_7\text{N}$	→	$^{247}_{99}\text{Es} (\text{Einsteinium}) + ^5_0n$
$^{238}_{92}\text{U}$	+ $^{16}_8\text{O}$	→	$^{250}_{100}\text{Fm} (\text{Fermium}) + ^4_0n$
$^{253}_{99}\text{Es}$	+ ^4_2He	→	$^{256}_{101}\text{Md} (\text{Mendelevium}) + ^1_0n$
$^{246}_{96}\text{Cm}$	+ $^{13}_6\text{C}$	→	$^{251}_{102}\text{No} (\text{Nobelium}) + ^8_0n$
$^{252}_{98}\text{Cf}$	+ $^{10}_5\text{B}$	→	$^{257}_{103}\text{Lw} (\text{Lawrencium}) + ^5_0n$
$^{242}_{94}\text{Pu}$	+ $^{22}_{10}\text{Ne}$	→	$^{260}_{104}\text{Ku} (\text{Kurchatovium}) + ^4_0n$
$^{249}_{98}\text{Cf}$	+ $^{15}_7\text{N}$	→	$^{260}_{105}\text{Ha} (\text{Hahnium}) + ^4_0n$

(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, P-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
$^{23}_{11}\text{Na}$	+ ^1_1H	→	$^{24}_{11}\text{Na} + ^1_1\text{H}$
$^{27}_{13}\text{Al}$	+ 1_0n	→	$^{24}_{11}\text{Na} + ^4_2\text{He}$
$^{59}_{27}\text{Co}$	+ 1_0n	→	$^{60}_{27}\text{Co}$
$^{27}_{13}\text{Al}$	+ ^4_2He	→	$^{30}_{15}\text{P} + ^1_0n$
$^{32}_{16}\text{S}$	+ 1_0n	→	$^{32}_{15}\text{P} + ^1_1\text{H}$
$^{14}_{7}\text{N}$	+ 1_0n	→	$^{14}_{6}\text{C} + ^1_1\text{H}$
$^{10}_{5}\text{B}$	+ ^4_2He	→	$^{13}_{7}\text{N} + ^1_0n$

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

Stable isotope (Non-radio- active isotope)	Bombarding projectile		Stable isotope (Non-radioactive isotope)
$^{14}_{7}\text{N}$	+ ^4_2He	→	$^{17}_{8}\text{O} + ^1_1\text{H}$
$^{10}_{5}\text{B}$	+ ^4_2He	→	$^{13}_{6}\text{C} + ^1_1\text{H}$
$^{23}_{11}\text{Na}$	+ ^4_2He	→	$^{26}_{12}\text{Mg} + ^1_1\text{H}$
$^{27}_{13}\text{Al}$	+ ^4_2He	→	$^{30}_{14}\text{Si} + ^1_1\text{H}$
$^{32}_{16}\text{S}$	+ ^4_2He	→	$^{35}_{17}\text{Cl} + ^1_1\text{H}$
$^{39}_{19}\text{K}$	+ ^4_2He	→	$^{40}_{20}\text{Ca} + ^1_1\text{H}$

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

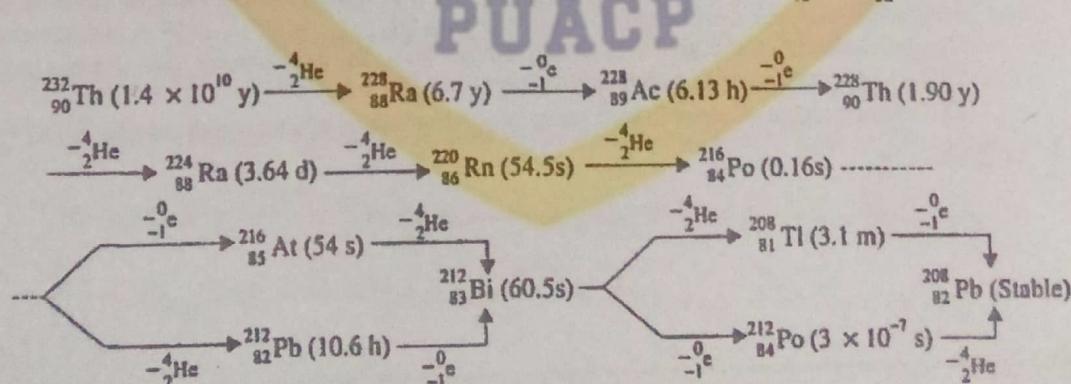
The isotopes of naturally occurring heavy elements like $^{232}_{90}\text{Th}$, $^{235}_{92}\text{U}$, $^{238}_{92}\text{U}$ etc. are unstable and hence are constantly emitting α and β particles and giving rise to the formation of new radioactive elements. Being radioactive, these new elements spontaneously 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 $^{232}_{90}\text{Th}$, $^{235}_{92}\text{U}$ and $^{238}_{92}\text{U}$ 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 $^{232}_{90}\text{Th}$, $^{235}_{92}\text{U}$ and $^{238}_{92}\text{U}$ are called natural radioactive series. Obviously these series are of three types as shown below:

(i) *Thorium-232 or 4n series* ($^{232}_{90}\text{Th} - ^{208}_{82}\text{Pb}$). 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).

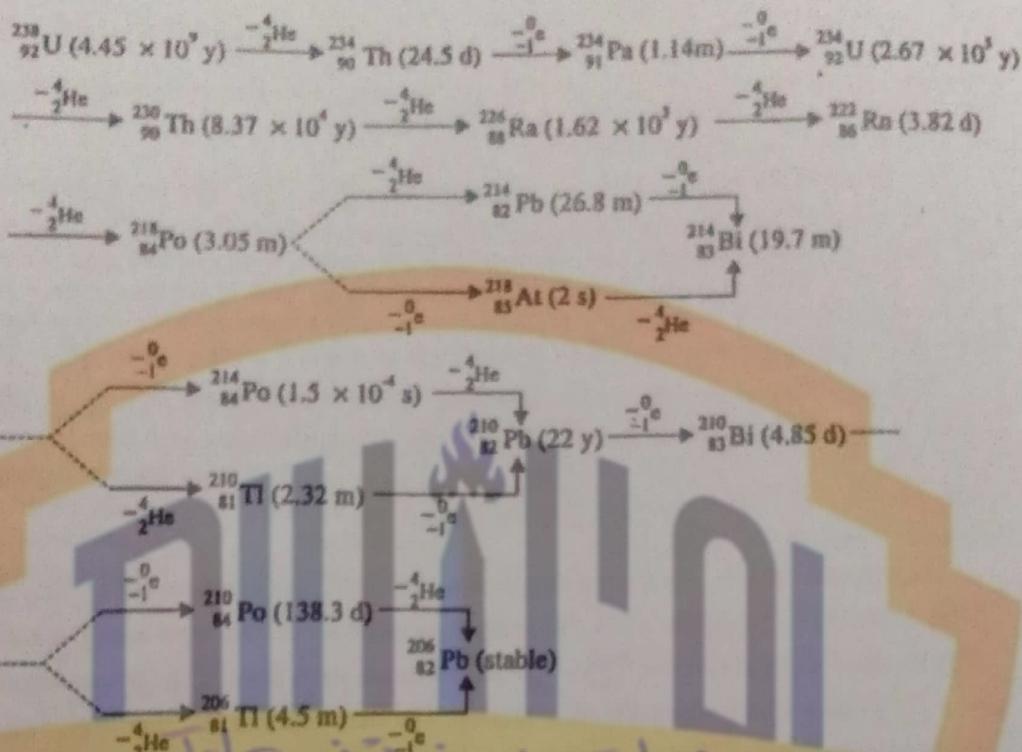
Table 6.3: Thorium-232 or 4n series (natural radioactive series [$^{232}_{90}\text{Th} - ^{208}_{82}\text{Pb}$ series])



(ii) *Uranium-238 or (4n+2) series* [$^{238}_{92}\text{U} - ^{206}_{82}\text{Pb}$]. This series has $^{238}_{92}\text{U}$ as its parent element and $^{206}_{82}\text{Pb}$ 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 $^{206}_{82}\text{Pb}$

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) [$^{238}_{92}\text{U} \rightarrow ^{206}_{82}\text{Pb}$ series]

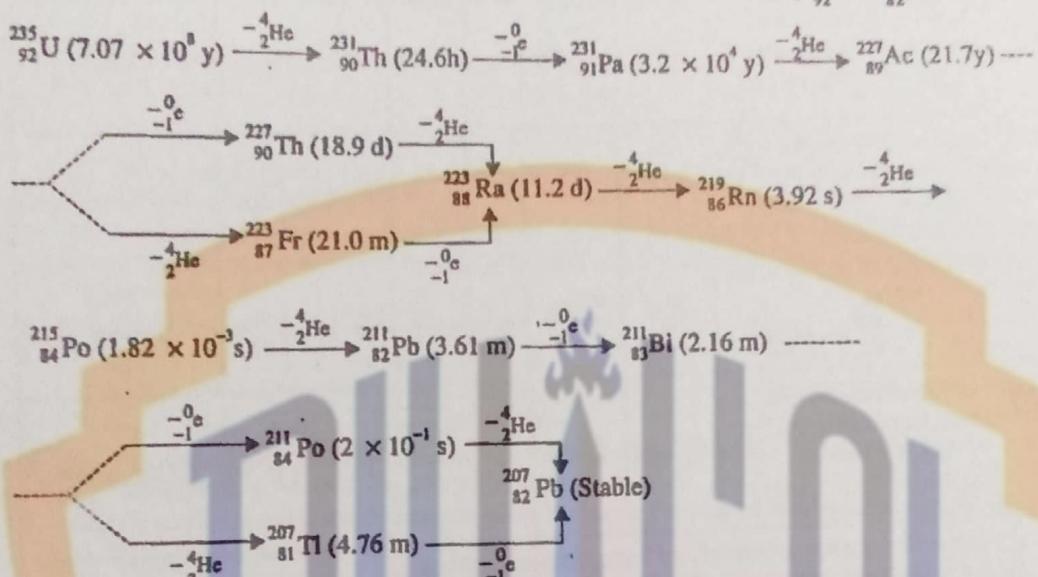


(iii) Uranium-235 or ($4n + 3$) series [$^{235}_{92}\text{U} \rightarrow ^{207}_{82}\text{Pb}$ series]. This series starts with $^{235}_{92}\text{U}$ and ends at $^{207}_{82}\text{Pb}$ which is a stable element. If the mass number of each member of this series is divided by 4, then 3 is obtained as a 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 $^{208}_{82}\text{Pb}$, $^{207}_{82}\text{Pb}$ or $^{206}_{82}\text{Pb}$.

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

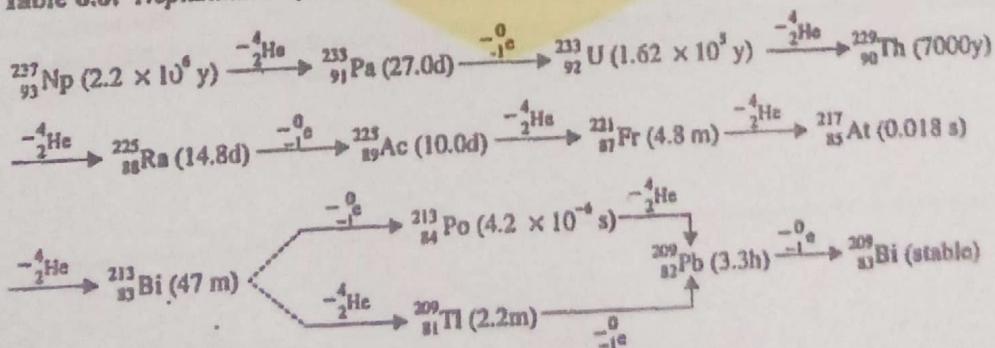


Neptunium-237 or (4n+1) series ($^{237}_{93}Np - ^{209}_{83}Bi$ Series) : Artificial radioactive series

This series was discovered after the discovery of trans-uranic elements. The possibility of the existence of this series was suggested by A.S. Russel 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, these members have been obtained by artificial methods in the laboratory.

This series starts with $^{237}_{93}Np$ (parent element : longest lived element) and ends at $^{209}_{83}Bi$ (end element) which is a stable element. The parent element viz. $^{237}_{93}Np$ decays into $^{233}_{91}Pa$ by emitting an α -particle. $^{233}_{91}Pa$ emits a β -particle to form $^{233}_{92}U$ and so on until a stable end product viz. $^{209}_{83}Bi$ 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 $^{237}_{93}Np$ and $^{209}_{83}Bi$ 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. $^{237}_{93}Np$ ($= 2.2 \times 10^6$ 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 $^{237}_{93}Np$ to $^{209}_{83}Bi$ can be calculated with the help of the equations $237 - 4x = 209$ and $93 - 2x + y = 83$ 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) [$^{237}_{93}Np - ^{209}_{83}Bi$ 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.

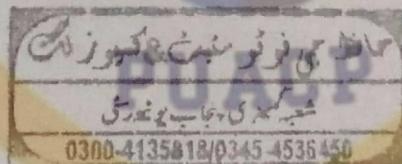
University Questions

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

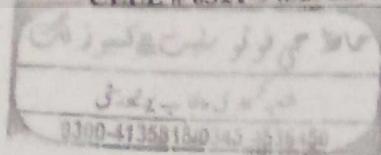
Advanced Inorganic Chemistry

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.
 (Meerut, 94)

(i) $^{24}_{11}\text{Na} \longrightarrow \text{X} + {}_{-1}^0\text{e}$	(ii) $^{24}_{11}\text{Na} + {}_0^1\text{n} \longrightarrow {}^{14}\text{Y} + {}_Z^Q$
(iii) $^{27}_{14}\text{Si} \longrightarrow {}^{27}_{13}\text{Q} + {}_{+1}^0\text{e}$	(iv) $\text{R} + {}_2^4\text{He} \longrightarrow {}^{15}_{7}\text{N} + {}_0^1\text{n}$
9. The amount of C-14 in a piece of wood is found to be one-sixth of its amount in a fresh piece of wood. Calculate the age of the wood.
 (Bahuguna, 92)
10. At radioactive equilibrium the ratio between atoms of the two radioactive elements A and B was found 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 the element B?
 (Meerut M.Sc., 94)
11. Complete the following nuclear reactions:
 (i) ${}^7\text{N}^{14} + \dots \longrightarrow {}^8\text{O}^{17} + {}_1\text{H}^1$ (ii) ${}^{15}\text{P}^{30} \longrightarrow {}^{14}\text{Si}^{30} + \dots$
 (iii) ${}^{13}\text{Al}^{27} + {}_0\text{n}^1 \longrightarrow \dots + {}_2\text{He}^4$ (iv) ${}^4\text{Be}^9 + {}_2\text{He}^4 \longrightarrow \dots + {}_0\text{n}^1$
 (v) $\dots + {}_0\text{n}^1 \longrightarrow {}^5\text{B}^{11} + {}_2\text{He}^4$
 (Meerut, 93)
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, 93)
13. The half-life period of a radioactive element is 1600 years. Calculate the disintegration constant.
 (Meerut, 96)
14. Complete the following:
 (i) ${}^7\text{N}^{14} + \dots \longrightarrow {}^6\text{C}^{11} + {}_2\text{He}^4$ (ii) ${}^{13}\text{Al}^{27} + \dots \longrightarrow {}^{12}\text{Mg}^{27} + {}_1\text{H}^1$
 (iii) ${}^{13}\text{Al}^{27} + \dots \longrightarrow {}^{15}\text{P}^{30} + {}_0\text{n}^1$ (iv) ${}^{11}\text{Na}^{24} \longrightarrow {}^{12}\text{Mg}^{24} + \dots$
 (v) ${}^4\text{Be}^9 + {}_2\text{He}^4 \longrightarrow {}^6\text{C}^{12} + \dots$
 (Meerut, 96)
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, 95)
16. What is artificial transmutation? Give the nuclear reactions induced by neutron, proton and α -particles.
 (Osmania, 93)
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 2.0 and 98.0 respectively. What are the decay constant (λ) for each of the separate paths.
 (I.I.T., 96)



Mam. Rabi



Detection of Radioactivity

Although some forms of electromagnetic energy, such as light and heat, can be detected by the human senses. One of the greatest draw backs to high energy radiation is the inability to detect it. We cannot see, feel, taste, smell, or hear the various forms of ionizing radiation. Fortunately, ionizing radiation interacts with matter which makes detection and measurement possible by utilizing specialized equipment. In this section we want to introduce you to the various ways and means of detecting and measuring ionizing radiation.

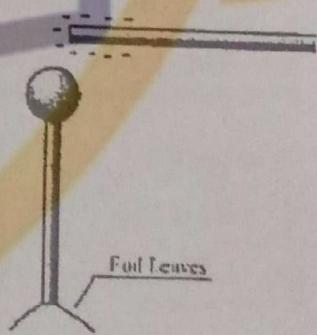
Becquerel discovered radioactivity because it left marks on photographic film. However, there are more definitive means commonly used by scientists and technicians who study and work with radiation. The equipment utilized for the detection and measurement of radiation commonly employs some type of substance or material that responds to radiation. Many common methods use either an ionization process or molecular excitation process as a basis. Remember that radiation interacts with matter. For detection and measurement purposes the process of ionization is the most commonly employed technique, based on the principle of charged particles producing ion pairs by direct interaction. These charged particles may collide with electrons, which remove them from their parent atoms, or transfer energy to an electron by interaction of electric fields.

There are three types of radiation detection devices:

- o The Electroscope
- o The Cloud Chamber
- o Other Detection Devices

THE ELECTROSCOPE

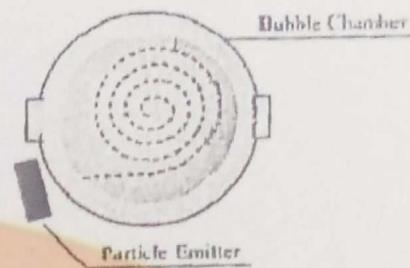
Marie Curie used an electroscope to study the radioactivity of Uranium ores. The electroscope is a fairly simple device comprised of a metal rod with two thin leaves attached to one end. If the electroscope is given a negative charge, the metal leaves will separate from each other. It is this characteristic that makes the electroscope useful as a detection device. A negatively charged electroscope will discharge when ions in the air remove electrons from it, and consequently, a positively charged electroscope will discharge when it takes electrons from the air around it. The rate of discharge of the electroscope is a measure of ions in the air and can be used as a basis of measurement and detection.



THE CLOUD CHAMBER

A unique device for detection and measurement is the Cloud Chamber, invented by the British physicist Charles Wilson in 1911. The Cloud chamber makes it possible to visually see the path of ionizing radiation thus making it possible to photograph it. The cloud chamber consists of a plastic or glass container, which sits on dry ice. A dark cloth

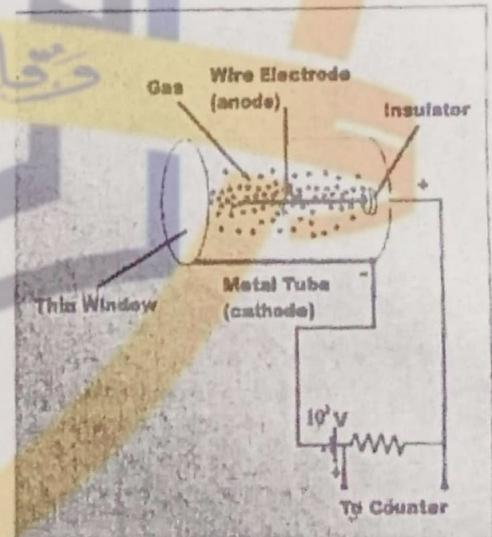
is saturated with alcohol and placed around the inside of the container near the top. A small radioactive material may be suspended from the lid of the container. In the chamber, the alcohol evaporates from the cloth and condenses as it reaches the cold region created by the dry ice at the floor of the container. Just above the floor of the chamber there is a region where the alcohol vapor does not condense unless there are seeds around, so that drops of alcohol can form. This condition is similar to that of seeding clouds with a chemical to form rain. The idea is that only seeds available in the chamber are those of ions produced by the interaction with radiation. The resulting trail of alcohol droplets can be seen against the black background in the bottom of the chamber.



These are only a few of the devices commonly utilized for purposes of detection and measurement of radioactivity and radiation. It is important to understand that when working with radioactivity/radiation, due to our inability to sense radiation, we need them to assist us in detecting the presence of radiation and we also need them to help monitor the radiation.

OTHER DETECTION DEVICES

Another common device used for detection and measurement is the ionization chamber. The **Geiger counter, survey meter, and personal dosimeters** work on the basis of the ionization chamber. The principle operation of an ionization chamber is that it will produce an electric current in the presence of a radioactive source. Ionization chambers consist of tubes filled with gas, such as argon. When radiation enters the tube and interacts with the gas, it removes electrons from the gas. The gas atoms become positively charged ions, and the free electrons move through the gas to a wire in the tube, setting up a current. The current is commonly amplified and sent to a recording or counting device. This in response may produce a flash of light, ticking sounds, or an analog readout. Ionization chambers are capable of measuring the amount of radiation by means of measuring the amount of current produced.



Measurement of Radioactivity

For measuring radioactivity, three types of devices are available:

1. Gas-filled tube counters e.g. the Geiger Muller Counter
2. Scintillation Counters
3. Semi-conductor Detectors

1. **The Geiger Counter:** A potential difference just below that required to produce a discharge is applied to the tube (1000 V). Any atoms of the gas struck by the γ -rays entering the tube are ionized, causing a discharge. Discharges are monitored and counted by electronic circuitry and the output is reported as counts/sec or Rontgens/hr or mR/hr. A Geiger counter will record "counts per minute", but this doesn't tell us what the radioactive substance is actually doing, merely what is reaching the detector. It also tells us nothing about the amount of damage being done to you.

2. **Scintillation Counters:** Crystals of certain substances e.g. cesium fluoride, cadmium tungstate, anthracine and sodium iodide emit small flashes of light when bombarded by γ -rays. The most commonly used phosphor in scintillation counters is NaI with a minute quantity of thallium added. In the instrument, the crystal is positioned against a photocell which in turn is linked to a recording unit. The number of flashes produced per unit time is proportional to the intensity of radiation. Small portable scintillation counters are available.

3. **Semi-Conductor Detectors:** A semi-conductor is a substance whose electrical conductivity is between that of a metal and an insulator. It is noted that Ge(Li) semi-conductors are excellent detectors of γ -rays with a resolution ten times higher than NaI (Th) scintillometers. The main disadvantage of these is a lower efficiency for higher energy α -rays. Besides, Ge(Li) semi-conductors need to be cooled by liquid nitrogen and are hence cumbersome and not suitable as field instruments.

Besides the above there are instruments known as γ -ray spectrometers, which can distinguish different energy peaks and hence make it possible to identify the source of radiation.

