31

NUCLEI AND RADIOACTIVITY

31.1 INTRODUCTION

You must have heard about the destructive powers of atom bombs. In the second world war, two big cities of Japan – Hiroshima and Nagasaki were completely destroyed by the effects of only one atom bomb falling on each cities. Can you imagine that such large amount of energy was released by breaking of nuclei of atoms. The atoms are themselves microscopic while the nuclei of atoms are still smaller about hundred thousandth part (1/100,000) of the size of an atom. Is it not surprising to know that such tiny masses have such large energies hidden in them? In an atom bomb, the breaking of the nuclei of atoms is a continuous, quick and uncontrolled process and hence vast amount of energy is released suddenly in a fraction of a second and causes destruction. However, the scientists have found a technique to release this nuclear energy in a controlled manner and convert it into useful forms of energy like heat and electricity etc.

The by-products of atom bomb and atomic reactors are also radioactive nuclei which emit certain radiations. These radiation can cause damage to human body. However, scientist have discovered some important uses of these radioactive sources of radiations. Do you know that the only available medical treatment of the fatal disease cancer is the exposure of the affected part to the γ (gamma) radiations from radioactive cobalt –60? In agriculture also, the fruits and vegetables can be preserved for years after exposure to gamma radiations. Not only this, radioactivity has been used in determining the age of old rocks and fossils. Would it not be interesting to know more about such nuclei and the property of radioactivity? For this let us study this lesson.

31.2 OBJECTIVES

After studying this lesson, you should be able to,

- *determine the number of protons and neutrons in the nuclei of different atoms;*
- *know about the nature of the nuclear forces;*
- *explain the mass defect and the binding energy;*
- *explain radioactivity and to distinguish between the three types of radiations – i.e. α, β and γ radiations.*
- *calculate the half life and average life and to measure the activity of a radioactive element; and*
- *explain the uses of radioactivity in various fields.*

31.3 ATOMIC NUCLEI

The discovery of the presence of positively charged nucleus containing protons inside the atom was made by Rutherford. It was later discovered by Chadwick (1932) that the nucleus also contains uncharged neutrons. Thus basic constituents of nucleus of every atom are protons and neutrons (except in the case of hydrogen atom which does not have any neutrons in its nucleus).

Atoms of different elements are found to have different number of protons in their nuclei. It is this number which distinguishes one type of atom from the other. Each elements has been assigned a number – called atomic number according to which they are arranged in the periodic table (for details of periodic table see chemistry book).

The number of protons in the nucleus of an atom of an element is called the 'atomic number' of that element. Atomic number is usually denoted by capital letter Z. Thus hydrogen atom having only one proton in its nucleus has Z = 1; sodium is given atomic number Z = 11 because it has 11 protons in its nucleus. ***No two different elements can have the same atomic number.*** The protons and neutrons together are called by the single name ***nucleons*** as they are the only constituents of the nucleus.

The total number of nucleons (i.e. the sum of the number of protons and neutrons) in the nucleus of an atom of an element is called the ***mass number*** of that element. Mass number is usually denoted by capital letter A. Thus the mass number of Lithium is A = 7, because the nucleus of every Lithium atom contains 3 protons and 4 neutrons i.e. a total of 7 nucleons.

The different elements can have same mass number though they may have different number of protons. For example, the mass number of some atoms of element Calcium (with Z = 20) and that of Argon atoms (with $Z = 18$) is $A = 40$ each. Such pair of atoms having same mass number (A-value) are called ***Isobars*** or ***Isobaric*** (*Iso* = equally; *baric* = heavy). Since Isobaric atoms belong to different elements (i.e. with different Z - values), they show different chemical properties but may resemble in some of their physical properties.

31.3.1 Atomic Mass Unit (a.m.u.)

The mass of proton (m_p) = 1836 times the mass of an electron (m_e) or = 1836 m_e and the mass of a neutron (m_n) = 1840 m_e.

Since the mass of an electron is negligibly small in comparison to the mass of a nucleon, the whole mass of an atom is effectively due to the total mass of its nucleons. But the neutron is slightly heavier than the proton. It is, therefore, required to choose some average mass as the atomic mass unit or a standard mass-unit in terms of which the masses of all atoms (and also that of protons and neutrons) can be expressed.

It is decided that the mass of a carbon-atom containing equal numbers of protons and neutrons in its nuclei (i.e. six-protons and six neutrons) with mass number 12, be taken equal to 12 atomic mass units. (Carbon is chosen because it is available everywhere on earth with same properties).

Thus, value of one atomic mass unit is defined as the 1/12th of the mass of a carbon atom with Z = 6 and A = 12.

Known value of the mass of a carbon atom = 1.99267×10^{-26} kg.
Now, since, mass of a carbon (A = 12) atom = 12 a.m.u.

Therefore,
$$1 \text{ a.m.u.} = 1/12 \times \text{mass of one carbon atom with } A = 12$$
$$= 1/12 \times 1.99267 \times 10^{-26} \text{ kg}$$
$$1 \text{ a.m.u.} = 1.66\,0565 \times 10^{-27} \text{ kg}$$
$$= 1.66 \times 10^{-27} \text{ kg approximately.}$$

mass of a proton = $m_p = 1.67264 \times 10^{-27}$ kg
mass of a neutron = $m_n = 1.67493 \times 10^{-27}$ kg

On this scale of measurement of mass for subatomic particles, we have,

$$m_p = \frac{1.67264 \times 10^{-27}}{1.660565 \times 10^{-27}} \text{ a.m.u.}$$

i.e. $$m_p = 1.00727 \text{ a.m.u.}$$

Similarly, $$m_n = \frac{1.67493 \times 10^{-27}}{1.660565 \times 10^{-27}} \text{ a.m.u.}$$

i.e. $$m_n = 1.00865 \text{ a.m.u.}$$

Can you now express the mass of an electron ($m_e = 9.1 \times 10^{-31}$ kg) in a.m.u.? Since, we will be using nuclear masses in a.m.u., therefore, it will be quite useful to know an energy – equivalent of 1 a.m.u., which can be found by using ***Einsteins mass-energy equivalence*** relation.

$$\text{Energy} = \text{mass} \times c^2$$

Where c is velocity of light in vacuum .

Therefore, $$1 \text{ a.m.u.} = 1.66 \times 10^{-27} \times (3 \times 10^8)^2$$

$$= 1.492 \times 10^{-10} \text{ Joule}$$

$$= \frac{1.492 \times 10^{-10}}{1.602 \times 10^{-13}} \text{ MeV} = 931 \text{ MeV}$$

31.3.2 Representation of an element by its atomic number and mass number

The elements are symbolically represented by writing its atomic number (Z) as lower prefix, and the mass – number (A) as upper superfix with its chemical symbol. For example, sodium having chemical symbol **Na**, atomic number $Z = 11$ and mass number $A = 23$ is symbolically represented as $_{11}Na^{23}$. More generally any element with chemical symbol X can be represented as $_Z X^A$

31.3.3 Isotopes and Isotones

It has been observed that some elements have the same atomic number but different mass number in their mass spectrograph studies.

Such atoms of the same element i.e. having same Z - value but different mass-numbers (i.e. different A-values) are called ***Isotopes***. For example, hydrogen is found to have three isotopic forms $_1H^1$, $_1H^2$, and $_1H^3$ called as hydrogen, deuterium and tritium. Similarly chlorine has two Isotopes — $_{17}Cl^{35}$ and $_{17}Cl^{37}$.

Thus, ***Isotopes of an element are atoms which have the same number of protons but different number of neutrons.***

Isotopes have identical chemical properties since they have the same number of electrons (equal to the number of protons in the nuclei) and occupy the same place in the periodic table. (In Greek – *Iso* means same, *topes* means place). Few elements consist of only one isotope; most are mixtures of isotopes.

However, two different atoms (i.e. with different Z - values) can have same number of neutrons in their nuclei. These are called ***Isotones***.
For example, nuclei of $_{11}Na^{23}$ and $_{12}Mg^{24}$ atoms have 12 neutrons each.

The atoms of different elements having same number of neutrons in their nuclei are called Isotones.

Example 31.1: *Mass of a Boron atom ($_5B^{10}$) is 10.811 a.m.u. What is its mass in kg?*

Solution : Since 1 a.m.u. = 1.660565×10^{-27} kg
Therefore 10.811 a.m.u. = $10.811 \times 1.660565 \times 10^{-27}$ kg
= $17.952368 \times 10^{-27}$ kg

Example 31.2: *Find the number of electrons, protons, neutrons and nucleons in an atom of element $_{92}U^{238}$*

Solution : This is symbol for Uranium.
Its atomic number $Z = 92$;
Mass number $A = 238$
Therefore the number of protons = 92
The number of electrons = the number of protons = 92
The total number of nucleons = 238 = Sum of the no. of protons and neutrons.
Therefore the number of neutrons = 238 – 92
= 146.

Example 31.3: *Select the pairs of Isotopes, Isobars and Isotones in the following list.*

$$_6C^{12},\ _{13}Al^{27},\ _{19}K^{39},\ _{14}Si^{28},\ _{32}Ge^{76},\ _{20}Ca^{40},\ _{34}Se^{76},\ _6C^{14}$$

Solution : Isotopes – (Same Z - value) - are $_6C^{12}$ and $_6C^{14}$
Isotones – [Same (A–Z) values] - are [$_{13}Al^{27}$ & $_{14}Si^{28}$], [$_{19}K^{39}$ & $_{20}Ca^{40}$]

Isobars– (same A values) - are $_{32}Ge^{76}$ and $_{34}Se^{76}$

INTEXT QUESTIONS 31.1

1) Make groups of the Isotopes, Isobars and Isotones from the following collection of different atoms :

$_8O^{16}$, $_{82}Pb^{207}$, $_6C^{12}$, $_{18}A^{40}$, $_1H^3$, $_3Li^7$, $_{32}Ge^{76}$, $_{34}Se^{76}$, $_2He^3$, $_{20}Ca^{40}$, $_4Be^7$, $_1H^2$, $_6C^{14}$, $_{92}U^{235}$, $_{82}Pb^{206}$, $_8O^{18}$ $_{92}U^{239}$, $_1H^1$, $_{11}Na^{23}$, $_{13}Al^{27}$, $_{12}Mg^{24}$, $_{14}Si^{28}$, $_{17}Cl^{37}$, $_{17}Cl^{35}$

2) Fill in the blanks :

i) Neutron is- than proton.

ii) The total number of protons and neutrons in atom is called the- - - - - - - - - - - - number of that atom.

iii) The protons and neutrons together are called by the name - - - - - - - - - - - - -

iv) The number of neutrons in $_{13}Al^{27}$ is = - - - - - - - - - - - - - - -

v) The number of protons in $_{14}Si^{28}$ is = - - - - - - - - - - - - - .

vi) Two atoms are said to belong to different elements if their - - - - - - - - - -numbers are different.

3) Which number cannot be different in two atoms of same element – mass number, atomic number, neutron number?

31.4 NUCLEAR FORCES

The size of the nucleus is about 10^{-15} m which is about 10^{-5} times the size of the atom. You have studied in the previous sections that the nucleus accomodates similarly charged (positively) protons in a small space. The similarly charged bodies repel each other with a force which is inversely proportional to the square of the distance between them. (Coulombian law in electrostatics). Thus very large repulsive force acting between the protons is not able to separate them apart or push them out of the nucleus. The nucleus is stable in all atoms of all elements (except radio active elements). The question arises '*what is that force which keeps all the protons together in a small space against such strong repulsive Coulombian forces*?

Will it not be interesting to guess about the reason of stability of nucleus and think about the internal forces acting between the nucleons with the help of our imagination?

It is assumed that the nucleons are kept bound together with characteristic nuclear forces which are ***attractive in nature*** and dominate over the repulsive Coulombian electrostatic forces. Since they do not pull the exterior (i.e. orbital) electrons into the nucleus, they are assumed to be ***short range forces*** operative within the nucleus only. Also since same forces are operative between all the types of nucleons i.e. be it a pair of protons or a pair of neutrons or a pair consisting of a proton and a neutron, the nuclear forces are assumed not to depend upon the charges. We can now say that,

- Nuclear forces are one of the strongest attractive forces available in nature.
- They are short range forces operative within the nucleus only.
- They are charge independent forces.

Later studies regarding the nature of nuclear forces have revealed following more information about them :

Nuclear forces have the property of saturation

This means that in the nucleus, because of short range order of nuclear forces, any one nucleon interacts with only a limited number of other nucleons nearest to it. This is apparent from the fact that their binding energy is proportional to the mass number '*A*' [i.e. binding energy per nucleon is nearly constant over a large range of values of mass number. See Fig. (31.1) on page3 8]. When a fresh nucleon is added to the nucleus, it interacts with a limited number of nearest nucleons, and so adds a constant amount of the binding energy. Therefore, the binding energy per nucleon does not change with a change in the number of nucleons.

31.4.1 Mass Defect

The mass of the nucleus of an atom of any element is always found to be less than the sum of the masses of its nucleons. This difference in mass is called ***mass-defect***. For example, let us consider an atom denoted by ($_ZX^A$). This has Z - protons and (A–Z) neutrons in the nucleus. Now let the mass of the nucleus be = *M*.

Also, the sum of the masses of the nucleons = $Z\, m_p + (A-Z)\, m_n$

Therefore, Mass defect = $\Delta m = \{[Z.m_p + (A-Z)m_n] - M\}$ kg

31.4.2 Binding Energy of Nucleons

The decrease in mass Δm (mass defect) of the nucleus, made of Z - protons and (A-Z) neutrons, is converted into energy and is liberated. This much energy must be supplied to the compound nucleus to break it into its constituent particles, hence it is called *binding energy* of the nucleus.

Binding Energy of the nucleons = $\Delta m\, c^2$ Joules

Therefore, Binding Energy per nucleon $B = \Delta m\ c^2/A$

$$\text{or} \qquad B = \frac{[Zm_p + (A-Z)\, m_n - M].c^2}{A} \text{ Joules per nucleon}$$

For Example, in the case of $_6C^{12}$

$Z = 6, A = 12$, Therefore $(A - Z) = 12 - 6 = 6$

Also $M = 12$ a.m.u.; (1 a.m.u. = 931.5 MeV)

$$\text{Therefore, } B = \frac{[6\, m_p + 6\, m_n - 12] \times 931.5}{12} \text{ MeV per nucleon}$$

$= 7.41474$ MeV per nucleon

[Using, $m_p = 1.00727$ a.m.u. and $m_n = 1.00865$ a.m.u.]

It, thus, suggests that on breaking the nucleus of any atom, this much energy can be released which can be used for various purposes. This is obtained in nuclear fission of a heavy atom like $_{92}U^{235}$ about which you will study in the next lesson. This is the source of energy in an atom-bomb.

The value of B is found to be increasing rapidly to about 8.8 MeV per nucleon as we move from Helium ($A = 4$) to Iron ($A = 56$); thereafter it remains practically constant over a large range upto $A = 170$ and then it is found to decrease to about 7.6 MeV per nucleon for the heaviest nuclei ${}_{92}U^{238}$. Figure (31.1) shows the variation of B with A (mass number).

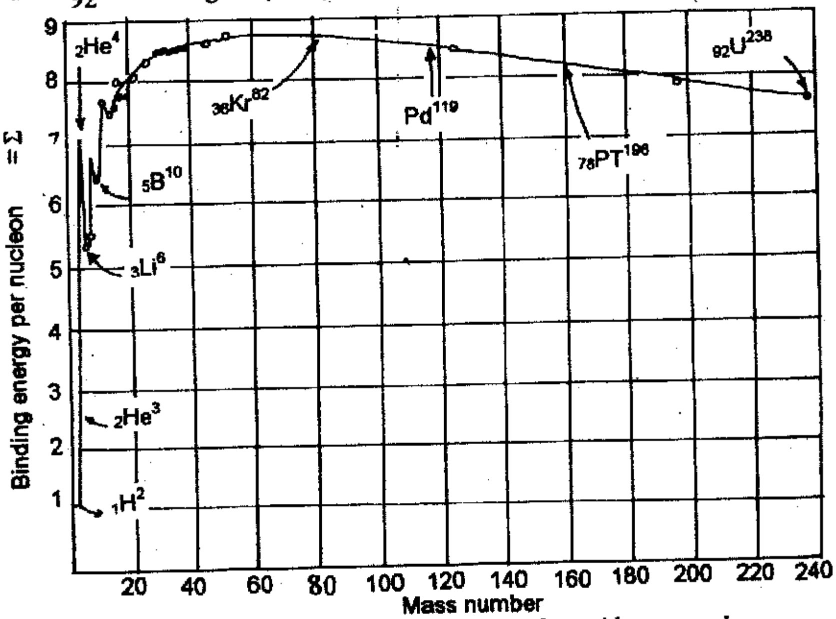

Fig. 31.1: The variation of binding energy per nucleon with mass number

The light nuclei with $A < 20$ are the least stable. For example, the value of B for heavy hydrogen (${}_1H^2$) is only 1.1 MeV per nucleon. The subsidiary peaks occurring at ${}_2He^4$, ${}_6C^{12}$, ${}_8O^{16}$ (even-even nuclei i.e. nuclei having even number of protons and even number of neutrons) indicate that these nuclei are more stable than their immediate neighbours.

31.4.3 Nuclear Radius

The radius of the nucleus is found to depend upon the mass, which in turn depends on the total number of nucleons, or the mass number (A). The radii (r) of most of the nuclei are fairly represented by

$$r = r_o (A)^{1/3}$$

where, r_o is an empirical constant = 1.2×10^{-15} m — the same for all nuclei. Since the volume of a nucleus is proportional to A (or the total mass), therefore, the mass per unit volume ($A/r^3 = r_o^{-3}$) is the same for all the nuclei, i.e. *all nuclei have approximately the same density* which is of the order of 2.4×10^{17} kg m^{-3} (i.e. 240 million metric tonnes per c.c.)

INTEXT QUESTIONS 31. 2

1) *What are the characteristic features of nuclear forces?*

2) *The mass of the nucleus of ${}_3Li^7$ atom is 6.01513 a.m.u. Calculate the mass defect and also the binding energy per nucleon. Given, m_p = 1.007276 a.m.u.; m_n = 1.008665 a.m.u. and 1 a.m.u. = 931 MeV*

3) *What is the radius of the nucleus of atom of ${}_4Be^8$?*
[Hint $r = r_o A^{1/3}$; $r_o = 1.2 \times 10^{-15}$ m]

31.5 RADIO ACTIVITY

What is the age of our earth? How do the geologists estimate the age of rocks and fossils found during excavations? What is radio-therapy which is used to treat a cancer patient? The answers to all these interesting and useful questions can be found if you study about radioactivity.

31.5.1 Discovery of the Radioactivity

The discovery of radioactivity was purely accidental. The story of its discovery is quite interesting. In 1896, the French physicist A.H. Becqueral was working on the phenomenon of fluorescence. This is the property of certain substances to transform ultraviolet radiation that falls on them into visible light. In one of the drawers of his desk, Becqueral kept a collection of various minerals, besides several unopened boxes of photographic plates. Somehow, the collection of materials remained untouched for a considerable period of time. One day Becqueral used one of the boxes of photographic plates in order to photograph something. When he developed the plate, he was disappointed to find that they were badly fogged as if previously exposed to light. He tried the other boxes of photographic plates and found them also to be in the same poor condition. He was puzzled to understand this because all the boxes were sealed and the plates inside were wrapped with thick black paper.

Being confused, Becqueral, investigated the situation. He found that uranium ore placed in his drawer had the ability to fog photographic plates through a thick cardboard box and a layer of black paper. So he concluded that there must be a new type of radiation originating from uranium ore. Becqueral found that these rays, like X-rays pass through many opaque substances. Thereafter, these rays were known as Becqueral rays. Thus the new phenomenon called radioactivity was discovered. The elements exhibiting this phenomena were called *radioactive elements*.

Soon after this discovery it was found that thourium also emitted these rays. In 1898, the Polish-born Madame Marie Curie alongwith her husband Pierre Curie (French Physicist) isolated an element from uranium ore by a painstaking method known as chemical fractioning. This new element which is million times richer in the mysterious rays than uranium was given the name Radium. Another radioactive element discovered by Madam Curie was even more active than radium and she named it polonium in honour of her native country.

In 1899, Lord Ernest Rutherford a British physicist, analysed the Becqueral rays, emitted by the radioactive elements. He found that in every case, the atoms of these radioactive element contained two different kinds of rays.

The nuclei of atom contains positively charged protons which repel each other strongly due to electrostatic repulsion. To overcome this repulsion, nature has added neutrons to increase the nuclear force and make the nuclei stable. But in case of nuclei with higher atomic number this electrostatic repulsion is so strong that in some cases even the addition of neutron is not able to keep the nucleus stable. To achieve the state stability, the heavy nuclei disintegrate spontaneously by emitting excess positive charge or excess mass by α and β particles along with γ rays as shown fig. 31.2

This process of emission of α particle or β particle followed by γ - ray emission from a nucleus in the ground state by itself is called radioactivity or natural radioactivity.

This type of tendency of emission can also be induced in the nucleus artificially by irradiating the stable nuclei with neutrons or particles etc. It is then called ***artificial radio-activity.***

The characteristic features of this phenomenon are that it is spontaneous and in the case of α or β emission, a new nucleus belonging to a new element is formed. Thus one element gets converted into another element by radioactivity. This is thus a nuclear disintegration phenomenon. Let us study in details about α , β, and γ radiations.

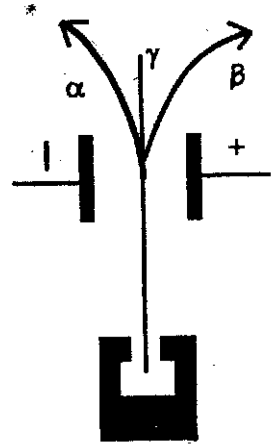

Fig. 31.2: Emission of α, β, and γ radiation

(i) α- Particles

α - Particles have been found to be a helium nuclei $({}_2He^4)^{++}$ consisting of a group of 2 protons (having two units of positive charges) and 2 neutrons. Further studies of α particles have revealed following properties :

- Being charged particles they get deflected in electric and magnetic fields.
- They produce fluorescence in substances like zinc sulphide and barium platino cyanide; affect a photographic plate; can induce radio-activity in certain elements and produce nuclear reactions.
- They have great ionizing power. A single particle in its journey through a gas can ionize thousands of gas atoms before being absorbed.
- They have little penetration power through solid substance, and get scattered by thin foils of metals. They can be stopped by 0.02 mm thick aluminum sheet.
- The energy of the particles emitted from a radioactive element is a characteristic of the emitting nucleus and ranges from 4.19 MeV to 6.78 MeV. This corresponds to a variation in velocity from 1.4×10^7 ms^{-1} to 2.05×10^7 ms^{-1}.
- Depending upon their initial kinetic energies their range of normal pressure in air varies from 3 cm to 8 cm.

(ii) β Particles

β Particles have been found to possess unit negative charge. They have been identified as electrons. Though the electrons are not present initially inside the nucleus, they are supposed to be created by the decay of a neutron into a proton and an electron inside the nucleus. That electron is emitted as a particle. Further studies of β particles have revealed following properties.

- Being negatively charged, they get deflected by electric and magnetic fields.
- They produce fluorescence in fluorescent materials like zinc-sulphide and barium platinocyanide; affect photographic plates.
- They also have ionizing power of gas atoms but much smaller than those of α particles
- They can pass through few mm of aluminium sheets. They are about 100 times more penetrating than α particles..
- Their average energies vary between 2 MeV to 3 MeV. Due to their small mass, their velocities vary in a large range from 0.33 *c* to 0.998 *c*, where *c* = velocity of light.

(iii) γ-rays

γ-rays are electro-magnetic waves of high frequency and hence are also called high energy photons. These are characterized with the following properties :

- They do not get deflected by electric or magnetic fields. They travel with velocity of light in free space.
- They have highest penetration power (i.e. more than α and β particles) and can penetrate through several centimeters of iron and lead sheets.
- They have ionizing power but smalles as compared to α and β particles.
- They can produce fluorescence in materials like willemite, affect a photographic plate and can produce nuclear reactions.
- They knock out electrons from the metal surfaces on which they fall and heat up the surfaces. Hard γ-rays (i.e. high energy γ-rays) are used in radio therapy of cancer.

31.5.2 Laws of Radioactive Decay

Rutherford and Soddy together made an exhaustive study of the phenomenon of radioactivity and summed up their conclusions in the form of following two laws named as laws of radioactive decays :

(i) Ist Law or Displacement Law

In any radioactive decay, spontaneous emission consists of either a single α particle or a β particle but never both. The emission of an α particle from a radioactive parent nucleus changes it into a new daughter nucleus (new element) with its atomic number decreased by two and its mass number decreased by four. Also, the emission of a β particle changes the parent nucleus into a daughter nucleus with its atomic number increased by unity but its mass number remains unchanged. The emission of γ-rays does not change the atomic number or the mass number of the parent nucleus and hence no new nucleus is formed. The above statements can be summarized as follows :

In a nuclear disintegration, the charge number (Z) and the mass number are always conserved. Since ***in α decay or β decay the position of the decayed nucleus of atom of any element gets displaced by two backwards (in case of α decay) or by one forward (in case of α decay) in the periodic table of elements***, this law is named as ***displacement law***. It should be remembered that α and β emission are always followed by γ-emission. Thus, since α particle = $_2He^4$, and β particle= $_{-1}e^0$; we can write following nuclear equations for the α decay and β decay of any radioactive nucleus denoted by $_ZX^A$,

$$_ZX^A \xrightarrow{\alpha \text{ decay}} \underset{(\alpha\text{-particle})}{_2He^4} + {_{Z-2}Y^{A-4}} + \gamma; \text{ where Y is the daughter nucleus}$$

$$_ZX^A \xrightarrow{\beta\text{-decay}} {_{-1}e^0} + \nu + {_{Z+1}Y^A} + \gamma; \text{ where Y is the daughter nucleus}$$

$$\underset{\text{Excited nucleus}}{(_ZX^A)^*} \xrightarrow{\gamma\text{-decay}} {_ZX^A} + \underset{(\gamma\text{-rays})}{\gamma}$$

(ii) 2nd law or Law of Decay

The rate of disintegration is independent of external factors like temperature, pressure etc. and depends only on the law of chance, which states that ***the number of radioactive atoms disintegrating per second is proportional to the number of radioactive atoms present at that instant of disintegration.*** This is called ***law of decay*** or ***statistical law.***

Let N_0 = Initial number of radioactive atoms i.e. at $t = 0$

N = Number of radioactive atoms at time 't'.

If dN = Small number of atoms decayed in small time dt. i.e. $N - dN$ = Number of radioactive atoms at time '$t + dt$' then according to the law of decay

Rate of decay $= -(dN/dt)$

or $= \lambda N$

Where, λ = decay constant, which is characteristic of the radioactive element undergoing decay.

$$\lambda = (-dN/dt)/N$$

Thus, decay constant (λ) may be defined as the ratio of the instantaneous rate of disintegration to the number of radioactive atoms of the parent element at that instant.

It is measured in units of *per second.* The ***activity*** of a radioactive substance at any instant of time is measured by its rate of disintegration at that instant. Its practical unit has been named as Becquerel after 'Becquerel'.

1 Becquerel = 1 disintegration per second;

Its another unit is ***Curie***, after the name of Madam Curie, a pioneer worker in the field of artificial radioactivity,

1 Curie = 3.7×10^{10} disintegrations per second.

which is the rate of disintegration of radium (Ra) measured per second per gram.

To honour the scientist *"Rutherford"*, the rate of disintegration i.e. activity is also sometimes measured in 'rutherford' (rd); where

1 rd = 10^6 disintegrations per second.

The law of decay is sometimes expressed in exponential form and is also called as *law of exponential decay*. The exponential form can be deduced as follows. According to law of decay,

Since, $-dN/dt = \lambda N$.

On solving it, we get

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

or it can be written in exponential form also, as given below

$$N = N_0 \lambda \exp(\lambda T_{1/2})$$

which is the law of exponential decay. The most important conclusion from this law is that N will become zero only when $t = \infty$. Thus, no radioactive parent element will disapperar completely even after very long time.

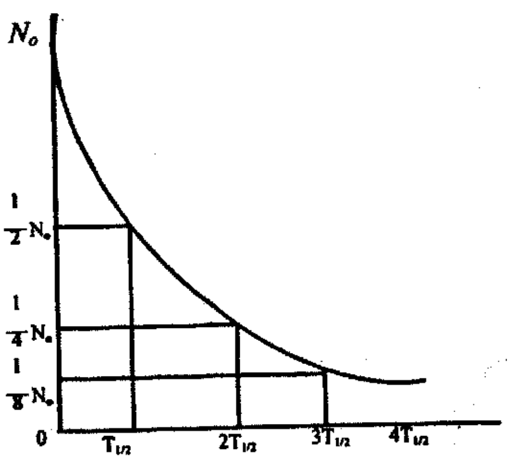

Fig. 31.3 : Radioactive decay curve.

Figure (31.3) shows the shape of the N *versus* t curve drawn on the law of exponential decay. The figure (31.3) shows that radioactive atoms of all elements having different values of λ. will take infinite time for complete disintegration of all their radioactive atoms, whatever may be their initial number N_o.

However, starting with the same N_o, different radioactive elements will have different value of N at the same instant due to different values of their decay constants (λs). They will thus show different rates of disintegration. This is determined by their half life ($T_{1/2}$) and average lives (T_a).

31.5.3 Half Life Period ($T_{1/2}$)

The half life period ($T_{1/2}$) of any radioactive element is defined as the period (time) in which the number of radioactive parent atom is reduced to half of its original number.

Since, $N = N_o \exp(-\lambda t)$; where $N = N_o$ at $t = 0$

Therefore, by definition, at $t = T_{\frac{1}{2}}$, $N = N_o/2$, This gives

$$N_o/2 = N_o \exp(-\lambda T_{\frac{1}{2}})$$

or $\exp(-\lambda T_{\frac{1}{2}}) = 1/2$

or $\lambda T_{\frac{1}{2}} = \log_e 2$

or
$$T_{\frac{1}{2}} = \frac{\log_e 2}{\lambda} = \frac{2.303 \times \log_{10} 2}{\lambda} = 2.303 \times 0.3010/\lambda$$

or
$$T_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

Thus, half life of any radioactive element is inversely proportional to its decay constant (λ) and is a characteristic property of the radioactive nucleus which cannot be altered by any method.

For example, the half life of ${}_6C^{14}$ (radioactive carbon) is 5730 years. This means, that 1 gram of ${}_6C^{14}$ will be reduced to 0.5 gram in 5730 years, which will be further reduced to 0.5/2 = 0.25 gram in another 5730 years i.e. in a total of 11460 years.

›1.5.4 Average Life Period (T_a)

· is defined as the sum of the actual life periods of all the radioactive atoms (which is 'fferent for each atom) divided by their total number i.e.]

T_a = Sum of the actual life periods of all the (N_o) radioactive atoms/N_o

Using integral calculus, it can be shown that

$$T_a = 1/\lambda = \text{Reciprocal of decay constant}$$

It is also obvious that

$$T_{\frac{1}{2}} = 0.693/\lambda = 0.693\, T_a$$

Example 31.4 : *An animal fossil obtained in the Mohanjodaro – excavation shows an ·tivity of 9 decay per minute per gram of carbon. Estimate the age of the Indus Valley ilisation. Given the activity of carbon (14) in living specimen of similar animal is 15 ..cays per minute per gram and half life of carbon (14) is 5730 years.*

Solution: Carbon (14) is the radioactive isotope of carbon. It remains in fixed percentage in the living species. However, on death, the percentage of carbon (14) starts decreasing due to radioactive decay. (The formation of carbon (14) takes place only in the living bodies to keep its percentage at constant level in the carbon content of the living body).
Since $-dN/dt = \lambda N$ = activity at time 't'.
Therefore Activity at present/Original activity when the specimen was alive $= N/N_0 = 9/15$ (given)

But $N = N_o . \exp(-\lambda t)$
Therefore, $N/N_o = \exp(-\lambda t)$
or $9/15 = \exp(-\lambda t)$
or $\log(9/15) = -\lambda t$ or $\log(15/9) = \lambda t$
This gives,
$$t = 1/\lambda\,[\log(15/9)]$$
But $T_{1/2} = 0.693/\lambda$ = 5730 years given.

Therefore $1/\lambda = 5730/0.693$

Hence $t = 2.303 \times 5730/0.693\,[\log_{10} 15 - \log_{10} 9]$ years
$= 2.303 \times 5730/0.693\,[1.1761 - 0.9542]$ years
$t = 4225.15$ years.

Thus, the specimen contained carbon (14) - (the living carbon) 4225.15 years ago. Hence Indus valley civilisation existed about 4225 years ago.

31.5.5 Applications of Radioactivity

Radioactivity finds great many applications in our day to day life. Some of them are as given below.

(i) ***In medical*** treatment for example in the treatment of cancer by using a Cobalt-source of γ-rays called radiotherapy.

(ii) ***In agriculture*** – by exposing the seeds to controlled γ radiation to improve their quality, fruits and vegetables to radiations before their storage for saving them from decay.

(iii) ***In geology*** in estimating the age of old fossils. The decay of single radioactive atom can be registered by an instrument at a remote location outside a container, wall,. This high sensitivity is utilized in *tracer-technique* as an important research tool in medical diagnostics, like detection of Ulcer in any part of the body by injecting radioactive atoms of harmless elements ($_{11}Na^{24}$) in very small amounts into the body of the patient, whose movement can then be recorded. The affected part absorbs the radioactive atoms whose motion is, therefore, stopped and the diseased part of the body is easily located before operation.

(iv) ***In industries*** the γ-radiations are used to find the flow or imperfections in the inner structure of solid iron girders. For example, if there is an air bubble inside, then penetration of γ-rays will be more at that point. The most important of these is the *carbon dating.*

Carbon dating

The normal activity of living carbon containing matter is found to be about 15 decays per minute for every gram of carbon. This activity arises from the small proportion of radioactive carbon (14) isotope present in the atmosphere with the ordinary carbon (12). This isotope

(C^{14}) is taken by plants from atmosphere and in consequence in animals that eat the plants. Thus, about one part in 10^8 is radioactive in carbon present in all living being (all animals and plants). When the organism is dead, its interaction with the atmosphere (i.e. absorption, which maintains the above equilibrium activity) ceases and its activity begins to fall from the brown half life (= 5730 years) of C^{14} and the measured activity, the age of the specimen can be approximately estimated. This is called ***carbon-dating*** and is the principle of determining age of old fossils by archeologists.

The same technique has been used in estimating the age of earth from measurements of relative amounts of U^{238} and Pb^{206} in geological specimens containing Uranium ore. Assum that the specimen of ore contained only Uranium and no lead at the time of birth of the earth with the passage of time uranium decayed into lead. The present age of the earth has been estimated to be about 4 billion years.

INTEXT QUESTIONS 31.3

1. *How can you say that radioactivity is a nuclear disintegration phenomenon?*
2. *Compare the ionizing power, penetration power of α, β and γ - radiations.*
3. *Apply the law of conservation of charge and mass numbers to find the values of a, and b in the following decay - equations.*
   i) $_{Z}X^{A} = 2He^{4} + {}_{a}Y^{6} + \gamma$
   ii) $_{Z}X^{A} = {}_{-1}e^{o} + \nu + {}_{a}Y^{b} + \gamma$
4. *The half life of a radioactive substance is 5 years. In how much time 10 grams of this substance will reduce to 2.5 grams?*

31.6 WHAT YOU HAVE LEARNT

- The central hard core of about 10^{-15}m radius of the atom is called its nucleus. The nucleus contains nucleons i.e. positively charged protons and uncharged neutrons.
- The number of protons inside the nucleus of an atom of any element is called the atomic number of that element (Z). Different elements have different number of protons in their nuclei.
- The sum of the number of protons and neutrons in any nucleus of an atom is called its mass number.
- The atoms with same atomic number but different mass numbers are called isotopes of each other.
- The atoms with same mass number but different atomic numbers are called isobars of each other.
- The atoms with same number of neutrons are called isotones of each other.
- The nucleons inside the nucleus of every atom are bounded together by strong attractive nuclear forces which are short range and charge independent.
- The mass of the atom is found to be always less than the sum of the masses of its nucleons. This difference in mass is called mass-defect (Δm) which gets converted into binding energy in accordance to Einstein's mass-energy equivalence formula.
- The size (volume) of the nucleus depends upon the total mass of the nucleons.
- The spontaneous emission of α particle or β particle followed by γ-emission from any nucleus is called radioactivity.
- The α particles have been identified as helium nuclei while β particles have been identified as fast moving electrons. The γ-rays are electromagnetic waves of extremely short wave length.

- According to 1st law of radioactive decay in a nuclear disintegration, the charge number and mass numbers are always conserved.
- According to 2nd law of radioactive decay – the number of radioactive atoms disintegrating per second is proportional to the number of radioactive atoms present at that instant.
- The half life period of a radioactive element is the time in which the number of radioactive atoms reduces to half of its original number.
- The average life period of a radioactive element is the average life time of all the radioactive atoms taken together.
- The law of exponential decay is $N = N_0 e^{-\lambda t}$
- The radioactivity finds varied applications in medicine, engineering, agriculture and geology etc.

31.7 TERMINAL QUESTIONS

1. What happens to the average life of the radio-active sample, when its mass decreases ?]
2. What is difference between isotopes and isobars ?
3. Explain the characteristics of binding energy per nucleon versus mass number curve.
4. What is the nature of nuclear forces ? Give their characteristics.
5. Explain how decay constant is related to half half and average life of a radioactive element ?
6. Fill in the blanks with suitable words.
   i) The atoms having the same number of neutrons in their nuclei are called---------.
   ii) ------------------forces are one of the strongest attractive forces available in nature.
   iii) The mass of an atom is slightly -------------than the sum of masses of the nucleons in its nucleus.
   iv) The radius of the nucleus is proportional to ----------- power of its mass number.
7. Define the following terms :
   (i) Atomic number; (ii) Mass number; (iii) Mass defect; (iv) Binding energy of nucleons (v) Half life period; (vi) Average life period; (vii) Decay constant.
8. Differentiate between the following :
   i) Isotopes and Isobars
   ii) α particles and helium atom
   iii) β–particle and electron.
9. State the laws of radioactive decay.
10. What is carbon dating? What is its importance?
11. Find the number of neutrons, protons and electrons in the following atoms.
    (i) $_{11}Na^{23}$; (ii) $_1H^2$; (iii) $_{92}U^{238}$; (iv) $_{17}Cl^{35}$
12. Calculate the mass defect and total binding energy of the nucleons for the following nuclei of atoms of different elements.
    (i) $_2He^4$; (ii) $_3Li^7$; (iii) $_7N^{14}$
    Given, 1 amu = 1.660566×10^{-27} kg = 931 MeV, Mass of a proton = 1.007276 amu.
    Mass of a neutron = 1.008665 a.m.u., Mass of $_2He^4$ atom = 4.00260 a.m.u.
    Mass of $_3Li^7$ atom = 7.01601 a.m.u, Mass of $_7N^{14}$ atom = 14.00307 a.m.u.
13. Using the present day abundance of the two main Uranium isotopes and assuming that the abundance ratio could never have been greater than unity, estimate the maximum possible age of the earth's crust. Given that the present day ratio of U^{238} and U^{235} is 137.8 : 1; Half life periods of U^{238} is = 4.5×10^9 year; and of U^{235} is 7.13×10^8 years.

14. Calculate the weight of RaB (Pb^{214}) showing the radioactivity of 1 Curie. The half life of RaB is 26.8 minutes.
15. If the activity of a radioactive sample drops to 1/16th of its initial value in 1 hr. and 20 min. What is its half life?
16. Calculate the weight in gram of one curie of Pb^{214} from its half life of 26.8 minute. [Hint : 1 Curie of Pb^{214} – means that number of Pb^{214} which has rate of disintegration as 1 Curie. Avagodro's Number $N = 6.02 \times 10^{23}$ atoms].

CHECK YOUR ANSWERS

Intext Questions 31.1

1)

Isotopes	Isobars	Isotones
$_6C^{12}$ and $_6C^{14}$	$_{32}Ge^{76}$ & $_{34}Se^{76}$	$_1H^2$ & $_2He^3$
$_1H^1$, $_1H^2$ & $_1H^3$	$_{18}A^{40}$ & $_{20}Ca^{40}$	$_6C^{14}$ & $_8O^{16}$
$_8O^{16}$, $_8O^{18}$	$_{32}Ge^{76}$ & $_{34}Se^{76}$	$_{11}Na^{23}$ & $_{12}Mg^{24}$
$_{17}Cl^{35}$ & $_{17}Cl^{37}$	$_1H^3$ & $_2He^3$	$_{13}Al^{27}$ & $_{14}Si^{28}$
$_{82}Pb^{206}$ & $_{82}Pb^{207}$	$_3Li^7$ & $_4Be^7$	
$_{92}U^{235}$ & $_{92}U^{239}$		

2) (i) heavier; (ii) mass; (iii) nucleons; (iv) 14; (v) 14; (vi) atomic.

3) Atomic number.

Intext Question 31.2

1) Attractive, short range, strongest charge independent, mass independent, spin dependent.
2) $\Delta m = 1.041358$ a.m.u.; 969.5 Mev.
3) 2.4×10^{-15} m.

Intext Questions 31.3

1. Nuclear disintegration usually involves α emission or β emission which results in the change of atomic number of the parent element. This shows that there is a change in the number of protons of the atom which are present in the nucleus only. Hence this is a nuclear disintegration phenomenon.
2. Ionizing power of

   $$\alpha > \beta > \gamma$$

   Penetration power of

   $$\alpha < \beta < \gamma$$
3. i) $a = Z - 2$ and $b = A - 4$

   ii) $a = Z + 1$ and $b = A$.
4. Two half life times are required – one for reduction from 10 to 5 grams and the other from 5 to 2.5 grams i.e. $2\,T_{1/2} = 10$ years.

Terminal Questions

13. 6×10^9 years
14. $3.1 \times 10^{[illegible]}$ g
15. 20 min
16. $30.52 \times 10^{[illegible]}$ g