312en26

26

NUCLEI AND RADIOACTIVITY

So far you have learnt that atom is the smallest entity that acts as the building block of all matter. It consists of an extremely small *central core,* called the *nucleus,* around which electrons revolve in certain specified orbits. Though nucleus is very tiny, it is *amazingly complex and you may like to know more about it*. The march towards our understanding the physics of nuclei began towards the end of nineteenth century with the chance discovery of the natural phenomenon of radioactivity; disintegration of atomic nuclei to attain stability. This discovery provided us tools to probe the structure of nucleus : What is its size and mass? What does it contain? What forces make its costituent particles cling together and why?

In fact, the α-particles used by Geiger and Marsden to 'see' what was inside an atom were obtained from naturally occuring radioactive element ^{214}Bi. These inverstigations opened up very fertile and new avenues of research. A lot of good new physics of the atom began to emerge out and changed the course of developments in a short span of time. You will learn about these now.

OBJECTIVES

After studying this lesson, you should be able to :

- *determine the number of neutrons and protons in nuclei of different atoms;*
- *calculate the sizes of atomic nuclei;*
- *explain the nature of forces between nucleons;*
- *explain the terms 'mass defect' and 'binding energy';*
- *draw binding energy per nucleon curve and discuss the stability of atomic nuclei;*
- *discuss the phenomenon of radioactivity, and identify the three types of radioactive radiations;*

- *explain the growth and decay of radioactivity in a sample;*
- *calculate the half-life, and decay constant of a radioactive substance; and*
- *explain the uses of radioactivity in various fields.*

26.1 THE ATOMIC NUCLEUS

Soon after the discovery of nucleus in an atom by Rutherford in 1911, physicists tried to study as to what resides inside the nucleus. The discovery of neutron by James Chadwick in 1932 gave an impetus to these searches as it clearly suggested to the scientific world that the building blocks of the nucleus are the protons and the neutrons.

26.1.1 Charge and Mass

The atomic nucleus contains two types of particles, ***protons and neutrons***. While *protons* are *positively charged, neutrons* are *neutral*. The *electrons,* which revolve in certain specified orbits around the nucleus, are *negatively charged* particles. The magnitude of charge on a proton in a nucleus is exactly equal to the magnitude of charge on an electron. Further, the number of protons in a nucleus is also equal to the number of electrons so that the atom is as a whole is electrically neutral.

Neutrons and protons are collectively referred to as *nucleons.* Their combined number in a nucleus, that is the number of nucleons, is called the *mass number.* It is denoted by A. The number of protons in a nucleus (or the number of electrons in an atom) is called the *atomic number*. It is denoted by Z. The number of neutrons in a nucleus is usually denoted by $N = A - Z$. Usually $N \geq Z$. The difference $(N–Z)$ increases as A increases. Note that for a lithium nucleus containing 3 protons and 4 neutrons, the atomic number Z is 3, and the mass number A is 7.

Protons are slightly lighter than neutrons and almost the entire mass of an atom is concentrated in its nucleus. The mass of a nucleus is nearly equal to the product of A and the mass of a proton (or that of a neutron). Since mass of a proton is 1.67×10^{-27} kg, and A lies between 1 and 240 for most nuclei, the masses of nuclei vary roughly between 1.67×10^{-27}kg and 4.0×10^{-25}kg.

The charge of a nucleus is equal to Ze, where e is the fundamental unit of charge (that is the magnitude of charge on an electron). You may recall that it is equal to 1.6×10^{-19}C. For naturally occurring nuclei, Z varies from 1 to 92, while for transuranic elements (i.e. the artificially produced elements), Z varies from 93 to 105.

26.1.2 Size

The sizes of atomic nuclei are usually quoted in terms of their radii. Many nuclei are nearly spherical in shape and the radius R is given approximately by the formula

$$R = r_0 A^{1/3}$$

Here r_0 is the unit nuclear radius and its numerical value is taken as 1.2 fermi, a unit of length in honour of famous physicist Enrico Fermi. It is equal to 10^{-15}m. The radius of the lightest nucleus (hydrogen) is thus about 1.2 *f*, as *A* for hydrogen is one. The radius of the heaviest naturally occuring nucleus (uranium) is approximately 7.5*f*, as *A* = 238. You may note here that since the volume of any spherical object of radius *r* is equal to (4/3) πR^3, the volume of a nucleus is proportional to *A*, the mass number.

Can you now guess the volume of a nucleus relative to that of an atom? Knowing that the sizes of the nucleus and of the atom are approximately 10^{-15} m and 10^{-10}m, respectively, the volume of an atom is roughly 10^{+5} times the volume of a nucleus. To enable you to visualise these dimensions, the volume of a nucleus relative to atom is something like the volume of a bucket of water relative to the volume of water in Bhakra Dam.

You may now also like to know the order of magnitude of the density of nuclear matter. If we consider the lightest nucleus, hydrogen, whose mass is 1.673×10^{-27} kg and the radius is 1.2×10^{-15} m, and take it to be spherical, the density can be calculated using the relation

$$d_{\mathrm{H}} = \frac{M_{\mathrm{H}}}{\frac{4\pi}{3} R_{\mathrm{H}}^3} = \frac{1.673 \times 10^{-27}\,\mathrm{kg}}{\frac{4\pi}{3} \times \left(1.2 \times 10^{-15}\,\mathrm{m}\right)^3} = 2.3 \times 10^{17}\,\mathrm{kg\ m^{-3}}.$$

For oxygen, $R_0 = 3 \times 10^{-15}$ m and $M_0 = 2.7 \times 10^{26}$ kg, so that

$$d_0 = 2.39 \times 10^{17}\ \mathrm{kg\ m^{-3}}$$

That is, the densities of hydrogen and oxygen are of the same order. You may recall that the density of water is 10^3 and density of mercury is 13.6×10^3 kgm^{-3}. It means that nuclear matter is extremely densely packed. To give you an idea of these magnitudes, if our earth were such a densely packed mass (= 6×10^{24} kg), it would be a sphere of radius 184m only. Similarly, the radius of nuclear sphere, whose mass will be equal to the mass of our sun will be 10 km!

26.1.3 Notation

The nucleus of an atom is represented by the chemical symbol of the element, with the *A* value as its superscript and *Z* value as its subscript; both on the left hand side of the chemical symbol. Thus if the chemical symbol of an element is, say, X, its nucleus is represented by ${}^{A}_{Z}\mathrm{X}$. For example, for the nucleus of chlorine, which has 17 protons and 18 neutrons, we write ${}^{35}_{17}\mathrm{Cl}$. Note that 35 here is mass number.

The atoms of different elements can have the same mass number, though they may have different number of protons. *Atoms having the same A value but different Z values are called Isobars.* Thus argon with $A = 40$ and $Z = 18$ is an isobar of calcium which has $A = 40$ and $Z = 20$. Note that isobars have different chemical properties since these are determined by Z. *Atoms of the same element having the same Z value but different A values are called isotopes.* Thus, chlorine with $Z = 17$ and $A = 35$, and chlorine with $Z = 17$ and $A = 37$, are isotopes of some element, chlorine. Since isotopes have same Z value, they show identical chemical properties. Note that isotopes differ in the number of neutrons in their nuclei. Atoms having the same number of neutrons in their nuclei are called the *isotones*. Thus, sodium with $A = 23$ and $Z = 11$ is an isotone of magnesium with $A = 24$ and $Z = 12$.

Example 26.1 : Calculate the number of electrons, protons, neutrons and nucleons in an atom of ${}^{238}_{92}U$.

Solution : ${}^{238}_{92}U$ symbolises uranium, which has 92 protons and 238 nucleus. Hence Atomic number $Z = 92$ = number of protons

Mass number $A = 238$ = number of (protons + neutrons) = Number of nucleons

$$\text{Number of neutrons} = A - Z$$
$$= 238 - 92$$
$$= 146.$$

Example 26.2 : Select the pairs of Isotopes, Isobars and Isotones in the following list.

${}^{12}_{6}C$, ${}^{27}_{13}Al$, ${}^{39}_{19}K$, ${}^{22}_{14}Si$, ${}^{76}_{32}Ge$, ${}^{40}_{20}Ca$, ${}^{76}_{34}Se$, ${}^{14}_{6}C$

Solution : Isotopes – (Same Z - value) : ${}^{12}_{6}C$ and ${}^{14}_{6}C$

Isotones – [Same $A - Z$ values] : $\left[{}^{27}_{13}Al \text{ and } {}^{28}_{14}Si\right]$, $\left[{}^{39}_{19}K \text{ and } {}^{40}_{20}Ca\right]$

Isobars – (Same A values) : ${}^{76}_{32}Ge$ and ${}^{76}_{39}Se$

INTEXT QUESTIONS 26.1

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

Notes

$^{16}_{8}O$, $^{207}_{82}Pb$, $^{12}_{6}C$, $^{40}_{18}A$, $^{3}_{1}H$, $^{7}_{3}Li$, $^{76}_{32}Ge$, $^{76}_{34}Se$, $^{3}_{2}He$, $^{40}_{20}Ca$, $^{7}_{4}Be$, $^{2}_{1}H$,

$^{14}_{6}C$, $^{235}_{92}U$, $^{206}_{82}Pb$, $^{18}_{8}O$, $^{239}_{92}U$, $^{1}_{1}H$, $^{23}_{11}Na$, $^{27}_{13}Al$, $^{27}_{12}Mg$, $^{28}_{14}Si$, $^{37}_{17}Cl$, $^{35}_{17}Cl$

2. Fill in the blanks :
   (i) Neutron is .... than proton.
   (ii) The total number of protons and neutrons in an atom is called the .... number of that atom.
   (iii) The protons and neutrons together are called ....
   (iv) The number of neutrons in $^{27}_{13}Al$ = ...
   (v) The number of protons in $^{28}_{14}Si$ = ...
   (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 the same element – mass number, atomic number, neutron number?

26.1.4 Unified Atomic Mass

It has been experimentally determined that mass of proton (m_p) is 1836 times the mass of electron (m_e), and the mass of neutron (m_n) is 1840 m_e. Since the mass of an electron is negligibly small compared to the mass of a nucleon, the mass of an atom is effectively due to the mass of its nucleons. However, the neutron is slightly heavier than the proton. It is, therefore, desirable to choose a standard to express the masses of all the atoms (and also that of protons and neutrons). Now a days, atomic masses are expressed in terms of the actual mass of $^{12}_{6}C$ isotope of carbon. The unit of atomic mass, abbreviated as u, is defined as $(1/12)^{th}$ of the actual mass of $^{12}_{6}C$. We know that the value of the mass of a carbon atom is 1.99267×10^{-26}kg. Hence

$$\begin{aligned} 1\text{u} &= (1/12) \times \text{mass of one carbon atom with } A = 12 \\ &= (1/12) \times (1.99267 \times 10^{-26}\text{kg}) \\ &= 1.660565 \times 10^{-27}\text{kg} \\ &= 1.66 \times 10^{-27}\text{ kg} \end{aligned}$$

Since mass of a proton (m_p) is 1.6723×10^{-27}kg, and mass of a neutron (m_n) is 1.6747×10^{-27}kg, we can express these in terms of u :

$$m_p = \frac{1.6723 \times 10^{-27}}{1.6606 \times 10^{-27}}\text{ u} = 1.00727\text{ u}$$

and $$m_n = \frac{1.6747\times10^{-27}}{1.6606\times10^{-27}}\text{ u} = 1.00865\text{ u}$$

Can you now express the mass of an electron ($m_e = 9.1 \times 10^{-31}$ kg) in terms of u? Since we will use nuclear masses in u, it is quite useful to know its energy – equivalent. To do so, we use *Einstein's mass-energy equivalence* relation, viz

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

where c is velocity of light in vacuum. Thus

$$1\text{u} = (1.66 \times 10^{-27}\text{kg})\ (2.9979\times10^8\text{ms}^{-1})^2$$

$$= 14.92\times10^{-11}\text{J}$$

$$= \frac{14.92\times10^{-11}}{1.60\times10^{-13}}\text{MeV}$$

$$= 931.3\text{MeV}$$

Note that joule (J) is too big a unit for use in nuclear physics. That is why we have expressed u in MeV (million electron volts). 1MeV is the energy gained by an electron when accelerated through a potential difference of one million volts. It is equal to 1.6×10^{-13}J.

26.1.5 Mass Defect and Binding Energy

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 constitutent nucleons. This difference in mass is called ***mass-defect***. For example, the nucleus of deuterium isotope of hydrogen has one proton and one neutron. The measured masses of these particles are 1.6723×10^{-27}kg and 1.6747×10^{-27} kg, respectively. It means that total mass of a proton and a neutron is 3.34709×10^{-27} kg. But the mass of deuterium nucleus is 3.34313×10^{-27}kg. It means that the measured mass of deuterium nucleus is 3.96242×10^{-30}kg less than the measured masses of a proton plus a neutron. So we say that mass defect in the case of deuterium is 3.96242×10^{-30} kg. Let us denote it by Δm. Mathematically, for an atom denoted by ${}^{A}_{Z}\text{X}$, we can write

Sum of the masses of the nucleons $= Zm_p + (A–Z)m_n$

$$\therefore \qquad \Delta m = [Z.m_p + (A–Z)m_n] – M \qquad (26.1)$$

where M is actual mass of nucleius.

Energy equivalent of mass defect is obtained by using mass-energy equivalence relation:

$$\text{BE} = \Delta m\, c^2 \text{ joules} \tag{26.2}$$

For Deuterium

$$\begin{aligned}\text{BE} &= (3.96242\times10\text{–}30\text{kg}) \times (2.998 \times 10^{8}\text{ms}^{-1})^2 \\ &= 35.164 \times10^{-14}\text{kg m}^2\,\text{s}^{-2} \\ &= 3.5164 \times10^{-13}\text{J} \\ &= 2.223 \times 10^{6}\text{eV}\end{aligned}$$

since 1eV = 1.602×10^{-19}J.

This means that we have to supply atleast 2.223MeV energy to free the constituent nucleons – proton and neutron – of deuterium nucleus. You can generalise this result to say that *mass defect appears as energy which binds the nucleons together*. This is essentially used up in doing work against the forces which make the nucleons to cling.

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

or
$$\text{B} = \frac{[Zm_\text{p} + (A - Z)m_\text{n} - M\,]\,c^2}{A} \tag{26.3}$$

For ${}^{12}_{6}\text{C}$, Z = 6 and A = 12. Therefore (A–Z) = 12 – 6 = 6. Also M = 12 u; (1u = 931.3MeV)

Therefore,

$$B = \frac{[6m_\text{p} + 6m_\text{n} - 12]\times 931.3}{12} \quad \text{MeV}$$

$$= 7.41\text{MeV}$$

where we have used m_p = 1.00727 u and m_n = 1.00865 u.

It suggests that on breaking the nucleus of carbon atom, nearly 90MeV energy will be released, which can be used for various purposes. This is obtained in nuclear fission of a heavy atom like ${}^{238}_{92}\text{U}$. You will learn about it in the next lesson. This is also the source of energy in an atom bomb.

The value of B is found to increase to about 8.8 MeV as we move from helium (A = 4) to iron (A = 56); thereafter it decreases gradually and drops to about 7.6 MeV for uranium (A = 238). Fig.26.2 shows the variation of binding energy per nucleons with mass number.

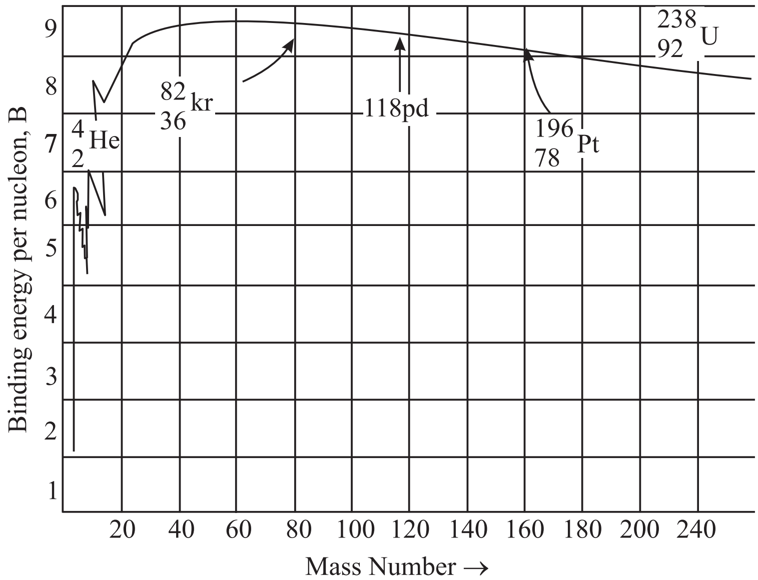


Fig. 26.2 : The variation of binding energy per nucleon with mass number

Note that binding energy curve shows sharp peaks for ${}^{4}_{2}\text{He}$, ${}^{12}_{6}\text{C}$, ${}^{16}_{8}\text{O}$ and ${}^{20}_{9}\text{Ne}$. Moreover, B is small indicating that light nuclei with A < 20 are less stable. For example, the value of B for heavy hydrogen (${}^{2}_{1}\text{He}$) is only 1.1 MeV per nucleon.

The subsidiary peaks occurring at ${}^{2}_{1}\text{He}$, ${}^{12}_{6}\text{C}$, ${}^{16}_{8}\text{O}$ (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.

The binding energy per nucleon curve is very useful in explaining the phenomena of nuclear fission and nucleon fusion.

Example 26.3 : Mass of a Boron (${}^{10}_{5}\text{B}$) atom is 10.811 u. Calculate its mass in kg.

Solution : Since u $= 1.660565 \times 10^{-27}$kg,

$$10.811\text{u} = 10.811 \times 1.660565 \times 10^{-27}\text{kg}$$

$$= 17.952368 \times 10^{-27}\text{kg}$$

INTEXT QUESTIONS 26.2

1. The mass of the nucleus of ${}^{7}_{3}\text{Li}$ atom is 6.01513 u. Calculate mass defect and binding energy per nucleon. Take, $m_p = 1.00727$ u.; $m_n = 1.00865$ u and 1 u = 931 MeV.

2. Calculate the radius of the nucleus of ${}^{8}_{4}\mathrm{Be}$ atom.

   [Use $R = r_0 A^{1/3}$; $r_0 = 1.2 \times 10^{-15}$m]

26.2 HOW DO NUCLEONS CLING TOGETHER : NUCLEAR FORCE

Once physicists accepted the neutron-proton hypothesis of nucleus, an important question arose : How do nucleons cling together? In other words : What is the nature of force that binds nucleons? Since gravitation and electromagnetic interactions explain most of the observed facts, you may be tempted to identify one of these forces as the likely force. However, the extremely small size of the nucleus, where protons and neutrons are closely packed, suggests that forces should be strong, short range and attractive. These attractive forces can not have electrostatic origin because electrostatic forces between protons are repulsive. And if only these were operative, the nucleons would fly away, which is contrary to experience. Moreover, the forces between nucleons are responsible for the large binding energy per nucleon (nearly 8 MeV). Let us consider the gravitational force. No doubt, it is a force of attraction between every pair of nucleons. However, it is far too weak to account for the powerful attractive forces between nucleons. If the magnitude of nucleon-nucleon force is taken to be unity, the gravitational force would be of the order of 10^{-39}. We may, therefore, conclude that the purely attractive forces between nucleons are of a new type with no analogy whatsever with the forces known in the realm of classical physics. This new attractive force is called **nuclear force**.

26.2.1 Characteristic Properties

You may recall that the gravitational as well as electrostatic forces obey inverse square law. However, the nucleons are very densely packed and the nuclear force that holds the nucleons together in a nucleus must exist between the neighbouring nucleons. Therefore, nuclear force should be a short range force operating over very short distances (~10^{-15}m).

These nuclear forces must account for the attractive force between :

– a proton and a neutron;

– two protons; and

– two neutrons.

Since binding energy per nucleon, B is the same, irrespective of the mix of neutrons and protons in the nucleus, we are quite justified in considering the force between them as equivalent. That is, nuclear force is *charge independent*.

The nuclear force shows the property of *saturation,* which means that nucleons show only limited attraction. That is, each nucleon in a nucleus interacts with only neighbouring nucleons instead of all nucleons from one end of the nucleus to the other.

If nuclear forces had only attractive character, nucleons should have coalesced under their influence. But we all know that the average separation between nucleons is constant, resulting in a nuclear volume proportional to the total number of nucleons. The possible explanation is that nuclear forces exhibit attractive character only so long as nucleons are separated through a certain critical distance. For distances less than this critical value, the character of nuclear forces changes abruptly; attraction should change to repulsion. (You should not confuse this repulsion with electrostatic repulsion.) These qualitative aspects of nuclear forces are shown in Fig. 26.3

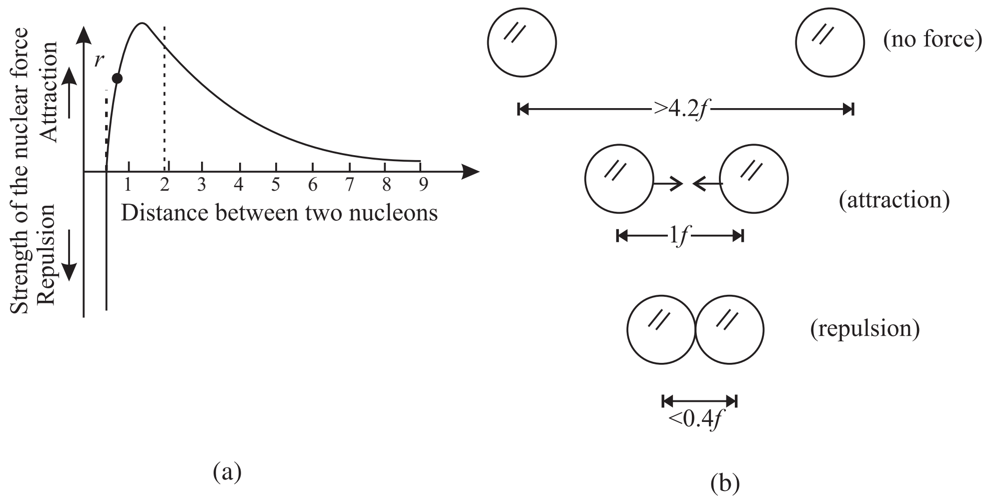


Fig. 26.3 : a) Typical variation of nuclear forces with distance, and **b)** effect of inter-nuclear distance on the force between nucleons.

26.3 RADIOACTIVITY

What is the age of our earth? How do geologists estimate the age of rocks and fossils found during excavations? What is radio-therapy which is used to treat malignant cells? The answers to all these interesting and useful questions are inherent in the study of radioactivity; a natural phenomenon in which atoms emit radiations to attain stability. Though it was discovered by chance, it opened flood gates for new physics. It finds wide use in industry, agriculture and medical care. Let us learn about it now.

26.3.1 Discovery

The story of discovery of radioactivity is very interesting. In 1896, French physicist A.H. Becquerel was working on the phenomenon of fluorescence (in which some substances emit visible light when they are exposed to ultra-violet radiations). In one of the drawers of his desk, he had kept a collection of various minerals, besides several unopened boxes of photographic plates. Somehow, the collection of minerals remained untouched for a considerable period of time. One day Becquerel used one of the boxes of photographic plates to photograph something. When he developed the plates, 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 in the same poor condition. He could not understand as to why plates were fogged because all the boxes were sealed and the plates inside were wrapped with thick black paper.

Becquerel was puzzled and investigated the situation further. He found that uranium placed in his drawer had done the damage and concluded that there must be some new type of penetrating radiation originating from the uranium salt. This radiation was named *Becquerel rays* and the phenomenon of emission of this radiation was named *radioactivity*. The elements exhibiting this phenomenon were called *radioactive elements*.

Soon after this discovery, and based on an exhaustive study, Madame Marie Curie alongwith her husband Pierre Curie, isolated an element from uranium ore by a painstaking method known as chemical fractionating. This new element, which was a million times richer in the mysterious rays than uranium, was given the name radium. Another radioactive element discovered by Madam Curie was named polonium in honour of her native country-Poland.

26.3.2 Nature of Radiations

In 1899, Lord Rutherford, a British physicist, analysed the Becquerel rays emitted by radioactive elements. He established the existence of two distinct components : α-particles and β-rays. The existence of third radiation – gamma rays – was established by P. Villard.

We know that nuclei of all atoms contain positively charged protons, which repel each other strongly due to electrostatic repulsion. To overcome this repulsion, neutrons in the nuclei act as glue. But in case of heavier nuclei, this electrostatic repulsion is so strong that even the addition of neutrons is not able to keep the nuclei stable. To achieve stability, such nuclei disintegrate spontaneously by emitting α and β particles along with γ-rays as shown in Fig 26.4. So, we can say that in natural radioactivity, α, β and γ-rays are emitted.

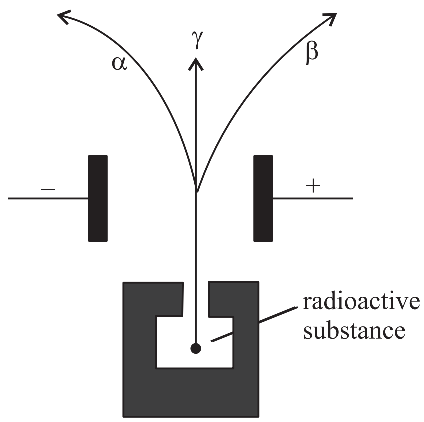


Fig. 26.4 : Emission of α, β and γ radiations

The emitted radiation is called the **radioactive radiation** and the process of disintegration (break-up) of atomic nuclei (by emitting α, β and γ-rays) is called **radioactive decay**. Sometimes, the break-up can be induced by bombarding stable nuclei with other light particles (like neutron and protons). 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. That is, one element gets converted into another element. This is thus a nuclear disintegration phenomenon and suggests the posibility of mutation of new nuclei. Let us first study the characteristic properties of α, β, and γ radiations.

(i) α-**particles**

Alpha particles are helium nuclei (^4_2He) and consist of two protons and two neutrons. Detailed studies of these particles revealed the 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 radioactivity 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 substances, and get scattered by thin foils of metals. They can be stopped by 0.02 mm thick aluminum sheet.
- The energies of α particles emitted from a radioactive substance is a characteristic of the emitting nucleus. This corresponds to a variation in their velocity from $1.4 \times 10^7 \text{m s}^{-1}$ to $2.05 \times 10^7 \text{m s}^{-1}$.

(ii) β-**particles**

β-Particles can be both positively and negatively charged. They originate in the nucleus in the process of conversion of a neutron into a proton, and vice versa. Further studies of β-particles have revealed the following properties.

- Being charged particles, they get deflected by electric and magnetic fields.
- They produce fluorescence in materials like zinc-sulphide and barium plationcynide; and affect photographic plates.
- They can ionize gas atoms but to a much smaller extent than the α-particles.
- Negatively charged β-particles can pass through a few mm of aluminium sheets. They are about 100 times more penetrating than α-particles.

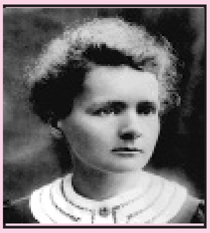
- Average energies of negative β-particles vary between 2 MeV and 3MeV. Due to their small mass, their velocities vary in range from 0.33*c* to 0.988*c*, where *c* is velocity of light.

(iii) **γ-rays**

γ-rays are electromagnetic waves of high frequency, and as such highly energetic. They 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.
- Their penetration power is more than that of α and β-particles; γ-rays can penetrate through several centimeters of iron and lead sheets.
- They have ionizing power that is smaller compared to that of α and β-particles.
- They can produce fluorescence in materials and affect a photographic plate.
- They knock out electrons from the metal surfaces on which they fall and heat up the surface. Hard γ-rays (i.e. high energy γ-rays) are used in radio therapy of malignant cells.

Marie Curie
(1867–1934)



Marie Curie shared the 1903 Nobel prize in physics with A. Henri Becquerel and her husband Pierre Curie for her studies in the field of radioactivity. She was the first person in the world to receive two Nobel prizes; the other Nobel prize she received was in chemistry in 1911. Later her daughter Joliot also won the Nobel prize in chemistry for her discovery of artificial radioactivity.

26.3.3 Radioactive Decay

In any radioactive decay, spontaneous emission consists of either a single α-particle or a β-particle. The emission of an α-particle from a radioactive nucleus (called *parent nucleus*) changes it into a new nucleus (new element is called *daughter nucleus*) with its atomic number decreased by two and its mass number decreased by four. Similarly, emission of a β particle changes the parent nucleus into a daughter nucleus with its atomic number increased by unity (if it is β^- emission) 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.

Note that in any nuclear disintegration, the charge number (Z) and the mass number (A) are always conserved. Thus for any radioactive nucleus, denoted by X, the nuclear transformations may be written as :

$$ {}^{A}_{Z}X \xrightarrow{\alpha-\text{decay}} {}^{4}_{2}He + {}^{A-4}_{Z-2}Y $$

(α-particle)

$$ {}^{A}_{Z}X \xrightarrow{\beta-\text{decay}} {}^{0}_{-1}e + {}^{A}_{Z-1}Y $$

(β-particle)

$$ ({}^{A}_{Z}X)^{*} \xrightarrow{\gamma-\text{decay}} {}^{A}_{Z}X + \gamma $$

The asterisk over the symbol of element implies that it is in an excited state.

26.3.4 Law of Radioactive Decay

We now know that if we have a given amount of radioisotope, it will gradually decrease with time due to disintegrations. The law describing radioactive decay is very simple. The rate of radioactive disintegration is independent of external factors such temperature, pressure etc. and depends only on the law of chance. It states that ***the number of radioactive atoms disintegrating per second is proportional to the number of radioactive atoms present at that instant of time.*** This is called ***law of radioactive decay.***

Let N_0 be the number of radioactive atoms, at $t = 0$, and $N(t)$ be the number of radioactive atoms at time t. If dN denotes the number of atoms that decay in time dt, then $(N - dN)$ signifies the number of radioactive atoms at time $(t + dt)$. Hence, rate of decay

$$ \frac{dN(t)}{dt} \propto N, $$

or

$$ \frac{dN(t)}{dt} = -\lambda N(t) \qquad (26.4) $$

where λ denotes decay constant, which is characteristic of the radioactive substance undergoing decay. The negative sign signifies that the number of nuclei decreases with time. This relation can be rearranged as

$$ \lambda = -\frac{1}{N(t)}\frac{dN(t)}{dt} \qquad (26.5) $$

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

The law of decay is sometimes also expressed in exponential form and is also called the *law of exponential decay.* To obtain the exponential form, we integrate Eq. (26.4) with respect to time :

$$ N(t) = N_0 \exp(-\lambda t) \qquad (26.6) $$

The most important conclusion from this law is that N will become zero only when $t = \infty$.

We rewrite Eqn. (26.4) as

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

On integration, we get

$\ln N(t) = -\lambda t + k$.

At $t = 0$, $N(t) = N_0$

$\therefore\ k = \ln N_0$

Hence

$\ln N(t) - \ln N_0 = -\lambda t$

$$ \text{or}\ \ln\left(\frac{N(t)}{N_0}\right) = -\lambda t $$

On taking antilog, we obtain the required result:

$N(t) = N_0 \exp(-\lambda t)$

Thus, no radioactive element will disappear completely even after a very long time.

The radioactive decay law clearly shows that even if the number of atoms N_0 for different radioactive elements is same initially, at a later time they will have different values of $N(t)$ due to different values of their decay constants (λ). They will thus show different rates of disintegration. This is determined by their half-life ($T_{1/2}$) and average lives (T_a).

Units of Disintegration

The decay constant 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. Its SI unit has been named becquerel :

1 becquerel = 1 disintegration per second.

Another unit of the decay constant is ***curie.***

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

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

Yet another unit is 'rutherford' (rd) :

1 rd = 10^6 disintegrations per second.

26.3.5 Half Life ($T_{1/2}$)

The half life ($T_{1/2}$) of any radioactive element is defined as the time in which the number of parent radioactive atoms decreases to half of the initial number.

By definition, at $t = T_{1/2}$, $N = N_0/2$. Therefore, using Eqn. (26.6), we can write

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

or $\quad \lambda T_{1/2} = \log_e 2$

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

$$= \frac{2.303 \times \log_{10} 2}{\lambda}$$

$$= \frac{2.303 \times 0.3010}{\lambda}$$

$$= \frac{0.693}{\lambda}$$

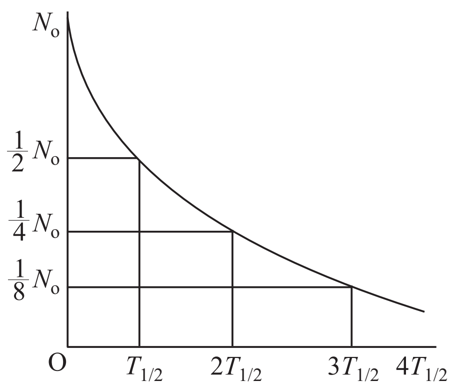


Fig. 26.5 : Radioactive decay curve

Thus, half-life of any radioactive substance is inversely proportional to its decay constant and is a characteristic property of the radioactive nucleus. The half-life of ${}^{14}_{6}C$ (radioactive carbon) is 5730 years. This means that one gram of ${}^{14}_{6}C$ will be reduced to 0.5 g in 5730 years. This number will be further reduced to $\frac{0.5}{2} = 0.25$ g in another 5730 years. i.e. in a total period of 11460 years. Refer to Fig. 26.5 to see how a radioactive sample decays with time.

Example 26.4 : An animal fossil obtained in the Mohanjodaro – excavation shows an activity of 9 decays per minute per gram of carbon. Estimate the age of the Indus Vally Civilisation. Given the activity of ${}^{14}C$ in a living specimen of similar animal is 15 decays per minute per gram, and half life of ${}^{14}C$ is 5730 years.

Solution : ${}^{14}C$ is radioactive isotope of carbon. It remains in fixed percentage in the living species. However, on death, the percentage of ${}^{14}C$ starts decreasing due to radioactive decay. Using radioactive decay law, we can write

$$N(t) = N_0 \exp(-\lambda t)$$

so that

$$N/N_0 = \exp(-\lambda t)$$

or

$$9/15 = \exp(-\lambda t)$$

or

$$\log_e (9/15) = -\lambda t$$

or

$$\text{loge} \left(\frac{15}{9}\right) = \lambda t$$

which gives

$$t = 1/\lambda\ [\log_e (15/9)]$$

Here $T_{1/2} = 0.693/\lambda = 5730$ years. Therefore,

$$t = 2.303 \times (5730/0.693)\ [\log_{10}15 - \log_{10}9]$$

Hence

$$t = 4224.47 \text{ years.}$$

Thus, the specimen containing carbon –14 existed 4224.47 years ago. Hence the estimated age of Indus valley civilsation is 4225 years.

INTEXT QUESTIONS 26.3

1. How can you say that radioactivity is a nuclear disintegration phenomenon?
2. Compare the ionizing and penetration powers of α, β and γ - radiations.

3. Apply the law of conservation of charge and mass numbers to determine the values of *a* and *b* in the following decay - equations :

(i) ${}^{A}_{Z}X = {}^{4}_{2}He + {}^{b}_{a}Y + \gamma$

(ii) ${}^{4}_{Z}X = {}^{0}_{-1}e + {}^{b}_{a}Y + \gamma$

4. The half-life of a radioactive substance is 5 years. In how much time, 10g of this substance will reduce to 2.5g?

Applications of Radioactivity

Radioactivity finds many applications in our every day life. Some of these are given below.

(i) ***In medicine :*** In the treatment of cancer (radiotherapy), a radio-active cobalt source which emits x-rays is used to destroy cancerous cells. The decay of a single radioactive atom can be registered by an instrument placed at a remote location outside a container wall. This high sensitivity is utilized in *tracer technique* as an important tool in medical diagnostics, like the detection of ulcer in any part of the body. A few radioactive atoms of some harmless element $\left({}^{24}_{11}Na\right)$ are injected into the body of a patient. Their movement can then be recorded. The affected part absorbs the radioactive atoms whose flow is, therefore, stopped and the diseased part of the body is easily located.

(ii) ***In agriculture :*** By exposing the seeds to controlled γ radiation, we are able to improve the quality and yield of crops, fruits and vegetables. Radiating these before their storage helps in saving from decay.

(iii) ***In geology :*** In estimating the age of old fossils. 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 present in the atmosphere with the ordinary carbon –12. This isotope (^{14}C) is taken by plants from the atmosphere and is present in animals that eat plants. Thus, about one part in 10^8 radioactive carbon is present in all living beings (all animals and plants). When the organism is dead, its interaction with the atmosphere (i.e. absorption, which maintains the above equilibrium) ceases and its activity begins to fall. From this, the age of the specimen can be approximately estimated. This is called ***carbon-dating*** and is the principle of determining the age of old fossils by archeologists.

The same technique has been used in estimating the age of earth from the measurements of relative amounts of ^{238}U and ^{206}Pb in geological specimens containing uranium ore. Assume 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 amount of lead present in any specimen will therefore indicate its age. The present age of the earth, using this method, has been estimated to be about 4 billion years.

(iv) ***In industry :*** γ-radiations are used to find the flaws (or imperfections) in the inner structure of heavy machinery. For example, if there is an air bubble inside, the penetration of γ-rays will be more at that point.

WHAT YOU HAVE LEARNT

- The nucleus in an atom contains positively charged protons and uncharged neutrons.
- The number of protons inside the nucleus of an atom of any element gives the atomic number of the element.
- The sum of the number of protons and neutrons in the nucleus of an atom is called its mass number.
- The atoms having same atomic number but different mass numbers are called isotopes.
- The atoms with same mass number but different atomic numbers are called isobars.
- The atoms with same number of neutrons are called isotones.
- The nucleons inside the nucleus of every atom are bound together by strong attractive nuclear forces which are short-range and charge-independent.
- The mass of a nucleus is found to be less than the sum of the masses of its nucleons. This difference in mass is called mass-defect. It is a measure of the binding energy.
- The size (volume) of the nucleus depends on its mass number.
- 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 wavelength.
- According to the 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 of a radioactive substance is the time during which the number of radioactive atoms reduce to half of its original number.
- The law of exponential decay is $N(t) = N_0 \exp(-\lambda t)$.

TERMINAL EXERCISE

1. When does a radioactive sample disintegrate?
2. Differentiate between isotopes and isobars.
3. Explain the characteristics of binding energy per nucleon versus mass number curve.
4. What is the nature of nuclear force? Give its characteristics.
5. Explain how decay constant is related to half-life of a radioactive substance.
6. Define the following terms:

   (i) Atomic number; (ii) Mass number; (iii) Mass defect;

   (iv) Binding energy of nucleons; (v) Half-life; (vi) Average life;

   (vii) Decay constant.
7. State the law of radioactive decay.
8. What is carbon dating? What is its importance?
9. Calculate the number of neutrons, protons and electrons in the following atoms.

   (i) ${}^{23}_{11}Na$; (ii) ${}^{2}_{1}H$; (iii) ${}^{238}_{92}U$; (iv) ${}^{35}_{17}Cl$;
10. Calculate the mass defect and binding energy of nucleons for the following nuclei.

    (i) ${}^{4}_{2}He$; (ii) ${}^{7}_{3}Li$; (iii) ${}^{14}_{7}N$;

Given, 1 u = 1.660566×10^{-27}kg = 931 MeV, Mass of a proton = 1.007276 u. Mass of a neutron = 1.008665 u, Mass of $_2He^4$ atom = 4.00260 u, Mass of ^7_3Li atom = 7.01601 u, Mass of $^{14}_7N$ atom = 14.00307 u.

11. 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 ^{238}U and ^{235}U is 137.8 : 1; Half life of ^{238}U is = 4.5×10^9 year; and that of ^{235}U is 7.13×10^8 years.

12. If the activity of a redioactive sample drops to $\frac{1}{16}$th of its initial value in 1 hour and 20 minutes, Calculate the half-life.

ANSWERS TO INTEXT QUESTIONS

26.1

1.

Isotopes	Isobars	Isotones
$^{12}_6C$ and $^{14}_6C$	$^{76}_{32}Ge$ & $^{76}_{34}Se$	^2_1H & ^3_2He
^1_1H and ^2_1H & ^3_1H	$^{40}_{18}A$ & $^{40}_{20}Ca$	$^{14}_6C$ & $^{18}_8O$
$^{16}_8O$ & $^{18}_8O$	$^{76}_{32}Ge$ & $^{76}_{34}Se$	$^{23}_{11}Na$ & $^{24}_{12}Mg$
$^{35}_{17}Cl$ & $^{37}_{17}Cl$	^3_1H & ^3_2He	$^{27}_{13}Al$ & $^{28}_{14}Si$
$^{206}_{82}Pb$ & $^{207}_{82}Pb$	^7_3Li & ^7_4Be	$^{27}_{13}Al$ & $^{28}_{14}Si$
$^{238}_{92}U$ & $^{239}_{92}U$		

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

3. Atomic number.

26.2

1. Δm = 1.041358 u; 969.5 MeV. 2. 2.4×10^{-15}m.

26.3

1. Nuclear disintegration usually involves α or β emission which results in change of atomic and mass numbers of the parent element. With the emission of α

and β particles, the heavier nuclei shed some of their mass resulting in comparatively lighter nuclei. Hence, it 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.. 10 years.

Answers to Problems in Terminal Exercise

9. (i) 12, 11, 11 (ii) 1, 1, 1 (iii) 146, 92, 921 (iv) 18, 17, 17

10. (i) 0.034, 28MeV (ii) 0.044, 37.86 MeV (iii) 0.10854, 101MeV

11. 6×10^9 years

12. 20 min