Chapter 21

NUCLEAR PHYSICS

Learning Objectives

At the end of this chapter the students will be able to:

1. Understand the qualitative treatment of Rutherford's scattering experiment and the evidence it provides for the existence and small size of nucleus.
2. Distinguish between nucleon number (mass number) and atomic number.
3. Understand that an element can exist in various isotopic forms each with a different number of neutrons.
4. Understand the use of mass spectrograph to demonstrate the existence of isotopes and to measure their relative abundance.
5. Understand mass defect and calculate binding energy using Einstein's equation.
6. Illustrate graphically the variation of binding energy per nucleon with the mass number.
7. Appreciate the spontaneous and random nature of nuclear decay.
8. Explain the meaning of half-life.
9. Recognize and use decay law.
10. Understand and describe the interaction of nuclear radiation with matter.
11. Understand the use of Wilson cloud chamber, Geiger Muller counter and solid state detectors to detect the radiations.
12. Appreciate that atomic number and mass number conserve in nuclear process.
13. Describe energy and mass conservation in simple reactions and in radioactive decay.
14. Understand and describe the phenomena of nuclear fission and nuclear fusion.
15. Explain the working principle of nuclear reactor.
16. Be aware of various types of nuclear reactors.
17. Show an awareness about nuclear radiation exposure and biological effects of radiation.
18. Describe in simple terms the use of radiations for medical diagnosis and therapy.
19. Understand qualitatively the importance of limiting exposure to ionizing radiation.
20. Outline the use of tracer technique to obtain diagnostic information about internal structures.
21. Describe examples of the use of radioactive tracers in diagnosis.
22. Describe basic forces of nature.
23. Describe the modern view of the building blocks of matter based on hadrons, leptons and quarks.

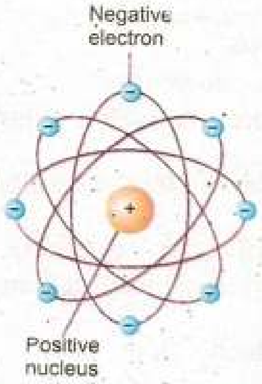
Soon after the discovery of electron and proton in an atom, the quest started to find the way in which these charged particles are present in an atom. From his experiments Ernest Rutherford developed a nuclear model of the atom. His model of the atom consisted of a small dense, positively charged nucleus with negative electrons orbiting about it. In 1920 Rutherford suggested that there is probably another particle within the nucleus, neutral one, to which he gave the name neutron. James Chadwick discovered neutron in 1932.

21.1 ATOMIC NUCLEUS

At the centre of each and every atom there is an infinitesimally small nucleus. The entire positive charge of the atom and about 99.9 percent of its mass is concentrated in the nucleus. The tininess of the nucleus can be imagined by comparing that the radius of the atom is 10^5 times the radius of the nucleus.

A nucleus consists of nucleons comprising of protons and neutrons. A proton has a positive charge equal to 1.6×10^{-19} C and its mass is 1.673×10^{-27} kg. A neutron has no charge on it, but its mass is 1.675×10^{-27} kg. The mass of a neutron is almost equal to mass of proton. To indicate the mass of atomic particles, instead of kilogram, unified mass scale (u) is generally used. By definition 1u is exactly one twelveth the mass of carbon^{12} atom ($1u = 1.6606 \times 10^{-27}$ kg). In this unit the mass of a proton is 1.007276 u and that of a neutron is 1.008665 u while that of an electron is 0.00055 u.

Do You Know?



From α-particles scattering experiments Lord Rutherford concluded that most of the part of an atom is empty and that mass is concentrated in a very small region called nucleus.

The charge on a proton is equal in magnitude to the charge on an electron. The charge on the proton is positive while that of an electron is negative. As an atom on the whole is electrically neutral, therefore, we can conclude that the number of protons inside the nucleus is equal to the number of electrons outside the nucleus. The number of protons inside a nucleus is called the atomic number or the charge number of an atom. It is denoted by Z. Thus the total charge of any nucleus is *Ze*, here *e* indicates charge on one proton.

The combined number of all the protons and neutrons in a nucleus is known as its mass number and is denoted by *A*.

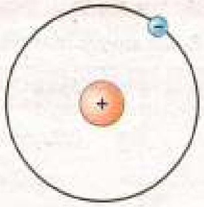
The number of neutrons *N* present in a nucleus is given by

$$N = (A - Z) \qquad \ldots\ldots\ldots\ldots \qquad (21.1)$$

We now consider different elements of the periodic table. Hydrogen atom is simplest of all the atoms. Its nucleus is composed of only one proton; that is for hydrogen A = 1, Z = 1. That is why hydrogen is represented by the symbol $^{1}_{1}H$. Next in the periodic table after the hydrogen element is the helium element. Its nucleus contains two protons and two neutrons. This means for helium A = 4 and Z = 2; and hence helium is represented as $^{4}_{2}He$. We now take the example of uranium - a heavy element of the periodic table. The charge number Z of uranium is 92 while its mass number A is 235. This is represented as $^{235}_{92}U$. It has 92 protons while the number of neutrons N is given by the equation $N = A - Z = 235 - 92 = 143$. In this way the number of protons and neutrons in atoms of all the elements of the periodic table can be determined. It has been observed that the number of neutrons and protons in the initial light elements of the periodic table is almost equal but in the later heavy elements the number of neutrons is greater than the number of protons in the nucleus.

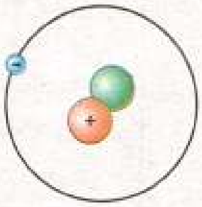
21.2 ISOTOPES

Isotopes are such nuclei of an element that have the same charge number Z, but have different mass number A, that is in the nucleus of such an element the number of protons is the same, but the number of neutrons is different. Helium, for example has two isotopes. These are symbolically represented as $^{3}_{2}He$ and $^{4}_{2}He$. As the charge number of helium is 2, therefore, there are two protons in the helium nucleus. The neutron number of the first isotope is, according to Eq. 21.1 is 3 - 2 = 1 and that in the second isotope $^{4}_{2}He$, the number of neutron is 4 - 2 = 2. Hydrogen has three isotopes represented by $^{1}_{1}H$, $^{2}_{1}H$, $^{3}_{1}H$. Its first isotope is called ordinary hydrogen or protium. There is only one proton in its nucleus. The second isotope of hydrogen is called deuterium. It has one proton and one neutron in its nucleus. Its nucleus is called deuteron. The third isotope of hydrogen has two neutrons and one proton in its nucleus and it is called tritium. The isotopes of hydrogen are shown in Figs. 21.1 (a,b,c).



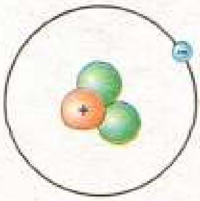
$^{1}_{1}H$

(a) (Protium)



$^{2}_{1}H$

(b) (Deuterium)



$^{3}_{1}H$

(c) (Tritium)

Fig. 21.1

The chemical properties of all the isotopes of an element are alike, as the chemical properties of an element depend only upon the number of electrons around the nucleus, that is upon the charge number Z, which for all the isotopes of an element is the same. It is, therefore, not possible to separate the isotopes of an element by chemical methods. Physical methods are found to be successful for this purpose. A

Do You Know?

Both Xenon and caesium each have 36 isotopes.

For Your Information

Some atomic masses

Particle	Mass (u)
e	0.00055
n	1.008665
^1H	1.007276
^2H	2.014102
^3H	3.01605
^3He	3.01603
^4He	4.002603
^7Li	7.016004
^{10}Be	10.013534
^{14}N	14.0031
^{17}O	16.9991

device with the help of which not only the isotopes of any element can be separated from one another but their masses can also be determined quite accurately is called mass spectrograph.

Mass Spectrograph

A simple mass spectrograph is shown in Fig. 21.2 (a). The atoms or molecules of the element under investigation, in vapour form, are ionized in the ions source S. As a result of ionization, one electron is removed from the particle, leaving with a net positive charge +*e*. The positive ions, escaping the slit S_1, are accelerated through a potential difference *V* applied between the two slits S_1 and S_2.

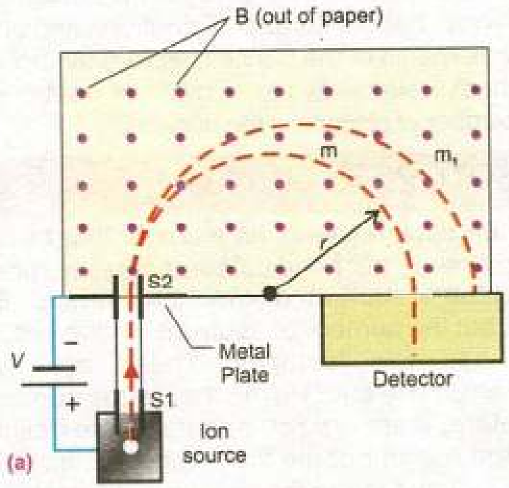


Fig. 21.2

The ions pass through the slit S_2 in the form of a narrow beam. The K.E. of singly charged ion at the slit S_2 will be given by

$$\frac{1}{2}mv^2 = Ve \qquad .... \qquad (21.2)$$

The ions are then subjected to a perpendicular and uniform magnetic field *B* in a vacuum chamber, where they are deflected in semicircular paths towards a detector. The detector records the number of ions arriving per second. The centripetal force applied by the magnetic field is given by

$$Bev = \frac{mv^2}{r} \qquad .... \qquad (21.3)$$

or

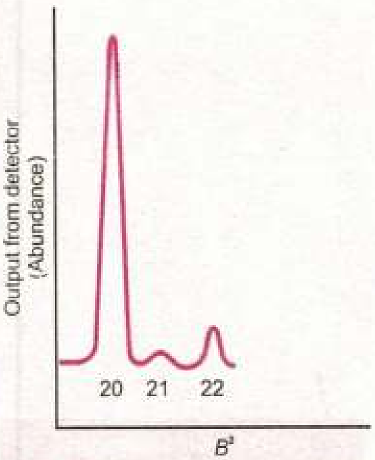
$$m = \frac{Ber}{v}$$

Substituting the values of v from Eq. 21.2, we get

$$m = \left(\frac{er^2}{2V}\right) B^2 \quad .... \quad (21.4)$$

The above equation shows that the mass of each ion reaching the detector is proportional to B^2. By adjusting the value of B and keeping the term in the parentheses constant, ions of different masses are allowed to enter the detector. A graph of the detector output as a function of B^2 then gives an indication of what masses are present and the abundance of each mass.

Fig. 21.2 (b) shows a record obtained for naturally occurring neon gas showing three isotopes whose atomic mass numbers are 20, 21, and 22. The larger is the peak, the more abundant is the isotope. Thus most abundant isotope of neon is neon-20.



(b) (Proportional to atomic mass)

Fig 21.2 The mass spectrum of naturally occurring neon, showing three isotopes whose atomic mass number are 20,21, and 22. The larger the peak, the more abundant the isotope.

21.3 MASS DEFECT AND BINDING ENERGY

It is usually assumed that the whole is always equal to the sum of its parts. This is not so in the nucleus. The results of experiments on the masses of different nuclei show that the mass of the nucleus is always less than the total mass of all the protons and neutrons making up the nucleus. In the nucleus the missing mass is called the mass defect m given by.

$$\Delta m = Z\, m_p + (A - Z)\, m_n - m_{\text{nucleus}} \quad .... \quad (21.5)$$

As Z is the total number of protons in the nucleus and m_p is the mass of a proton, then Zm_p is the total mass of all the protons. As shown in Eq. 21.1, $(A - Z)$ is the total number of neutrons and as m_n is the mass of a single neutron, $(A - Z)\, m_n$ is the total mass of all the neutrons. The term m_{nucleus} is the experimentally measured mass of the entire nucleus. Hence, Eq. 21.5 represents the difference in mass between the sum of the masses of its constituents and the mass of the nucleus itself.

The missing mass is converted to energy in the formation of the nucleus. This energy is found from Einstein's mass energy relation

$$E = (\Delta m)\, c^2 \quad .... \quad (21.6)$$

and is called the binding energy ($B.E.$) of the nucleus. From equations 21.5 and 21.6, the binding energy of a nucleus is

$$B.E. = (\Delta m)\, c^2 = Zm_p c^2 + (A - Z)\ mc^2_{\text{nucleus}} - mc^2 \quad ..... \quad (21.7)$$

Let us consider the example of the deuteron nucleus to make the concept of mass defect and binding energy more clear.

Example 21.1: Find the mass defect and binding energy of the deuteron nucleus. The experimental mass of deuteron is 3.3435×10^{-27} kg.

Solution:

Using equation 21.5, we get the mass defect of deuteron as

$$m = m_p + m_n - m_D$$
$$= 1.6726 \times 10^{-27}\,\text{kg} + 1.6749 \times 10^{-27}\,\text{kg} - 3.3435 \times 10^{-27}\,\text{kg}$$
$$= 3.9754 \times 10^{-30}\,\text{kg}$$

The B.E. of deuteron as found from Eq. 21.6 is $\Delta m c^2$

$\Delta m c^2 = 3.9754 \times 10^{-30}\,\text{kg} \times (3 \times 10^8\,\text{ms}^{-1})^2 = B.E. = 3.5729 \times 10^{-13}\,\text{J}$

To express the result in eV units, divide the B.E. obtained in joules by 1.6×10^{-19} J. Thus

$$B.E. = \frac{3.5729 \times 10^{-13}\,\text{J}}{1.6 \times 10^{-19}\,\text{J(eV)}^{-1}} = 2.33 \times 10^6\ \text{eV} = 2.23\ \text{MeV}$$

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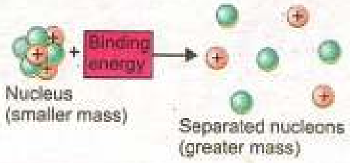


Energy must be supplied to break the nucleus apart into its constituent protons and neutrons.

Therefore, the bound constituents have less energy than when they are free. That is the *B.E.* comes from the mass that is lost in the process of formation. Conversely, the binding energy is the amount of energy that must be supplied to a nucleus if the nucleus is to be broken up into protons and neutrons. Experiments have revealed that such mass defects exist in other elements as well. Shown in Fig. 21.3 is a graph between the mass defect per nucleon and charge

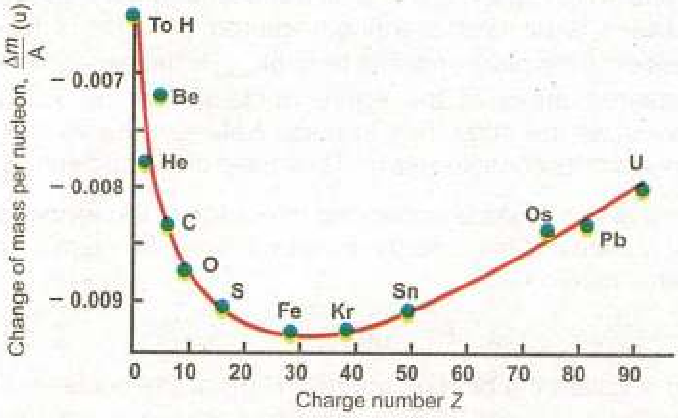


Fig. 21.3

number Z is obtained by finding the difference of mass between the total mass of all the protons and neutrons that form the nucleus and the experimental mass of the nucleus and dividing this difference by mass number A, i.e.,

Mass defect per nucleon

$$\frac{\Delta m}{A} = \frac{m_{\text{nucleus}} - [Zm_p + (A - Z)\,m_n]}{A}$$

where Δm is the mass defect. From the definition of mass defect it is quite obvious that for hydrogen, mass defect is zero. The mass defect is made clear with Einstein's equation $E = \Delta mc^2$. This equation shows that if for any reason a mass Δm is lost, them it is converted into energy.

Let us now calculate the BE of helium. For ${}^4_2\text{He}$

$$\Delta m = 2\,m_p + 2\,m_n - m_{He}$$

$$= 2.01519\,\text{u} + 2.01796\,\text{u} - 4.00281\,\text{u} = 0.03034\,\text{u}$$

since $\quad 1\,\text{u} = 1.66 \times 10^{-27}\,\text{kg}$

$\therefore \quad \Delta m = 0.03034\,\text{u} \times 1.66 \times 10^{-27}\,\text{kgu}^{-1} = 5.03 \times 10^{-29}\,\text{kg}$

Thus $\quad B.E. = \Delta mc^2 = 5.03 \times 10^{-29}\,\text{kg} \times 9 \times 10^{16}\,\text{m}^2\text{s}^{-2}$

$$= 4.5 \times 10^{-12}\,\text{J} = \frac{4.5 \times 10^{-12}\,\text{J}}{1.6 \times 10^{-19}\,\text{J(eV)}^{-1}} = 2.82 \times 10^7\,\text{eV} = 28.2\,\text{MeV}$$

This means that when two protons and two neutrons fuse together to make helium nucleus, if an amount of 28.2 MeV energy is given to the helium nucleus then it breaks up into two protons and two neutrons. From this, we conclude that

$$1\,\text{u} = 1.6606 \times 10^{-27}\,\text{kg} = 931\,\text{MeV}$$

In this way we can calculate binding energy of every element. Shown in Fig. 21.4 is a graph between binding energy per nucleon and the mass number of different elements. This graph shows that the binding energy per nucleon increases

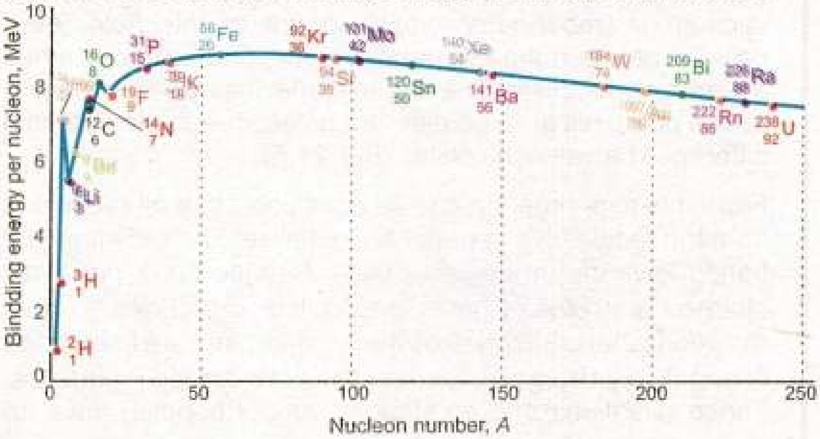
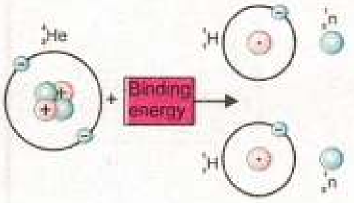


Fig. 21.4

For Your Information



with the mass number till it reaches a maximum value of 8.8 MeV at mass number 58 and then it gradually decreases to a value of 7.6 MeV at mass number 238. The binding energy per nucleon is maximum for iron. This shows that of all the elements iron is the most stable element. Later in this chapter it will be shown with the help of graph of Fig. 21.4 that when heavy element breaks into lighter elements or the lighter elements are fused to form heavier element then a large amount of energy can be obtained.

21.4 RADIOACTIVITY

It has been observed that those elements whose charge number Z is greater than 82 are unstable. Some invisible radiations, that can affect the photographic plates emanate out of these elements. Such elements are called radioactive and the phenomenon is called radioactivity. The radiations coming out of the radioactive elements are called alpha (α), beta (β), and gamma (γ) radiation. Radioactivity was discovered by Henri Becquerel in 1896. He found that an ore containing uranium ($Z = 92$) emits an invisible radiation that penetrates through a black paper wrapping a photographic plate and affects the plate. After Becquerel's discovery Marie Curie and Pierre Curie discovered two new radioactive elements that they called polonium and radium.

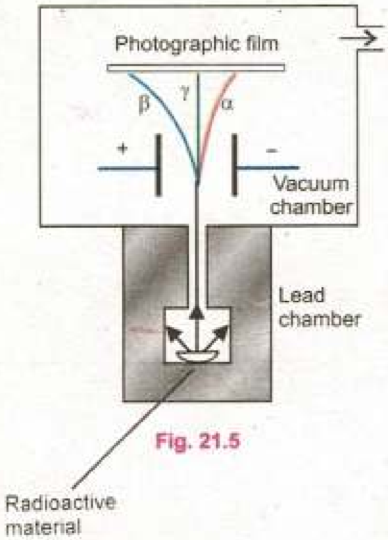


Fig. 21.5

The analysis of the radiations emanating out of a radioactive material can be carried out by a simple experiment. The radioactive material is placed at the centre of a block of lead by drilling a hole in the block. Radioactive radiations enter a vacuum chamber after emerging out of this hole. After passing between the two parallel plates the radiations strike a photographic plate. These radiations, instead of impinging at one point, fall at three different points due to the potential difference between the plates (Fig. 21.5).

From this experiment it can be concluded that all radiations from the radioactive material are not alike. The radiation that bends towards the negative plate is made up of positively charged particles. These are called α-particles. Those radiations that bend towards the positive plate are composed of negatively charged particles. These are called β-particles. Those radiations that go straight without bending have no charge on them. These are called γ-rays.

Further experiments reveal that α-particles are helium nuclei. The charge on them is $+2e$ while their mass is 4u (atomic mass unit) that is every α-particle has two protons and two neutrons in it. β-particles are in fact fast moving electrons which come out of the nucleus of a radioactive element. γ-rays like X-rays, are electromagnetic waves which issue out of the nucleus of a radioactive element. The wavelength of these rays is much shorter, compared with the wavelength of X-rays.

Nuclear Transmutation

Radioactivity is purely a nuclear phenomenon. This is not affected by any physical or chemical reaction. Whenever any particle / radiation is emitted out of any radioactive element, it is always accompanied by some changes in the nucleus of the element. Therefore, this element changes into a new element. This phenomenon is called radioactive decay. The element formed due to this change is called daughter element. The original element is called the parent element. During the nuclear changes the laws of conservation of mass, energy, momentum and charge remain applicable.

We know that three types of radiations α-particle, β-particle and γ-rays are emitted by the naturally occurring radioactive elements. When α-particle is emitted out of any nucleus then due to law of conservation of matter, the mass number of the nucleus decreases by 4, and due to law of conservation of charge, the charge of the nucleus decreases by a magnitude of $2e$ i.e., the charge number of the nucleus decreases by 2. It is due to the fact that the mass number and charge number of the emitted particle α is 4 and 2 respectively. The emission of the α-particle is represented by the following equation

$$^{A}_{Z}X \longrightarrow\ ^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

Here X represents the parent and Y the daughter element.

To explain the emission of α-particles we take the example of radium $^{226}_{88}Ra$. The emission of an α-particle from radium 226, results in the formation of radon gas $^{222}_{86}Rn$. This change is represented by the following equation

$$^{226}_{88}Ra \longrightarrow\ ^{222}_{86}Rn + {}^{4}_{2}He$$

It may be remembered that the sum of the mass numbers and the charge numbers on both sides of the

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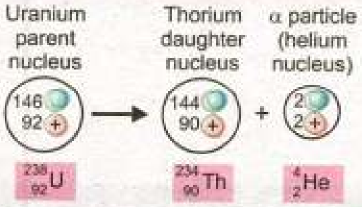

α - decay occurs when an unstable parent nucleus emits an α - particle and in the process it is converted into a different (or daughter) nucleus.

equation are equal. When a β-particle is emitted out of any nucleus, then its mass number does not undergo any change but its charge number increases by one. The emission of a β-particle from any element X is represented by the following equation

$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{-1}e $$

Negative β-particle is an electron and its emission from the nucleus becomes an incomprehensible enigma, as there is no electron present in the nucleus. However, the emission of electron from the nucleus can be thought of as a neutron emitting an electron and becoming a proton, although the modern explanation is not that simple.

This means that the β-particle is formed at the time of emission. That is why at the time of emission of a β-particle the charge number of the nucleus increases by one but no change in its mass number takes place as the mass of electron is exceedingly small as compared to the mass of a proton or a neutron. The transformation of an electron at the moment of its emission is given below by an equation

$$ {}^{1}_{0}n \longrightarrow {}^{1}_{1}H + {}^{0}_{-1}e $$

It has been observed that thorium ${}^{234}_{90}Th$ is transformed into protactinium ${}^{234}_{91}Pa$ after the emission of β-particle. The following equation represents this reaction

$$ {}^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e $$

When a γ-radiation issues out of nucleus then neither the charge number *Z* not the mass number *A* of the nucleus undergoes any change. It is due to the fact that a γ-radiation is simply a photon that has neither any charge nor any mass. Its emission from the nucleus has some resemblance with the emission of a photon of light from an atom. We know that when any electron of an atom absorbs energy it jumps from the ground state to a higher energy state and the atom becomes excited. When the electron of this excited atom returns to its ground state then it emits the absorbed energy in the form of a photon. In much the same way the nucleus is sometimes excited to a higher state following the emission of α or β-particle. This excited state of the nucleus is unstable state, in coming back to its ground state from the excited state, γ-radiation is emitted.

The emission of γ-radiation from a nucleus is generally represented by this equation

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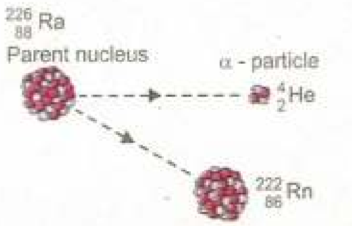
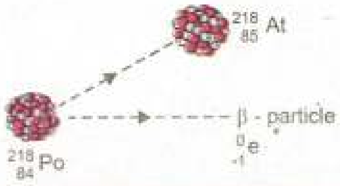
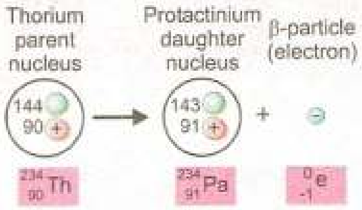


The emission of α-particle from Radium-226 results in the formation of Radon-222 gas.



The emission of β-particle from Polonium-218 results in the formation of Astatine-218.

Do You Know?



β - decay occurs when a neutron in an unstable parent nucleus decays into a proton and an electron, the electron being emitted as the β - particle. In the process, the parent nucleus is transformed into daughter nucleus.

$${}^{A}_{Z}X^{*} \longrightarrow {}^{A}_{Z}X + \gamma \text{ radiation}$$

Here ${}^{A}_{Z}X^{*}$ represents an excited nucleus while ${}^{A}_{Z}X$ shows ground state of the nucleus.

21.5 HALF LIFE

We have seen that whenever an α or β-particle is emitted from a radioactive element, it is transformed into some other element. This radioactive decay process is quite random and is not subjected to any symmetry. This means that we cannot foretell about any particular atom as to when will it decay. It could decay immediately or it may remain unchanged for millions of year. Thus we cannot say anything about the life of any particular atom of a radioactive element.

Let us take the example of a city with a population of one million and we know that on the average ten person die every day. Even with this knowledge we cannot say with certainty that which particular person will die on which particular day. We can only say that on the whole ten person will die. The greater the population of the city, the greater the accuracy of such predictions. Like the population of a city, it is not possible to talk about an atom of a radioactive element. For more accurate result we always talk about large groups of atoms and laws of statistics are applied upon them. Let us suppose that we bring a group of 100,000 atoms under consideration and wait till such time that half of these i.e., 50,000 decay into their daughter element. This time is called the half-life $T_{1/2}$ of this element. If the half-life of the said element be one day, then after one day only 25,000 atoms will remain behind and after two days 12,500 atoms will remain behind. That is with the passage of every one day, the number of atoms remaining behind becomes half of the number already present. This example provides us the definition of half-life of a radioactive element i.e.,

> **"The half-life $T_{1/2}$ of a radioactive element is that period in which half of the atoms decay".**

Besides getting the definition of half-life we can deduce two other conclusions from this example. These are, firstly no radioactive element can completely decay. It is due to the reason that in any half-life period only half of the nuclei decay and in this way an infinite time is required for all the atoms to decay.

Secondly, the number of atoms decaying in a particular period is proportional to the number of atoms present in the beginning of the period. If the number of atoms to start with is large then a large number of atoms will decay in this period and if the number of atoms present in the beginning is small then less atoms will decay.

We can represent these results with an equation. If at any particular time the number of radioactive atoms be N, then in an interval Δt, the number of decaying atom, ΔN is proportional to the time interval Δt and the number of atoms N, i.e.,

$$\Delta N \propto -N\Delta t$$

or $$\Delta N = -\lambda N \Delta t \qquad .... \qquad (21.8)$$

where λ is the constant of proportionality and is called decay constant. Eq. 21.8 shows that if the decay constant of any element is large then in a particular interval more of its atoms will decay and if the constant λ is small then in that very interval less number of atoms will decay. From Eq. 21.8 we can define decay constant λ as given below

$$\lambda = -\frac{\Delta N / N}{\Delta t}$$

here $\Delta N / N$ is the fraction of the decaying atoms. Thus decay constant of any element is equal to the fraction of the decaying atoms per unit time. The unit of the decay constant is s^{-1}. The negative sign in the Eq. 21.8 indicates the decrease in the number of atoms N.

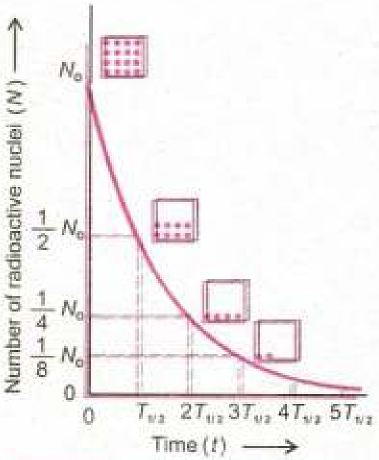


Fig. 21.6 The half life $T_{1/2}$ of a radioactive decay is the time in which one-half of the radioactive nuclei disintegrate.

The decay ability of any radioactive element can be shown by a graphic method also.

We know that every radioactive element decay at a particular rate with time. If we draw a graph between number of atoms in the sample of the radioactive element present at different times and the time then a curve as shown in Fig. 21.6 will be obtained. This graph shows that in the beginning the number of atoms present in the sample of the radioactive element was N_0, with the passage of time the number of these atoms decreased due to their decay. This graph is called decay curve.

After a period of one half-life $N_0 / 2$ number of atoms of this radioactive element are left behind. If we wait further for another half-period then half of the remaining $N_0 / 2$ atoms decay, and $1/2 \times N_0 / 2 = (1/2)^2 N_0$ atoms remain behind. After the expiry of further period of a half-life, half of the remaining $(1/2)^2 N_o$ atoms decay. The number of atoms that remain un-decayed is $1/2 \times (1/2)^2 N_o = (1/2)^3 N_o$. We can conclude from this example that if we have N_o number of any radioactive element then after a period of n half-lives the number of atoms left behind is $(1/2)^n N_o$.

It has been found that the estimate of decay of every radioactive element is according to the graph of Fig.21.6 but the half-life of every radioactive element is different. For example the half-life of uranium-238 is 4.5×10^9 years while the half-life of radium-226 is 1620 years. The half-life of some radio active elements is very small, for example, the half-life of radon gas is 3.8 days and that of uranium-239 is 23.5 minutes.

From the above discussion it is found that the estimate of any radioactive element can be made from its half-life or by determining its decay constant λ. It can be proved with the help of calculus that the following relations exist between the decay constant λ and the half-life $T_{1/2}$

$$\lambda T_{1/2} = 0.693 \qquad \ldots\ldots\ldots \qquad (21.9)$$

Eq. 21.9 shows that if the decay constant λ of any radioactive element is known, its half-life can be found.

Any stable element, besides the naturally occurring radioactive element, can be made radioactive. For this very high energy particles are bombarded on the stable element. This bombardment excites the nuclei and the nuclei after becoming unstable become radioactive element. Such radioactive elements are called artificial radioactive elements.

Example 21.2: Iodine-131 is an artificial radioactive isotope. It is used for the treatment of human thyroid gland. Its half-life is 8 days. In the drug store of a hospital 20 mg of iodine-131 is present. It was received from the laboratory 48 days ago. Find the quantity of iodine-131 in the hospital after this period.

Solution:

As the half-life of iodine is 8 days, therefore in 8 days half of the iodine decays. Given below in the table is the amount of iodine present after every 8 days.

Interval in days	Quantity of Iodine	Interval in days	Quantity of Iodine
0	20 mg	32	1.25 mg
8	10 mg	40	0.625 mg
16	5 mg	48	0.3125 mg
24	2.5 mg		

Thus 48 days after the receipt, the amount of iodine-131 left behind is only 0.3125 mg.

21.6 INTERACTION OF RADIATION WITH MATTER

An α-particle travels a well defined distance in a medium before coming to rest. This distance is called the range of the particle. As the particle passes through a solid, liquid or gas, it loses energy due to excitation and ionization of atoms and molecules in the matter. The ionization may be due to direct elastic collisions or through electrostatic attraction. Ionization is the main interaction with matter to detect the particle or to measure its energy. The range depends on the

i. charge, mass and energy of the particle and
ii. the density of the medium and ionization potentials of the atoms of the medium.

Since α-particle is about 7000 times more massive than an electron, so it does not suffer any appreciable deflection from its straight path, provided it does not approach too closely to the nucleus of the atom. Thus α-particle continues producing intense ionization along its straight path till it loses all its energy and comes almost to rest. It, then, captures two electrons from the medium and becomes a neutral helium atom.

β-particles also lose energy by producing ionization. However, its ionizing ability is about 100 times less than that of α-particles. As a result its range is about 100 times more than α-particles. β-particles are more easily deflected by collisions than heavy α-particles. Thus the path of β-particles in matter is not straight but shows much straggling or scattering. The range of β-particles is measured by the effective depth of penetration into the medium not by the length of erratic path. The more dense the material through which the particle moves, the shorter its range will be.

α and β-particles both radiate energy as X-ray photons when they are slowed by the electric field of the charged particles in a solid material.

Photons of γ-rays, being uncharged, cause very little ionization. Photons are removed from a beam by either scattering or absorption in the medium. They interact with matter in three distinct ways, depending mainly on their energy.

(i) At low energies (less than about 0.5 MeV), the dominant process that removes photons from a beam is the photoelectric effect.

(ii) At intermediate energies, the dominant process is Compton scattering.

(iii) At higher energies (more than 1.02 MeV), the dominant process is pair production.

In air γ-rays intensity falls off as the inverse square of the distance from the source, in much the same manner as light from a lamp. In solids, the intensity decreases exponentially with increasing depth of penetration into the material. The intensity I_0 of a beam after passing through a distance x in the medium is reduced to intensity I given by the relation $I = I_0 e^{-\mu x}$

where μ is the linear absorption coefficient of the medium. This coefficient depends on the energy of the photon as well as on the properties of the medium.

Charged particles α or β and γ-radiation produce fluorescence or glow on striking some substance like zinc sulphide, sodium iodide or barium platinocyanide coated screens.

"Fluorescence is the property of absorbing radiant energy of high frequency and re-emitting energy of low frequency in the visible region of electromagnetic spectrum".

Neutrons, being neutral particles, are extremely penetrating particles. To be stopped or slowed, a neutron must undergo a direct collision with a nucleus or some other particle that has a mass comparable to that of the neutron. Materials such as water or plastic, which contain more low-mass nuclei per unit volume, are used to stop neutrons. Neutrons produce a little indirect ionization when they interact with materials containing hydrogen atoms and knock out protons.

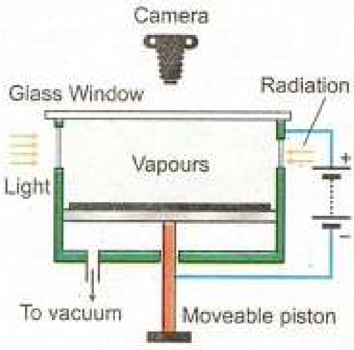
Table 21.1 The summary of the nature of α, β & γ radiation

Characteristics	α–particles	β–particles	γ–rays
1. Nature	Helium nuclei of charge 2*e*	Electrons or positrons from the nucleus of charge $\pm e$	E. M. waves from excited nuclei with no charge
2. Typical sources	Radon-222	Strontium-94	Cobalt-60
3. Ionization (Ion pairs mm^{-1} in air)	About 10^4	About 10^2	About 1
4. Range in air	Several centimetres	Several metres	Obeys inverse square law
5. Absorbed by	A paper	1~5 mm of Al sheet	1~10 cm of lead sheet
6. Energy spectrum	Emitted with the same energy	Variable energy	Variable energy
7. Speed	$\sim 10^7\ \text{ms}^{-1}$	$\sim 1 \times 10^8\ \text{ms}^{-1}$	$\sim 3 \times 10^8\ \text{ms}^{-1}$

21.7 RADIATION DETECTORS

Nuclear radiations cannot be detected by our senses, hence, we use some observable detecting methods employing the interaction of radiation with matter. Most detectors of radiation make use of the fact that ionization is produced along the path of the particle. These detectors include Wilson cloud chamber, Geiger counter and solid state detectors.

Wilson Cloud Chamber

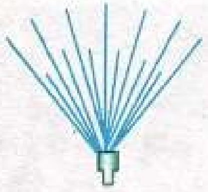


Wilson Cloud Chamber

Fig. 21.7

It is a device which shows the visible path of an ionizing particle. It makes use of the fact that supersaturated vapours condense preferentially on ions. If an ionizing particle passes through a region in which cloud droplets are about to form, the droplets will form first along the particle's path, showing the path as a trail of droplets. The apparatus consists of a cylindrical glass chamber closed at the upper end by a glass window and at the lower end by a movable piston (Fig. 21.7). A black felt pad soaked in alcohol is placed on a metal plate inside the chamber. The air soon becomes saturated with alcohol vapours. A rapid expansion is produced by pulling quickly the piston of the bicycle pump having the leather washer reversed so that it removes air. The sudden cooling resulted from adiabatic expansion helps to form supersaturated vapours. As radiation passes through the chamber, ions are produced along the path. The tiny droplets of moisture condense about these ions and form vapour tracks showing the path of the radiation. These are the atomic versions of the ice crystals left in the sky by a jet plane when suitable conditions exist. The fog tracks are illuminated with a lamp and may be seen or photographed through the glass window.

The α-particles leave thick, straight and continuous tracks due to intense ionization produced by them as shown in Fig. 21.8 (a), β-particles form thin and discontinuous tracks extending in erratic manner showing frequent deflections (Fig. 21.8 b) and γ-rays leave no definite tracks along their path (Fig. 21.8 c). The length of the cloud tracks has been found proportional to the energy of the incident particle. A high potential difference of the order of 1 kV between the top and bottom of the chamber provides an electric field which clears away all the unwanted ions from the chamber to make it ready for use. The tracks seen are, therefore, those of rays that pass the chamber as the expansion occurs.


(a) α- Particle


(b) β- Particle

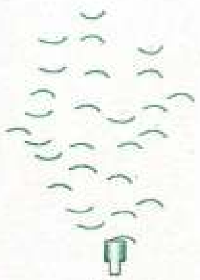

(c) γ-Rays

Fig. 21.8 Cloud chamber tracks of α, β, γ radiations

The chamber may be placed in a strong magnetic field which will bend the paths providing information about the charge, mass and energy of the radiating particle. In this way, it has helped in the discovery of many new particles.

Geiger-Muller Counter

Geiger-Muller tube is a well-known radiation detector (Fig. 21.9 a). The discharge in the tube results from the ionization produced by the incident radiation. It consists of a stiff central wire acting as an anode in a hollow metal cylinder acting as a cathode filled with a suitable mixture of gas at about 0.1 atmospheric pressure. One end of the tube has a thin mica window to allow the entry of α or β-particles and other end is sealed by non-conducting material and carries the connecting pins for the two electrodes. A high potential difference, (about 400 V for neon - bromine filled tubes) but slightly less than that

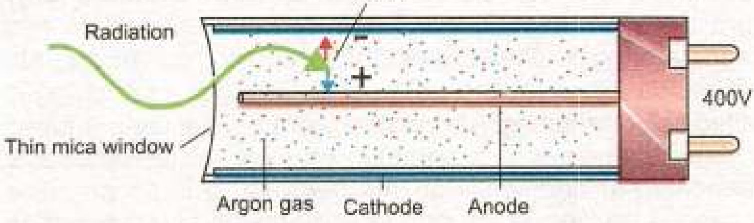


Fig. 21.9 (a) Geiger – Muller Tube

necessary to produce discharge through the gas is maintained between the electrodes. When radiation enters the tube, ionization is produced. The free electrons are attracted towards the positively charged central wire. As they are accelerated towards the wire by a strong electric field, they collide with other molecules of the gas and knock out more electrons which in turn do the same and produce a cascade of electrons that move towards the central wire. This makes a short pulse of electric current to pass through an external resistor. It is amplified and registered electronically. The counter, which also provides the power, is called a scaler.

(b) G.M. Tube with scaler unit

Fig. 21.9

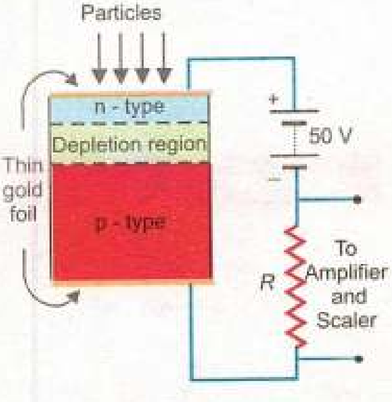
The cascade of electrons produced by the entry of an ionizing particle is counted as a single pulse of approximately of the same size whatever the energy or path of the particle maybe. It cannot, thus, discriminate between the energies of the incident particle as output pulses are same. The entire electron pulse takes less than 1μ s. However, positive ions, being very massive than the electrons, take several hundred times as long to reach the outer cathode. During this time, called the dead time ($\sim 10^{-4}$ s) of the counter, further incoming particles cannot be counted. When positive ions strike the cathode, secondary electrons are emitted from the surface. These electrons would be accelerated to give further spurious counts. This is prevented by mixing a small amount of quenching gas with the principal gas.

The quenching gas must have an ionization potential lower than that of inert or principal gas. Thus, the ions of quenching gas reach the cathode before principal gas ions. When they reach near the cathode, they capture electrons and become neutral molecules. Following neutralization, the excess energy of the quenching molecules is dissipated in dissociation of the molecules rather than in the release of electrons from the cathode. For example, bromine gas is added to neon gas. The bromine molecules absorb energy from the ions or secondary electrons and dissociate into bromine atoms. The atoms then readily recombine into molecules again for the next pulse. The gas quenching is called self quenching. Although all commercial Geiger tubes are self quenched, it is common practice to use electronic quenching in addition. For this purpose, a large negative voltage is applied to the anode immediately after recording the output pulse. This reduces the electric field bleow the critical value for ionization by collision. The negative voltage remains until all the positive ions are collected at cathode thus preventing secondary pulses.

Geiger counter can be used to determine the range or penetration power of ionizing particles. The reduction in the count rate by inserting metal plates of varying thickness between the source and the tube helps to estimate the penetration power of the incident radiation.

Geiger counter is not suitable for fast counting. It is because of its relatively long "dead time" of the order of more than a millisecond which limits the counting rate to a few hundred counts per second. If particles are incident on the tube at a faster rate, not all of them will be counted since some will arrive during the dead time. Solid state detectors are fast enough, more efficient and accurate.

Solid State Detector



Solid state detector

Fig. 21.10

A solid state detector is a specially designed p-n Junction (Fig. 21.10) operating under a reversed bias in which electron-hole pairs are produced by the incident radiation to cause a current pulse to flow through the external circuit. The detector is made from a p-type silicon or germanium. An n-type thin layer is produced by doping the top surface with donor type impurity. The top and bottom surfaces are coated with a thin layer of gold to make good conducting contact with external circuit. The combined thickness of n-type and gold layer absorbs so less energy of the incident particle that the junction may be assumed to be situated at the front surface. This is known as the surface barrier type detector. A reverse bias is applied through the two conducting layers of gold. This enlarges the charge free region around the junction called depletion region. Normally no current flows through the circuit. When an incident particle penetrates through the depletion region, it produces electron-hole pairs. These mobile charge carriers move towards the respective sides due to applied electric field. This gives rise to a current in the external circuit due to which a pulse of voltage is generated across the resistance R. This pulse is amplified and registered by a scaler unit. The size of the pulse is found proportional to the energy absorbed of the incident particle. The energy needed to produce an electron-hole pair is about 3 eV to 4 eV which makes the device useful for detecting low energy particles. The collection time of electrons and holes is much less than gas filled counters and hence a solid state detector can count very fast. It is much smaller in size than any other detector and operates at low voltage. The above mentioned type detector is used for detecting α or β-particles but a specially designed device can be used for γ-rays.

21.8 NUCLEAR REACTIONS

While studying radioactivity, we have seen that an α particle is emitted from radium-226 and radon-222 is obtained. This nuclear change is represented by the following equation

$$^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$$

Such an equation represents a nuclear reaction. Above mentioned nuclear reaction takes place on its own accord. However, it was Rutherford who, first of all, expressed his opinion that besides natural radioactive decay processes, other nuclear reactions can also occur. A particle x is bombarded on any nucleus X and this process yield a nucleus Y and a light object y as given below

$$X + x \rightarrow Y + y$$

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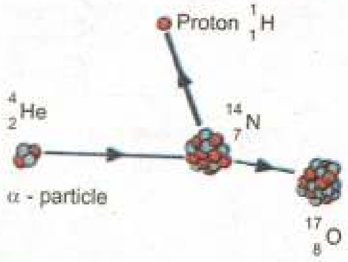


An alpha- proton nuclear reaction

Rutherford performed an experiment on the nuclear reaction in 1918. He bombarded α-particles on nitrogen. He observed that as a result of this reaction, oxygen is obtained and a proton is emitted. That is

$$^{14}_{7}N + {}^{4}_{2}He \longrightarrow {}^{17}_{8}O + {}^{1}_{1}H$$

This reaction indicated that when α-particle enters the nucleus of $^{14}_{7}N$, then an excitation is produced in it. And as a result of it $^{17}_{8}O$ and a proton are produced. Since the experiment of Rutherford, innumerable nuclear reactions have been observed. For nuclear reactions to take place, the fulfillment of certain conditions is a must.

Before and after any nuclear reaction the number of protons and neutrons must remain the same because protons and neutrons can neither be destroyed nor can they be created. We elaborate this point from the example of Rutherford's nuclear reaction of $^{14}_{7}N$ and $^{4}_{2}He$, here

$$^{14}_{7}N + {}^{4}_{2}He \longrightarrow {}^{17}_{8}O + {}^{1}_{1}H$$

Number of protons $= 7 + 2 = 8 + 1$
Number of neutrons $= 7 + 2 = 9 + 0$

A nuclear reaction can take place only when the total energy of the reactants including the rest mass energy is equal to the total energy of the products. For its explanations we again take the example of the nuclear reaction of Rutherford involving $^{14}_{7}N$ and $^{4}_{2}He$. In this reaction the mass of the reactants is

Mass of $^{14}_{7}N$ = 14.0031 u

Mass of $^{4}_{2}He$ = 4.0026 u

Total mass of the reactants = 18.0057 u

In the same way the mass of the products is

Mass of $^{17}_{8}O$ = 16.9991 u

Mass of $^{1}_{1}H$ = 1.0078 u

Total mass of the products after the reaction = 18.0069 u

This shows that the total mass after the reaction is greater than the total mass before the reaction by 0.0012 u. We know that a 1u mass = 931 MeV energy, therefore, a mass difference of 0.0012u is equivalent to an energy of 931 MeV x 0.0012 u = 1.13 MeV. Hence this reaction is possible only when an additional mass of 0.0012 u is added into the reactants or the minimum kinetic energy of the α-particle is 1.13 MeV such as obtained from $^{214}_{84}Po$. The energy of these α-particles is equal to 7.7 MeV which is greater than 1.13 MeV. Had these α-particles been obtained from a source that give out α-particles whose energy was less than 1.13 MeV then this reaction would not have taken place.

From the conditions described above we can tell whether any nuclear reaction is possible or not. There is an interesting aspect in a nuclear reaction that it can take place in the opposite direction also. We know that $^{17}_{8}O$ is obtained by the interaction $^{14}_{7}N$ with an α-particle of appropriate energy. If we accelerate protons, with the help of a machine like cyclotron, and increase their velocity and then bombard these high velocity protons on $^{17}_{8}O$, Rutherford's nuclear reaction of $^{14}_{7}N$ and α-particle will proceed in the backward direction as

$$^{17}_{8}O + ^{1}_{1}H \longrightarrow ^{14}_{7}N + ^{4}_{2}He$$

By bombarding different elements with α-particles, protons and neutrons, many nuclear reactions have been produced. Now we describe one such nuclear reaction with the help of which James Chadwick discovered neutron in 1932. When $^{9}_{4}Be$ was bombarded with α-particles emitted out of $^{210}_{84}Po$, then as a result of a nuclear reaction, $^{12}_{6}C$ and a neutron were obtained. This reaction is shown below with an equation

$$^{9}_{4}Be + ^{4}_{2}He \longrightarrow ^{12}_{6}C + ^{1}_{0}n$$

As neutron carries no charge, therefore, it presented a great amount of difficulty for its identification. Anyhow when neutrons were passed through a block of paraffin, fast moving protons were ejected out and these were easily identified. It may be remembered that a large amount of hydrogen is present in paraffin and the nuclei of hydrogen atoms are protons. The emission of protons is the consequence of elastic collisions between the neutrons and the protons. This indicates that the mass of neutron is equal to the mass of the proton. It may be remembered that when an object of certain mass collides with another object of equal mass at rest, then as a result of elastic collision, the moving object comes to rest and the stationary object begins to move with the velocity of the colliding object. The discovery of neutron has brought in a revolution in nuclear reactions, as the neutrons carry no charge so they can easily enter the nucleus. Fig. 21.11 shows the arrangement of Chadwick's experiment for the discovery of neutron.

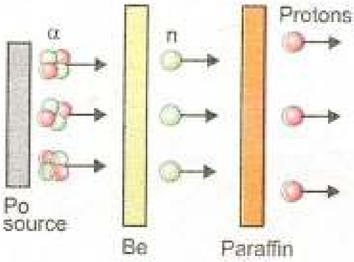


Fig. 21.11

21.9 NUCLEAR FISSION

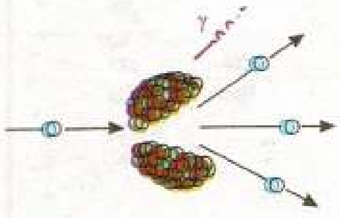
Otto Hahn and Fritz Strassmann of Germany while working upon the nuclear reactions made a startling discovery. They observed that when slow moving neutrons are bombarded on $^{235}_{92}U$, then as a result of the nuclear reaction $^{141}_{56}Ba$, $^{92}_{36}Kr$ and an average of three neutrons are obtained. It may be remembered that the mass of both krypton and barium is less than that of the mass of uranium. This nuclear reaction was different from hither to studied other nuclear reactions, in two ways. First as a result of the breakage of the uranium nucleus, two nuclei of almost equal size are obtained, whereas in the other nuclear reactions the difference between the masses of the reactants and the products was not large. Secondly a very large amount of energy is given out in this reaction.

"Such a reaction in which a heavy nucleus like that of uranium splits up into two nuclei of roughly equal size along with the emission of energy during the reaction is called fission reaction".

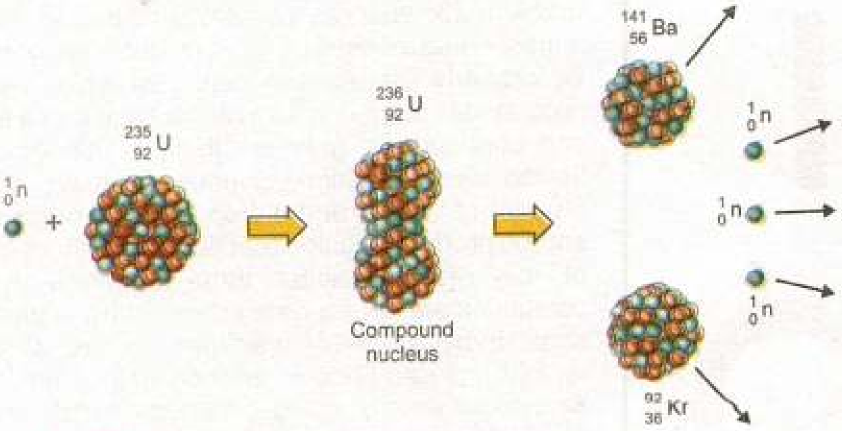
Fission reaction of $^{235}_{92}U$ can be represented by the equation

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + Q$$

here Q is the energy given out in this reaction. By comparing the total energy on the left side of the equation with total energy on the right side, we find that in the fission of one uranium nucleus about 200 MeV energy is given out. It may be kept in mind that there is no difference between the sum of the mass and the charge numbers on both sides of the equation. Fission reaction is shown in Fig. 21.12 (a) and (b). Fission reaction can be easily explained with the help of graph of Fig. 21.4. This graph shows that the binding energy per nucleon is greatest for the middle elements of the periodic table and this binding energy per nucleon is a little less for the light or very heavy elements i.e., the nucleons in the light or very heavy elements are not so rigidly bound. For example the binding energy per nucleon for uranium is about 7.7 MeV and the products of the fission reaction of uranium, namely barium and krypton, have binding energy of about 8.5 MeV per nucleon. Thus when a uranium nucleus breaks up, as a result of fission reaction, into barium and krypton, then an energy at the rate of (8.5-7.6) = 0.9 MeV per nucleon is given out. This means that an energy 235 x 0.9 = 211.5 MeV is given out in the fission of one uranium nucleus.



(a)



(b)

Fig. 21.12 Process of Fission reaction

The fission process of uranium does not always produce the same fragments (Ba, Kr). In fact any of the two nuclei present in the upper horizontal part of binding energy could be produced. Two possible fission reactions of uranium are given below as an example:

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{132}_{50}Sn + ^{101}_{42}Mo + 3\ ^{1}_{0}n + Q$$

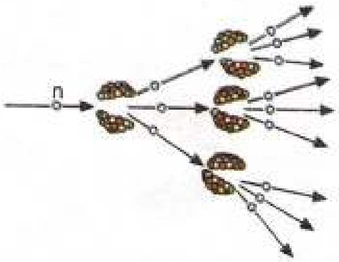


Fig. 21.13

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2\, ^{1}_{0}n + Q$$

Hence in the uranium fission reaction several products may be produced. All of these products (fragments) are radioactive. Fission reaction is not confined to uranium alone; it is possible in many other heavy elements. However, it has been observed that fission takes place very easily with the slow neutrons in uranium-235 and plutonium-239, and mostly these two are used for fission purposes.

Fission Chain Reaction

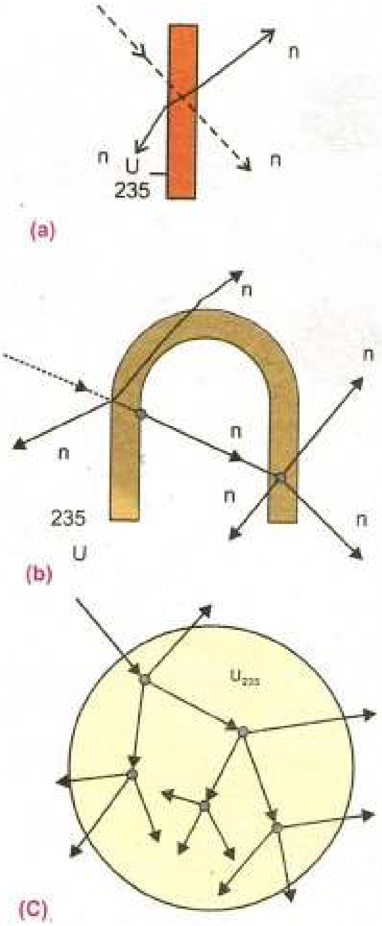


Fig 21.14

We have observed that during fission reaction, a nucleus of uranium-235 absorbs a neutron and breaks into two nuclei of almost equal masses besides emitting two or three neutrons. By properly using these neutrons fission reaction can be produced in more uranium atoms such that a fission reaction can continuously maintain itself. This process is called fission chain reaction. Suppose that we have a definite amount of $^{235}_{92}U$ and a slow neutron originating from any source produces fission reaction in one atom of uranium. Out of this reaction about three neutrons are emitted. If conditions are appropriate these neutrons produce fission in some more atoms of uranium. In this way this process rapidly proceeds and in an infinitesimal small time a large amount of energy along with huge explosion is produced. Fig.21.13 is the representation of fission chain reaction.

It is possible to produce such conditions in which only one neutron, out of all the neutrons created in one fission reaction, becomes the cause of further fission reaction. The other neutrons either escape out or are absorbed in any other medium except uranium. In this case the fission chain reaction proceeds with its initial speed. To understand these conditions carefully look at Fig. 21.14. In Fig. 21.14 (a) a fission reaction in a thin sheet of $^{235}_{92}U$ is shown to be in progress. The resulting neutrons scatter in the air and so they cannot produce any fission chain reaction. Fig. 21.14 (b) shows some favourable conditions for chain reaction. Some of the neutrons produced in the first fission reaction produce only one more fission reaction but here also no chain reaction is produced. In Fig. 21.14 (c) a sphere of $^{235}_{92}U$ is shown. If the sphere is sufficiently big, then most of the neutrons produced by the fission reaction get absorbed in $^{235}_{92}U$ before they escape out of the sphere and produce chain reaction. Such a mass of uranium in which one neutron, out of all the neutrons produced in one fission reaction, produces further fission is called critical mass. The volume of this mass of uranium is called critical volume.

If the mass of uranium is much greater than the critical mass, then the chain reaction proceeds at a rapid speed and a huge explosion is produced. Atom bomb works at this principle. If the mass of uranium is less than the critical mass, the chain reaction does not proceed. If the mass of uranium is equal to the critical mass, the chain reaction proceeds at its initial speed and in this way we get a source of energy. Energy, in an atomic reactor, is obtained according to this principle. The chain reaction is not allowed to run wild, as in an atomic bomb but is controlled by a series of rods, usually made of cadmium, that are inserted into the reactor. Cadmium is an element that is capable of absorbing a large number of neutrons without becoming unstable or radioactive. Hence, when the cadmium control rods are inserted into the reactor, they absorb neutrons to cut down on the number of neutrons that are available for the fission process. In this way the fission reaction is controlled.

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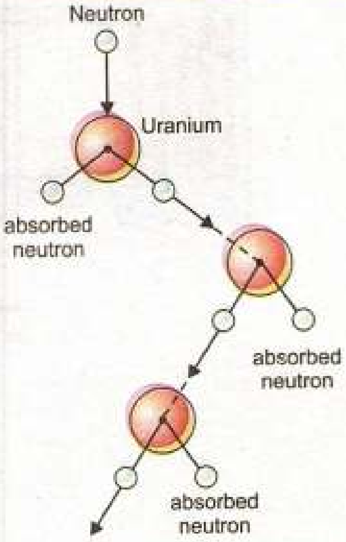


In a controlled chain reaction, only one neutron, on average, from each fission event causes another nucleus to fission. As a result, energy is released at a steady or controlled rate.

Nuclear Reactor

In a nuclear power station the reactor plays the same part as does furnace in a thermal power station. In a furnace, coal or oil is burnt to produce heat, while in a reactor fission reaction produces heat. When fission takes place in the atom of uranium or any other heavy atom, then an energy at the rate of 200 MeV per nucleus is produced. This energy appears in the form of kinetic energy of the fission fragments. These fast moving fragments besides colliding with one another also collide with the uranium atoms. In this way their kinetic energy gets transformed in heat energy. This heat is used to produce steam which in turn rotates the turbine. Turbine rotates the generator which produces electricity. A sketch of a nuclear power station is shown in Fig. 21.15.

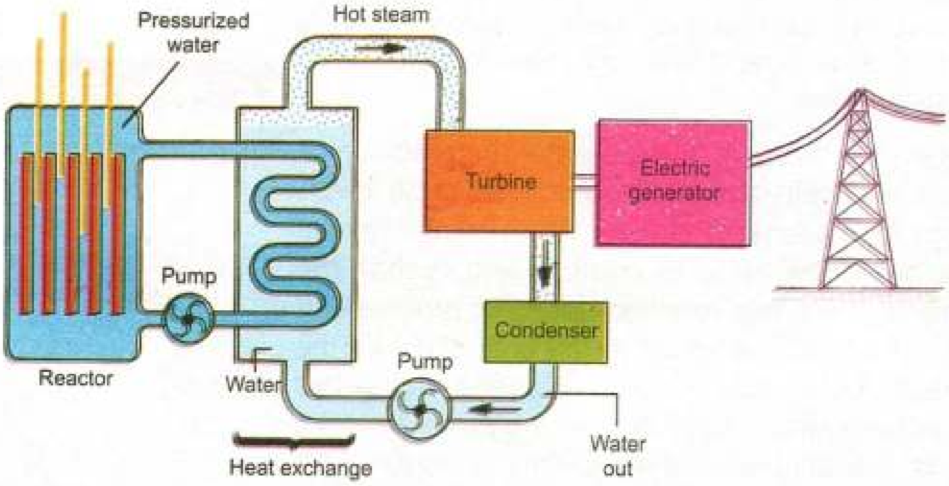


Fig. 21.15

A reactor usually has four important parts. These are:

1. The most important and vital part of a reactor is called core. Here the fuel is kept in the shape of cylindrical tubes. Reactor fuels are of various types. Uranium was used as fuel in the elementary reactors. In this fuel the quantity of $^{235}_{92}U$ is increased from 2 to 4 percent. It may be remembered that the quantity of $^{235}_{92}U$ in the naturally occurring uranium is only 0.7 percent. Now-a-days plutonium-239 and uranium-233 are also being used as fuel.

2. The fuel rods are placed in a substance of small atomic weight, such as water, heavy water, carbon or hydrocarbon etc. These substances are called moderators. The function of these moderators is to slow down the speed of the neutrons produced during the fission process and to direct them towards the fuel. Heavy water, it may be remembered, is made of $^{2}_{1}H$, a heavy isotope of hydrogen instead of $^{1}_{1}H$. The neutrons produced in the fission reaction are very fast and energetic and are not suitable for producing fission in reactor fuel like $^{235}_{92}U$ or $^{239}_{94}Pu$ etc. For this purpose slow neutrons are more useful. To achieve this, moderators are used.

3. Besides moderator there is an arrangement for the control of number of neutrons, so that of all the

neutrons produced in fission, only one neutron produces further fission reaction. The purpose is achieved either by cadmium or by boron because they have the property of absorbing fast neutrons. The control rods made of cadmium or boron are moved in or out of the reactor core to control the neutrons that can initiate further fission reaction. In this way the speed of the chain reaction is kept under control. In case of emergency or for repair purposes control rods are allowed to fall back into the reactor and thus stop the chain reaction and shut down the reactor.

4 Heat is produced due to chain reaction taking place in the core of the reactor. The temperature of the core, therefore, rises to about 500 °C. To produce steam from this heat, it is transported to heat exchanger with the help of water, heavy water or any other liquid under high pressure. In the heat exchanger this heat is used to produce high temperature steam from ordinary water. The steam is then used to run the turbine which in turn rotates the generator to produce electricity. The temperature of the steam coming out of the turbine is about 300 °C. This is further cooled to convert it into water again. To cool this steam, water from some river or sea is, generally, used. In Karachi nuclear power plant (KANUP), heavy water is being used as a moderator and for the transportation of heat also from the reactor core to heat exchanger, heavy water is used. To cool steam coming out of the turbine, sea water is being used.

The nuclear fuel once used for charging the reactor can keep on operation continuously for a few months. There after the fissile material begins to decrease. Now the used fuel is removed and fresh fuel is fed instead. In the used up fuel intensely radioactive substances remain. The half-life of these radioactive remnant materials is many thousand years. The radiations and the particles emitted out of this nuclear waste is very injurious and harmful to the living things. Unfortunately there is no proper arrangement of the disposal of the nuclear waste. This cannot be dumped into oceans or left in any place where they will contaminate the environment, such as through the soil or the air. They must not be allowed to get into the drinking water. The best place so far found to store these wastes is in the bottom of old salt mines, which are very dry and are thousands of metres below the surface of the Earth. Here they can remain and decay without polluting the environment.

Types of Reactors

There are two main types of nuclear reactors. These are:

(i) Thermal reactors (ii) Fast reactors

The thermal reactors are called "thermal" because the neutrons must be slowed down to "thermal energies" to produce further fission. They use natural uranium or slightly enriched uranium as fuel. Enriched uranium contains a greater percentage of U-235 than natural uranium does. There are several designs of thermal reactors. Pressurized water reactors (PWR) are the most widely used reactors in the world. In this type of reactors, the water is prevented from boiling, being kept under high pressure. This hot water is used to boil another circuit of water which produces steam for turbine rotation of electricity generators.

Fast reactors are designed to make use of U-238, which is about 99% content of natural uranium. Each U-238 nucleus absorbs a fast neutron and changes to plutonium-239.

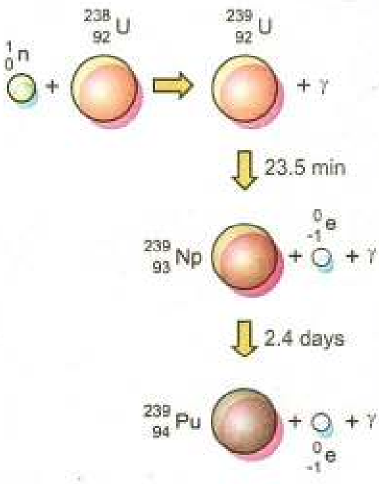
$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{93}Np + ^{0}_{-1}\beta$$

$$^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta$$

Plutonium can be fissioned by fast neutrons, hence, moderator is not needed in fast reactors. The core of fast reactors consists of a mixture of plutonium and uranium dioxide surrounded by a blanket of uranium-238.

Neutrons that escape from the core interact with uranium-238 in the blanket, producing thereby plutonium-239. Thus more plutonium fuel is bred in this way and natural uranium is used more effectively.

Do You Know?



An induced nuclear reaction in which $^{238}_{92}U$ is transmuted into the transuranium element plutonium $^{239}_{94}Pu$.

21.10 FUSION REACTION

We know that the energy given out per nucleon per fission of heavy element like that of uranium is 0.9 MeV. It is due to the fact that the binding energy per nucleon of the fission fragments is greater than uranium. In fact energy is obtained from any nuclear reaction in which the binding energy per nucleon of the products increases. Is there any other reaction besides the fission reaction from which energy could be obtained? In order to answer this question we must ponder over Fig.21.4 again. This graph shows that the binding energy per nucleon increases upto A = 50. Hence when two light nuclei merge together to form a heavy nucleus whose mass number A is less than 50, then energy is given out. In section on "Mass Defect and Binding Energy" we have observed that when two protons and two neutrons merge to form a helium nucleus, then about 28 MeV energy is given out.

"Such a nuclear reaction in which two light nuclei merge to form a heavy nucleus is called fusion reaction".

During a fusion reaction some mass is lost and its equivalent energy is given out. In a fusion reaction, more energy per nucleon can be obtained as compared to the fission reaction. But unfortunately it is comparatively more difficult to produce fusion. Two positively charged light nuclei must be brought very close to one another. To do so work has to be done against the electrostatic force of repulsion between the positively charged nuclei. Thus a very large amount of energy is required to produce fusion reaction. It is true that a greater amount of energy can be obtained during a fusion reaction compared to that produced during a fission reaction, but in order to start this reaction a very large amount of energy is spent. On the contrary no difficulty is faced to start the fission reaction because neutron has no charge on it and it has to face no repulsive force while reaching the nucleus.

Let us now take the example of a fusion reaction when two deuterons are merged to form a helium nucleus, 24 MeV energy is released during this process i.e.,

$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \longrightarrow ^{4}_{2}\mathrm{He} + 24\ \mathrm{MeV}$$

But there is a very little chance of the formation of $^{4}_{2}\mathrm{He}$ nucleus by the merger of two deuterons. The probability of occurring such a reaction is great where one proton or one neutron is produced as given below:

$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \longrightarrow ^{3}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} + 4.0\ \mathrm{MeV}$$

or

$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \longrightarrow ^{3}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n} + 3.3\ \mathrm{MeV}$$

In both of these reactions about 1.0 MeV energy per nucleon is produced which is equal to the energy produced during fission. If $^{2}_{1}\mathrm{H}$ and $^{3}_{1}\mathrm{H}$ are forced to fuse then 17.6 MeV energy is obtained i.e.,

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \longrightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n} + 17.6\ \mathrm{MeV}$$

We know that for fusion of two light nuclei the work has to be

Do You Know?

Ozone on the surface of Earth is a corrosive and poisonous gas but at the height of 20-50 km from the Earth surface becomes vital to life as it absorbs almost all u.v. radiations which are harmful to living things.

For Your Information

Ultra violet radiations cause
(i) Sunburn, blindness and skin cancer
(ii) Severe crop damage
(iii) decay of micro-organisms
(iv) disrupt the ocean ecosystem

done to overcome the repulsive force which exists between them. For this the two nuclei are hurled towards one another at a very high speed. One method to do so is to give these nuclei a very large velocity with the help of an accelerator. This method has been used in the research study of nuclear fusion of $^{2}_{1}H$ and $^{3}_{1}H$. But this method of nuclear fusion for getting energy cannot be used on a large scale.

There is another method to produce fusion reaction .It is based upon the principle that the speed of atoms of a substance increases with the increase in the temperature of that substance. To start a fusion reaction the temperature at which the required speed of the light nuclei can be obtained is about 10 million degrees celsius. At such extraordinarily high temperature the reaction that takes place is called thermo-nuclear reaction. Ordinarily such a high temperature cannot be achieved. However during the explosion of am atom bomb this temperature can be had for a very short time.

Until now the fusion reaction is taking place only in a hydrogen bomb. That extraordinary high temperature is obtained during the explosion of an atom bomb, due to this high temperature the fusion reaction between $^{2}_{1}H$ and $^{3}_{1}H$ sets in. In this way a very large amount of energy is given out with the explosion.

A very large amount of energy can be had from a fusion reaction, but till now this reaction has not been brought under control like a fission reaction and so is not being used to produce electricity. Efforts are in full swing in this field and it is hoped that in near future some method would be found to control this reaction as well.

Nuclear Reaction in the Sun

The Sun is composed primarily of hydrogen. It has a little amount of helium and a slight amount of other heavy elements. A tremendous amount of energy keeps issuing out of it continuously at all times. The temperature of its core is about 20 million degrees celsius and its surface temperature is about 6000 degrees celsius. Its energy is due to fusion reaction called p-p reaction. During this process two hydrogen nuclei or two protons fuse to from deuteron. This reaction takes place as

$$^{1}_{1}H + ^{1}_{1}H \longrightarrow ^{2}_{1}H + ^{0}_{+1}e + \text{Energy}$$

With the fusion reaction of deuteron with proton, $^{3}_{2}He$ an isotope of helium is formed i.e.,

$$^{2}_{1}H + ^{1}_{1}H \longrightarrow ^{3}_{2}He + \gamma + \text{Energy}$$

In the last stage the two nuclei of $^{3}_{2}He$ react in the following manner:

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

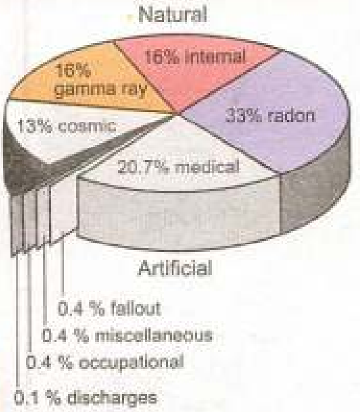
In this reaction six protons take part and finally a helium nucleus and two protons are formed. That is, the result of different stages of this reaction is that four protons have formed one helium nucleus. It has been estimated that in this p-p chain reaction, 25.7 MeV energy is given out i.e., 6.4 MeV per nucleon energy is obtained which is much greater than the energy given out per nucleon (1 MeV) during a fission reaction.

21.11 RADIATION EXPOSURE

When a Geiger tube is used in any experiment, it records radiation even when a radioactive source is nowhere near it. This is caused by radiation called background radiation. It is partly due to cosmic radiation which comes to us from outer space and partly from naturally occurring radioactive substance in the Earth's crust. The cosmic radiation consists of high energy charged particles and electromagnetic radiation. The atmosphere acts as a shield to absorb some of these radiations as well as ultraviolet rays. In recent past, the depletion of ozone layer in the upper atmosphere has been detected which particularly filters ultraviolet rays reaching us. This may result in increased eye and skin diseases. The depletion of ozone layer is suspected to be caused due to excessive release of some chemicals in the atmosphere such as chloroflourocarbons (CFC) used in refrigeration, aerosol spray and plastic foam industry. Its use is now being replaced by environmentally friendly chemicals. Many building materials contain small amounts of radioactive isotopes. Radioactive radon gas enters buildings from the ground. It gets trapped inside the building which makes radiation levels much higher from radon inside than outside. A good ventilation can reduce radon level inside the building. All types of food also contain a little radioactive substance. The most common are potassium-40 and carbon-14 isotopes.

Some radiation in the environment is added by human activities. Medical practices, mostly diagnostic X-ray probably contribute the major portion to it. It is an unfortunate fact that many X-ray exposures such as routine chest X-ray

For Your Information



Pie-chart showing proportion of radiation from different sources absorbed by average person.

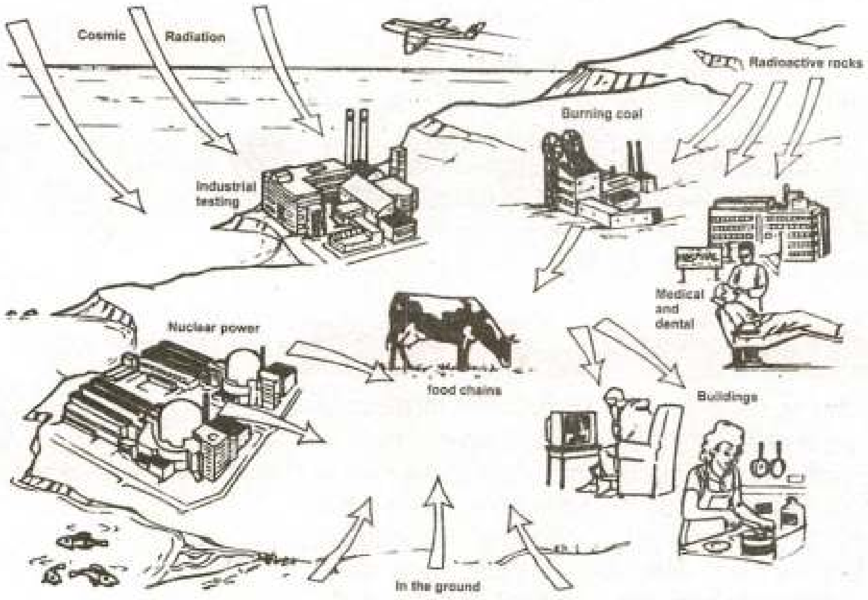
Do You Know?

This symbol is universally used to indicate an area where radioactivity is being handled or artificial radiations are being produced.

and dental X-ray are made for no strong reason and may do more harm than good. Every X-rays exposure should have a definite justification that outweighs the risk. The other sources include radioactive waste from nuclear facilities, hospitals, research and industrial establishments, colour television, luminous watches and tobacco leaves. A smoker not only inhales toxic smoke but also hazardous radiation. Low level background radiation from natural sources is normally considered to be harmless. However, higher levels of exposure are certainly damaging. We cannot avoid exposure to radiation. However, the best advice is to avoid unnecessary exposure to any kind of ionizing radiation.

For Your Information

Sources of natural radiation



21.12 BIOLOGICAL EFFECTS OF RADIATION

To study the effects of radiation, we need to define some of the units of radiation. The strength of the radiation source is indicated by its activity measured in becquerel (Bq). One becquerel is one disintegration per second. A larger unit is curie (Ci) which equals 3.7×10^{10} disintegrations per second. The effect of radiation on a body absorbing it relates to a quantity called absorbed dose D defined as the energy E absorbed from ionizing radiation per unit mass m of the absorbing body.

$$D = \frac{E}{m} \qquad \ldots\ldots\ldots\ldots \qquad (21.10)$$

Table 21.2
Relative Biological Effectiveness (RBE)

Radiation	RBE
X-rays, γ -rays and α-particles of 30 keV or more	1.0
α - particles of less than 30 keV	1.7
Neutrons and protons below 10 MeV	10 (body) 30 (eyes)
α-particles from natural radioactivity	10
Heavy recoil nuclei	20

Its SI unit is gray (Gy) defined as one joule per kilogram.

$$1\ \text{Gy} = 1\ \text{Jkg}^{-1}$$

An old unit is rad, an acronym for radiation absorbed dose.

$$1\ \text{rad} = 0.01\ \text{Gy}$$

Equal doses of different radiations do not produce same biological effect. For the same absorbed dose, α-particles are 20 times more damaging than X-rays. The effect also depends on the part of the body absorbing the radiation. For example, neutrons are particularly more damaging to eyes than other parts of the body. To allow this, the absorbed dose is multiplied by a quality factor known as relative biological effectiveness or RBE (Table 21.2). The equivalent dose D_e of any absorbed radiation is defined as the product of absorbed dose and RBE of the kind of radiation being absorbed.

$$D_e = D \times \text{RBE} \quad \ldots\ldots\ldots \quad (21.11)$$

The SI unit of equivalent dose is sievert (Sv).

$$1\ \text{Sv} = 1\ \text{Gy} \times \text{RBE}$$

An old unit, the rem is equal to 0.01 Sv.

$$1\ \text{rem} = 0.01\ \text{Sv}$$

The background radiation to which we are exposed, on the average, is 2 mSv per year. Doses of 3 Sv will cause radiation burns to the skin. For workers in the nuclear facilities or mines, a weekly dose of 1 mSv is normally considered safe (Table 21.3).

Table 21.3

Average radiation doses from a number of common sources of ionizing radiation.

Types of Exposure	mSv
Watching television for a year	10
Radiation from nuclear power stations for a year	10
Wearing a radioactive luminous watch for a year (now not very common)	30
Having a chest X-ray	200
Radiation from a brick house per year	750
Maximum dose allowed to general public from artificial sources per year	1000
Working for a month in a uranium mine	1000
Typical dose received by a member of the general public in a year from all sources	2500
Maximum dose allowed to workers exposed to radiation per year	50000

The damage from α-particles is small unless the source enters the body. α and β-particles can cause redness and sores on the skin. Some other low level radiation effects are loss of hair, ulceration, stiffening of the lungs, and a drop in the white blood cells which is followed by a sickness pattern of diarrhea, vomiting and fever known as radiation sickness (Fig. 21.16). High levels of radiation may disrupt the blood cells seriously leading to diseases such as anaemia and leukaemia. Chromosome abnormalities or mutation may cause delayed genetic effects such as cancer, eye cataracts and abnormalities in the future generations. These may develop many years after exposure to harmful radiation.

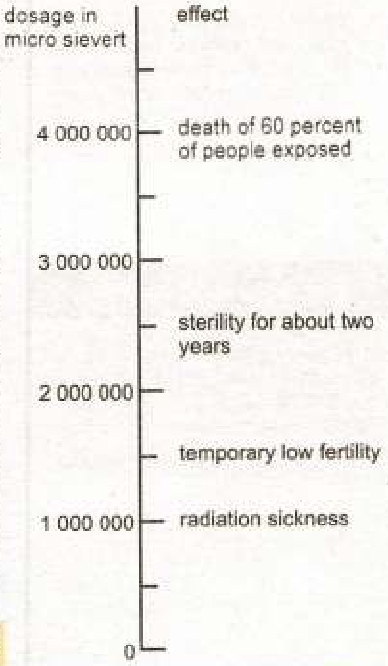


Fig 21.16 The effects of exposure to high levels of ionizing radiation

Example 21.3: How much energy is absorbed by a man of mass 80 kg who receives a lethal whole body equivalent dose of 400 rem in the form of low energy neutrons for which RBE factor is 10?

Solution:

$$\text{RBE factor} = 10$$

$$D_e = 400\text{ rem} = 400 \times 0.01\text{ Sv} = 4\text{ Sv} \quad , \quad D = ?$$

Using Eq. 21.4

$$D = \frac{D_e}{\text{RBE}} = \frac{4\text{ Sv}}{10} = 0.4\text{ Gy}$$

Since 1 Gy is 1 J kg^{-1}, hence total energy absorbed by the whole body = $mD = 80 \times 0.4\text{ Gy} = 32\text{ J}$

It is a very small amount of thermal energy. Obviously, the damage done by ionizing radiation has nothing to do with thermal energy. The harmful effects arise due to disruption of the normal functions of the tissues in which it is absorbed.

For Your Information

Film badge dosimeter are used to monitor radiation received by workers in nuclear facilities.

21.13 BIOLOGICAL AND MEDICAL USES OF RADIATION

Radioisotopes of many elements can be made easily by bombardment with neutrons and other particles. As such isotopes have become available and are inexpensive, their use in medicine, agriculture, scientific research and industries has expanded tremendously.

Radioisotopes are used to find out what happens in many complex chemical reactions and how they proceed. Similarly in biology, they have helped in investigating into chemical reactions that take place in plants and animals. By mixing a small amount of radioactive isotope with fertilizer, we can easily measure how much fertilizer is taken up by a plant using radiation detector. From such measurements, farmers know the proper amount of fertilizer to use. Through the use of radiation-induced mutations, improved varieties of certain crops such as rice, chickpea, wheat and cotton have been developed. They have improved plant structure. The plants have shown more resistance to diseases and pest, and give better yield and grain quality. Radiation is also used to treat cancers. Radioactive tracers and imaging devices have helped in the understanding and diagnosis of many diseases.

Do You Know?

Radioactive wastes are of three types i.e., high level, medium and low level. All these wastes are dangerous for ground water and land environment.

For Your Information

It is very difficult to dispose off radioactive waste safely due to their long half lives e.g., 'Pu' half life is 24,000 years, therefore, it remains dangerous for about 1,92,000 years.

Tracer Techniques

A radioactive isotope behaves in just the same way as the normal isotope inside a living organism. But the location and concentration of a radioactive isotope can be determined easily by measuring the radiation it emits. Thus, a radioactive isotope acts as an indicator or tracer that makes it possible to follow the course of a chemical or biological process. The technique is to substitute radioactive atoms for stable atoms of the same kind in a substance and then to follow the 'tagged' atoms with the help of radiation detector in the process. Tracers are widely used in medicine to detect malignant tumors and in agriculture to study the uptake of a fertilizer by a plant. For example, if a plant is given radioactive carbon-14, it will use it in exactly the same way as it always uses stable carbon-12. But the carbon-14 releases β-radiations and thus by measuring radioactivity in different parts of the plant, the path taken by the carbon atoms can be known. This technique has helped to understand more elaborately the complex process of photosynthesis. The tracer technique was also used to identify faults in the underground pipes of the fountain system of the historical Shalimar gardens of Lahore by the scientists of Pakistan Atomic Energy Commission.

Table 21.4

Isotope	Half-life	Gamma energies /MeV	Example of use
Sodium ^{24}Na	15 hours	1.37, 2.75	Plasma volume
Iron ^{59}Fe	45 days	1.29, 1.10 0.19	Iron in Plasma
Technetium ^{99}Te	6 hours	0.14	Thyroid uptake scans
Iodine ^{131}I	8 days	0.72, 0.64 0.36, 0.28 0.08	Kidney tests
Iodine ^{125}I	60 days	0.035	Plasma volume Vein flow

Medical Diagnostics and Therapy

Tracers are widely used in medicine to study the process of digestion and the way chemical substances move about in the body.

Some chemicals such as hydrogen and sodium present in water and food are distributed uniformly throughout the body. Certain other chemicals are selectively absorbed by certain organs. Radio-iodine, for example, is absorbed mostly by the thyroid gland, phosphorus by bones and cobalt by liver. They can serve as tracers. Small quantity of low activity radioisotope mixed with stable isotope is administered by injection or otherwise to a patient and its location in diseased tissue can be ascertained by means of radiation detectors. For example, radioactive iodine can be used to check that a person's thyroid gland is working properly. A diseased or hyperactive gland absorbs more than twice the amount of normal thyroid gland. A similar method can be used to study the circulation of blood using radioactive isotope sodium-24.

Experiments on cancerous cells have shown that those cells that multiply rapidly absorb more radiation and are more easily destroyed than normal cells by ionizing radiation. Radiotherapy with γ-rays from cobalt-60 is often used in the treatment of cancer. The γ-rays are carefully focussed on to the malignant tissue. Strict safety precautions are necessary for both patient and attendant medical staff. Radioactive iodine-131 is used to combat cancer of the thyroid gland. Since iodine tends to collect in the thyroid gland, radioactive isotopes lodge where they can destroy the malignant cells. In some cases encapsulated "seeds" are implanted in the malignant tissue for local and short ranged treatment. For skin cancers, phosphorus-32 or strontium-90 may be used instead. These produce β-radiation. The dose of radiation has to be carefully controlled otherwise the radiation could do more damage than help. Patients undergoing radiation treatment often feel ill, because the radiation also damages the healthy cells.

Radiography

Fig. 21.17

The γ-rays radiographs are used in medical diagnosis such as internal imaging of the brain to determine precisely the size and location of a tumor or other parts of the body. Cracks or cavities in castings or pipes can also be detected by scanning. Any sudden increase in count rate indicates a cavity within the object.

The gamma camera is designed to detect γ-radiations from sites in the body where a γ-emitting isotope is located. An image as shown in Fig. 21.17, consisting of many dots of the γ-emitting sources in the patient body is formed. The camera can also be used to obtain a sequence of images to observe an organ such as a kidney in action.

21.14 BASIC FORCES OF NATURE

The man has always desired to comprehend the complexity of nature in terms of as few elementary concepts as possible. Among his quest, in Feynman's words, has been the one for "wheels within wheels", the task of Natural Philosophy being to discover the inner most wheels if any such exist. A second quest has concentrated itself with the fundamental forces, which make the wheels go round and enmesh with one another.

Although we have been familiar with the basic forces and about some of the basic building blocks of the matter, but here we are going to study the modern concepts about both of these. We know that the basic forces are:

1. Gravitational force
2. Magnetic force
3. Electric force
4. Weak nuclear force
5. Strong nuclear force

The electric and magnetic forces were unified to get an electromagnetic force by Faraday and Maxwell, who were able to prove that a current is induced in a coil whenever the magnetic flux passing through the coil is changed; leaving behind four fundamental forces, the strong nuclear force, the electromagnetic force, the weak nuclear force and the gravitational force. These four fundamental forces of nature have seemed for some time quite different from one another. Despite its different effective strength, the strong nuclear force is effective only within sub-nuclear distances and therefore, confines the neutrons and protons within the nucleus. The electromagnetic force is long-range and causes all chemical reactions. It binds together atoms, molecules, crystals, trees, buildings and you. This force acting on a microscopic level is responsible for a variety of apparently different macroscopic forces such as friction, cohesion and adhesion. The weak nuclear force is short range, like the strong nuclear force, and is responsible for spontaneous breaking up of the radioactive elements. It is a sort of repulsive force of very short range (10^{-17} m). It is usually masked by the effect of the strong and electromagnetic forces inside the nuclei. The gravitational force, like the electromagnetic force, is again long range, extending upto and beyond the remotest stars and galaxies. It keeps you, the atmosphere and the seas fixed to the surface of the planet. It gives rise to the ocean tides and keeps the planets moving in their orbits around the Sun.

These widely disparate properties of the four basic forces have not stopped the scientists from finding a common cause for them all.

One hundred years after the unification of electric and magnetic forces into electromagnetic force, in 1979, the physics nobel prize was conferred on Glashow, Weinberg and Abdus Slam for the unification of electromagnetic and weak forces.

It is further expected that a strong nuclear force will eventually unite with electroweak force to make up a single entity resulting in the grand unified electro-nuclear force.

21.15 BUILDING BLOCKS OF MATTER

Subatomic particles are divided into three groups.

1. Photons 2. Leptons 3. Hadrons

For Your Information

Composition of Matter

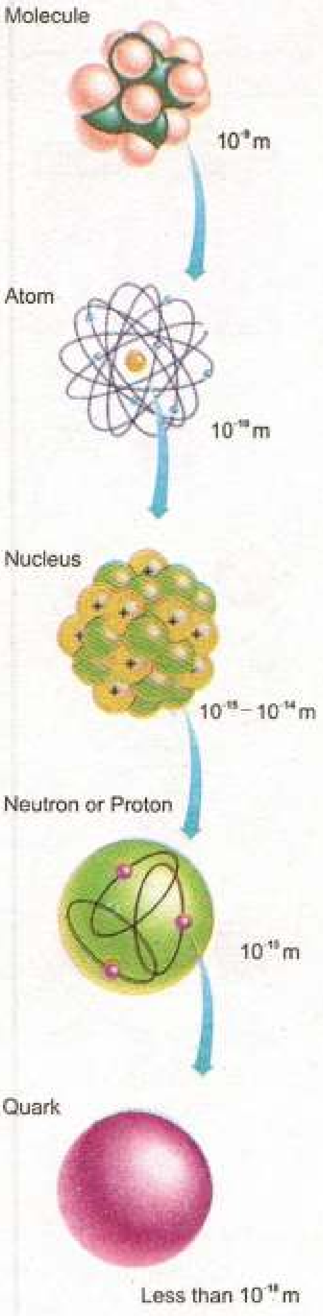


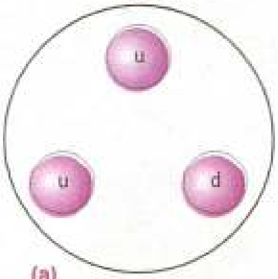
Table 21.5
Quarks and Antiquarks

Name	Symbol	Charge
Up	*u*	$+\frac{2}{3}e$
Down	*d*	$-\frac{1}{3}e$
Strange	*s*	$-\frac{1}{3}e$
Charm	*c*	$+\frac{2}{3}e$
Top	*t*	$+\frac{2}{3}e$
Bottom	*b*	$-\frac{1}{3}e$

Antiquarks

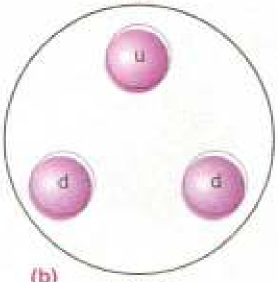
Symbol	Charge
$\bar{u}$	$-\frac{2}{3}e$
$\bar{d}$	$+\frac{1}{3}e$
$\bar{s}$	$+\frac{1}{3}e$
$\bar{c}$	$-\frac{2}{3}e$
$\bar{t}$	$-\frac{2}{3}e$
$\bar{b}$	$+\frac{1}{3}e$

Proton



(a) Charge
2/3 + 2/3 - 1/3 = 1

Neutron



(b) Charge
2/3 - 1/3 - 1/3 = 0

Fig. 21.18

Elementary particles are the basic building blocks of matter. All photons and leptons are elementary particles. Hadrons are not elementary particles but are composed of elementary particles called quarks. Scientists now believe that all matter belongs to either the quark group or the lepton group.

Hadrons

Hadrons are particles that experience the strong nuclear force. In addition to protons, neutrons and mesons are hadrons. The particles equal in mass or greater than protons are called baryons and those lighter than protons are called mesons.

Leptons

Leptons are particles that do not experience strong nuclear force. Electron, muons and neutrinos are leptons.

Quarks

According to quark theory initiated by M. Gell-Mann and G. Zweig, the quarks are proposed as the basic building blocks of the mesons and baryons. A pair of quark and antiquark makes a meson and 3 quarks make a baryon. It is proposed that there are six quarks, the (1) up (2) down (3) strange (4) charm (5) bottom and, (6) top. The charges on these quarks are fractional as shown in Table 21.5.

A proton is assumed to be made up of two up quarks and one down quark as shown in Fig.21.18 a. The neutron is assumed to be made of one up quark and two down quarks as shown in Fig. 21.18 (b). Currently, the hundred of hadrons can be accounted for in terms of six quarks and their antiquarks. It is believed that quarks cannot exist on their own, their existence has been indirectly verified.

SUMMARY

- The combined number of all the protons and neutrons in a nucleus is known as mass number and is denoted by *A*.

- The protons and neutrons present in the nucleus are called nucleons.
- The number of neutrons present in a nucleus is called its neurons number and is denoted by *N*.
- The number of protons inside a nucleus or the number of electrons outside of the nucleus is called the atomic number or the charge number of an atom and is denoted by *Z*.
- Isotopes are such nuclei of an element that have the same charge number *Z*, but have different mass number *A*.
- The mass of the nucleus is always less than the total mass of the protons and neutron that make up the nucleus. The difference of the two masses is called mass defect. The missing mass is converted to energy in the formation of the nucleus and is called the binding energy.
- The emission of radiations (α, β and γ) from elements having charge number *Z* greater than 82 is called radioactivity.
- The change of an element into a new element due to emission of radiations is called radioactive decay. The original element is called parent element and the element formed due to this decay is called daughter element.
- Half-life of a radioactive element is that period in which half of the atoms of the parent element decay into daughter element.
- Such a reaction in which a heavy nucleus like uranium splits up into two nuclei of equal size along with the emission of energy during reaction is called fission reaction.
- Such a nuclear reaction in which two light nuclei merge to form a heavy nucleus along with the emission of energy is called fusion reaction.
- The strength of the radiation source is indicated by its activity measured in becquerel. One becquerel (Bq) is one disintegration per second. A larger unit is curie (Ci) which equals 3.7×10^{10} disintegrations per second.
- The effect of radiation on a body absorbing it relates to a quantity called absorbed dose *D* defined as the energy *E* absorbed from ionizing radiation per unit mass *m* of the absorbing body.
- The basic forces are:

  i. Gravitational force ii. Electromagnetic force
  iii. Weak nuclear force iv. The strong force
- Subatomic particles are divided into following three groups:

  i. Photons ii. Leptons iii. Hadrons

  Elementary particles are the basic building blocks of matter.

QUESTIONS

21.1 What are isotopes? What do they have in common and what are their differences?

21.2 Why are heavy nuclei unstable?

21.3 If a nucleus has a half-life of 1 year, does this mean that it will be completely decayed after 2 years? Explain.

21.4 What fraction of a radioactive sample decays after two half-lives have elapsed?

21.5 The radioactive element $^{226}_{88}Ra$ has a half-life of 1.6×10^3 years. Since the Earth is about 5 billion years old, how can you explain why we still can find this element in nature?

21.6 Describe a brief account of interaction of various types of radiations with matter.

21.7 Explain how α and β-particles may ionize an atom without directly hitting the electrons? What is the difference in the action of the two particles for producing ionization?

21.8 A particle which produces more ionization is less penetrating. Why?

21.9 What information is revealed by the length and shape of the tracks of an incident particle in Wilson cloud chamber?

21.10 Why must a Geiger Muller tube for detecting α-particles have a very thin end window? Why does a Geiger Muller tube for detecting γ-rays not need a window at all?

21.11 Describe the principle of operation of a solid state detector of ionizing radiation in terms of generation and detection of charge carriers.

21.12 What do we mean by the term critical mass?

21.13 Discuss the advantages and disadvantages of nuclear power compared to the use of fossil fuel generated power.

21.14 What factors make a fusion reaction difficult to achieve?

21.15 Discuss the advantages and disadvantages of fission power from the point of safety, pollution and resources.

21.16 What do you understand by "background radiation"? State two sources of this radiation.

21.17 If someone accidently swallows an α-source and a β-source which would be the more dangerous to him? Explain why?

21.18 Which radiation dose would deposit more energy to the body (a) 10 mGy to the hand, or (b) 1 mGy dose to the entire body.

21.19 What is a radioactive tracer? Describe one application each in medicine, agriculture and industry.

21.20 How can radioactivity help in the treatment of cancer?