Chapter 21

NUCLEAR PHYSICS

LEARNING OBJECTIVES

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

- Understand the qualitative treatment of Rutherford's scattering experiment and the evidence it provides for the existence and small size of nucleus.
- Distinguish between nucleon number (mass number) and atomic number.
- Understand that an element can exist in various isotopic forms each with a different number of neutrons.
- Understand the use of mass spectrograph to demonstrate the existence of isotopes and to measure their relative abundance.
- Understand mass defect and calculate binding energy using Einstein's equation.
- Illustrate graphically the variation of binding energy per nucleon with the mass number.
- Appreciate the spontaneous and random nature of nuclear decay.
- Explain the meaning of half-life.
- Recognize and use decay law.
- Understand and describe the interaction of nuclear radiation with matter.
- Appreciate that atomic number and mass number conserve in nuclear process.
- Understand and describe the phenomena of nuclear fission and nuclear fusion.
- Explain the working principle of nuclear reactor.
- Be aware of various types of nuclear reactors.
- Describe in simple terms the use of radiations for medical diagnosis and therapy.
- Understand qualitatively the importance of limiting exposure to ionizing radiation.
- Describe examples of the use of radioactive tracers in diagnosis.
- Describe basic forces of nature.
- Describe the modern view of the building blocks of matter based on hadrons, leptons and quarks.

INTRODUCTION

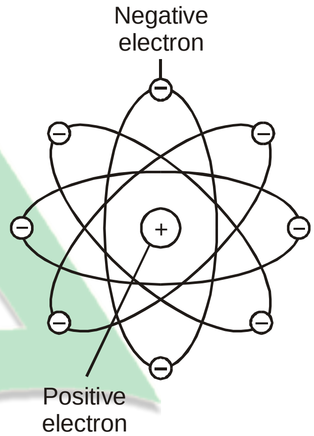
Soon after the discovery of electron and proton in an atom, the quest started to find the way in which these charged particles are present in an atom. From his experiments Rutherford developed a nuclear model of the atom. His model of the atom consists of a small dense, positively charged nucleus with 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.

Q.1 Describe the atomic nucleus.

Ans. 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 nucleus is so small that the radius of the atom is 10^5 times the radius of the nucleus.

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.

Nucleons

A nucleus consists 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.

Unified Mass Scale (U)

Mass of atomic particles is generally expressed in unified mass scale (U) instead of kilogram. By definition

"1U is exactly one twelveth (1/12) the mass of carbon atom (1u = 1.6606×10^{-27} kg)".

In this unit the mass of proton is 1.007276 U and that of deutron is 1.008665 u while that of an electron is 0.00055 u.

Number of Protons are Equal to Number of Electrons

The charge on a proton is equal to the magnitude of charge on an electron. The charge on proton is positive while that of an electron is negative. 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.

Q.2 Define the terms mass number and atomic number. Also describe the symbolic notation of nuclei elements.

Ans. ATOMIC NUMBER

"The number of protons inside the nucleus is called atomic number or charge number of an atom".

It is denoted by Z. Thus total charge of any nucleus is "Ze" where e is the charge on one proton.

Mass Number

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

The number of neutrons present in a nucleus is given by

$$N = (A - Z) \qquad \ldots\ldots (1)$$

Determination of Protons and Neutrons in an Element

We consider different elements of the periodic table. Hydrogen atom is the simplest of all the atoms. Its nucleus is composed of only one proton i.e., for hydrogen.

$$A = 1 \quad \text{and} \quad Z = 1$$

Therefore, hydrogen is represented by ${}^{1}_{1}H$. $\boxed{\left({}^{A}_{Z}H\right) = {}^{1}_{1}H}$

Next in the periodic table (after hydrogen element) is the helium element. Its nucleus contains (composed of) two protons and two neutrons i.e., for helium.

$$A = 4 \quad \text{and} \quad Z = 2$$

Therefore, helium is represented by ${}^{4}_{2}He$.

We now take the example of unanium, a heavy element of periodic table. For uranium:

$$Z = 92 \quad \text{and} \quad A = 235$$

Therefore, uranium is represented by ${}^{235}_{92}U$.

In uranium number of protons = 92

Number of neutrons are:

$$N = A - Z = 235 - 92 = 143$$

In this way the number protons and neutrons in atoms can be determined.

Q.3 Define isotopes of an element.

Ans. **ISOTOPES**

The nuclei of an element that have the same charge number but different mass number are called isotopes of the element.

In an isotope of an element, the number of protons is the same, but the number of neutrons is different.

Isotopes of Helium

Helium 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 number of neutrons in first isotopes, ${}^{3}_{2}He$ is:

$$N = A - Z = 3 - 2 = 1$$

The number of neutrons in 2nd isotopes, ${}^{4}_{2}He$ is:

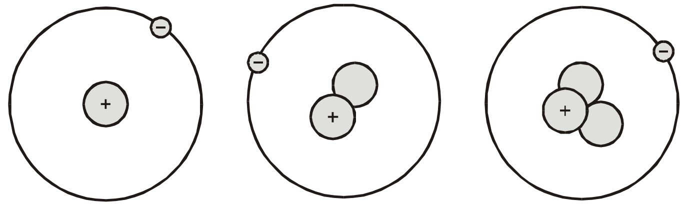
$$N = A - Z = 4 - 2 = 2$$

Do You Know?

[illegible]

Isotopes of Hydrogen

Hydrogen has three isotopes represented by ${}^1_1H$, ${}^2_1H$, ${}^3_1H$. First isotope is called ordinary hydrogen or protium, it has only one proton in the nucleus. The second isotope of hydrogen is called deuterium. It has only one proton and one neutron in its nucleus. Its nucleus is called deuteron. The third isotope of hydrogen is called tritium.



${}^1_1H$ **(a)** (Protium) ${}^2_1H$ **(b)** (Deuterium) ${}^3_1H$ **(c)** (Tritium)

It has two neutrons and one proton in its nucleus.

The isotopes of hydrogen are shown below:

Properties of Isotopes

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, therefore, successful for this purpose.

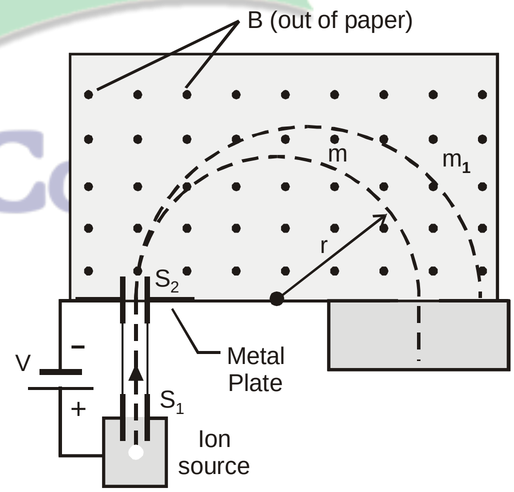
Q.4 Describe mass spectrograph and how it can be used for the detection of isotopes.

Ans. **MASS SPECTROGRAPH**

A simple mass spectrograph is shown in figure.

(1) Ion Source

In figure 'S' is the ion source. This source ionizes the atoms or moleculeules of the element under investigation, in the form of vapours. One electron is removed from the particle (atom) making ions with net positive charge +e.



(2) Working

These ions are allowed to escape from the source through slits S_1 and S_2 by applying a potential difference v.

eam. The ions pass through S_2

The K.E of the single charged ion at the slit S_2 will be given by

$$\frac{1}{2}mv^2 = Ve \qquad \ldots\ldots (i)$$

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.

(3) Identification of Isotopes

The centripetal force applied by the magnetic field is given by:

$$Bev = \frac{mv^2}{r}$$

$$\Rightarrow \quad m = \frac{Ber}{v} \qquad \ldots\ldots \text{(i)}$$

From eq. (1)

$$\frac{1}{2}mv^2 = Ve$$

$$v^2 = \frac{2Ve}{m}$$

$$V = \sqrt{\frac{2Ve}{m}}$$

Putting this value in eq. (i), we get:

$$m = \frac{Ber}{\sqrt{\frac{2Ve}{m}}}$$

Squaring: $$m^2 = \frac{B^2e^2r^2}{\frac{2Ve}{m}}$$

$$m^2 = B^2e^2r^2 \times \frac{m}{2Ve}$$

$$\boxed{m = \left(\frac{er^2}{2V}\right)B^2} \qquad \ldots\ldots \text{(ii)}$$

$$r^2 = \frac{2Vm}{eB^2}$$

$$r = \sqrt{\frac{2Vm}{eB^2}}$$

$$r = \sqrt{\frac{2V}{eB^2}}\sqrt{m}$$

$$\sqrt{\frac{2V}{eB^2}} = \text{Constant}$$

$$\therefore \quad r \propto \sqrt{m}$$

Since isotopes have different masses, so they have different radii. In this way we identify the isotopes.

For Your Information

Some atomic masses

Particle	Mass (u)
e	0.00055
n	1.008665
^{1}H	1.007276
^{2}H	2.014102
^{3}He	3.01605
^{3}He	3.01603
^{4}He	4.002603
^{7}Li	7.016004
^{10}Be	10.013534
^{14}N	14.0031
^{17}O	16.991

Abundance of Masses (Ions)

As $\quad m = \left[\frac{er^2}{2V}\right]B^2$

The above equation shows that mass of each ion reaching the detector is proportional to B^2. By adjusting the value of B and keeping the term in parentheses (bracket) constant, ions of different mass are allowed to enter the detector.

Then a graph of detector output is plotted as a function of B^2. This graph gives information what masses are present and the abundance of each mass.

Figure shows a record obtained for naturally occurring neon gas showing three isotopes whose atomic mass number are 20, 21 and 22. The larger the peak, the more abundant is the isotope. Thus most abundant isotope of neon is newon-20.

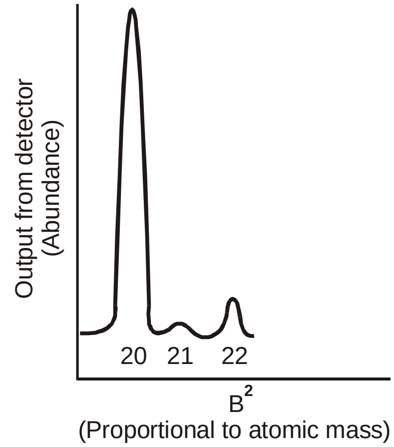


Fig. The mass spectrum of naturally occurring neon, showing three isotopes whose atomic mass number are 20, 21 and 22. The larger the peak, the more abundant the isotope.

Q.5 What is the mass defect and binding energy?

Ans. **MASS DEFECT AND BINDING ENERGY**

(i) Mass Defect

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 nuclie 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 missing mass is called the mass defect 'm' given by

$$\Delta m = Zm_p + (A - Z)m_n - m_{nucleus} \quad \ldots\ldots (1)$$

where Δm = Mass defect

Z = Total number of protons in the nucleus

m_p = Mass of a proton

$\therefore \quad Zm_p$

$A - Z$ = Total number of neutrons

m_n = Mass of a neutron

$\therefore \quad (A - Z)m_n$ = Total mass of all neutron

$m_{nucleus}$ = Experimentally measured mass of entire nucleus

Thus we can defined mass defect as:

Definition

"Mass defect is the difference in mass between the sum of the masses of its constituents and the mass of the nucleus itself".

(ii) Binding Energy:

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

$$E = (\Delta m)c^2 \qquad \ldots\ldots (2)$$

and is called Binding energy (B.E) of the nucleus.

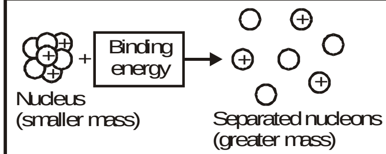
Putting eq. (1) in (2), we get Binding energy:

$$B.E = (\Delta m)c^2 = (Zm_p + (A-Z)m_n - m_{nuclues})\, c^2$$

or

$$B.E = Zm_pc^2 + (A-Z)m_nc^2 - mc^2 \qquad \ldots\ldots (3)$$

For Your Information



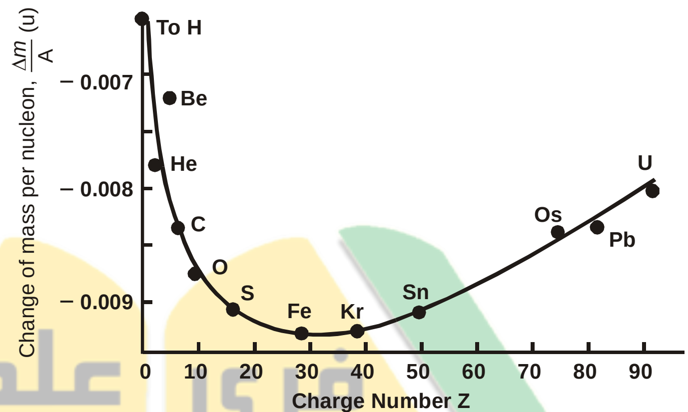
Energy must be supplied to break the nucleus apart into its constituent protons and neutrons.

Mass Defect Per Nucleon

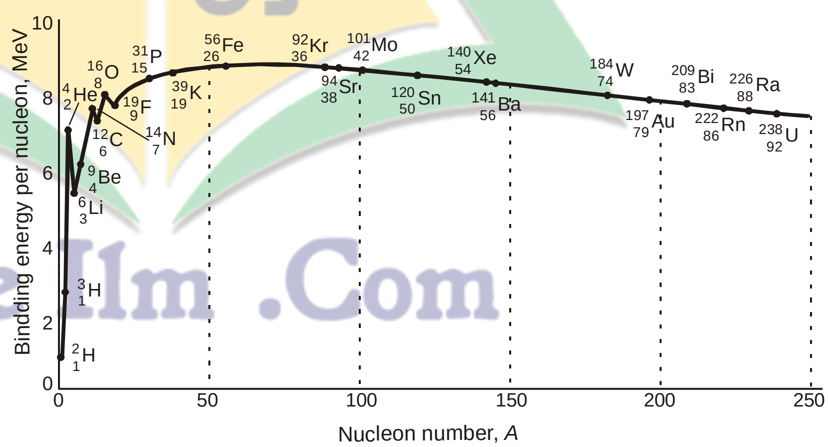
Experiments have shown that mass defect exist in elements. The figure, shows a graph between the mass defect per nucleon and charge number Z for different elements.

The value of mass defect per nucleon is given by formula:

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



The following diagram is a graph between binding energy per nucleon and mass number of different elements.



This graph shows that the binding energy per nucleon increases 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.

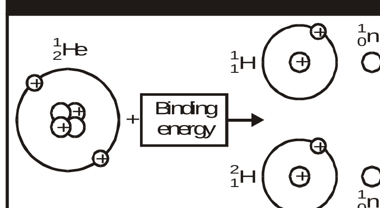
Note:

(1) The binding energy per nucleon is maximum for iron this shows that of all the elements iron is most stable element.

(2) Mass defect for hydrogen is zero.

(3) When heavy elements breaks into lighter elements or the lighter elements are fused to form heaver element then a large amount of energy can be obtained.

For Your Information



The following shows a graph between atomic numbers of different elements, and corresponding values of mass defect per nucleon.

The value of mass defect per nucleon is given by the formula mass defect per nucleon = $\frac{\Delta m}{A} = \frac{Zm_p + (A - Z)m_n - m}{A}$.

Let us now calculate the binding energy of helium.

Q.6 *What is radioactivity? Discuss emission of α, β and γ-particles from radioactive nuclei.*

Ans. **RADIOACTIVITY**

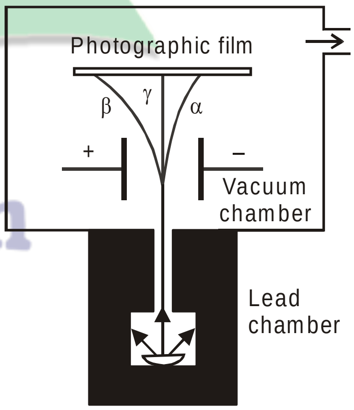
It has been observed that those elements whose charge number Z is greater than 82 are unstable. Some invisible radiations that can affect the photographic plates are emitted out of these elements. Such elements are called radioactive elements and the phenomenon is called radioactivity.

The radiations coming out of the elements are alpha (α), beta (β) and gamma (γ) radiations.

Discovery of Radioactive Elements

Radioactivity was discovered by Henri Becquerel in 1896. He found that an ore containing uranium (Z = 92) emits an invisible radiation that can penetrate through a black paper wrapping a photographic plate and affects the plate. After Becquerel's discovery Marie Curie and Pierre Currie discovered two new radioactive elements polonium and radium.

Experiment



The analysis of the radiations emitted from a radioactive material can be studied by simple experiment.

The radioactive material is placed at the centre of a block of lead by drilling a hole in the block.

Radiations enter the chamber after passing through two parallel plates. These radiations fall on three different points on photographic film. From this experiment it can be concluded that radiations emitted from radioactive element are not alike.

Types of Radiations

Radioactive radiations are of three types:

(i) α-particle (ii) β-particles (iii) γ-rays

(i) α-particles

The radiations that bend towards the negative plate are positively charged particles. These are called α-particles.

α-particles are helium nuclei. The charge on them is +Ze while their mass is 4u. i.e., every α-particle has two protons and two neutrons in it.

(ii) β-particles

The radiations that bend towards the positive plate are negatively charged particles. These are called β-particles.

β-particles are infact fast moving electrons which come out of the nucleus of radioactive element.

(iii) γ-rays

The radiations that go straight without bending have no charge on them. These are called γ-rays.

γ-rays are electromagnetic waves like X-rays. The wavelength of these rays is much shorter as compared to wavelength of X-rays.

Q.7 What is the phenomenon of nuclear transmutation radio active decay?

Ans. NUCLEAR TRANSMUTATION

Radioactive is purely a nuclear phenomenon. This is not effected by any physical or chemical reaction. Whenever any particle (radiation) is emitted from a nucleus it always changes into nucleus of another element. Therefore, the element changes into new element. The phenomenon is called radioactive decay or nuclear transmutation.

(1) Daughter Element

The element formed due to this change is called daughter element.

(2) Parent Element

The original element is called parent element. During the nuclear changes the laws of conservation of mass, energy, momentum and charge are applicable.

During nuclear decay α-particles, β-particles and γ-rays are emitted. These are called α, β and γ decays.

α-decay

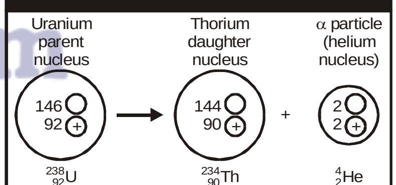
When an α-particle is emitted out of nucleus then the nucleus loses ${}^{4}_{2}He$ i.e., the mass number of nucleus is decreased by 4 and charge number by 2.

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

where X represents the parent element

and Y represents the daughter element

Do You Know?



α-decay occurs when an unstable

and in the process it is converted into a different (or daughter) nucleus.

Example: Let us take the example of ${}^{226}_{88}Ra$.

When α-particle is emitted from radium 226 then it converts into radon gas ${}^{222}_{86}Rn$. This change is represented as

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

β-decay

When a β-particle is emitted out of nucleus then the nucleus loses $^{0}_{-1}e$ i.e., the mass number of nucleus is not changed but charge number is increased by one.

The emission of β-particle is represented as:

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

Example: Let us take the example of thorium $^{232}_{90}Th$.

When a β-particle is emitted from thorium 232 then it converts into Protactinium $^{231}_{91}Pa$. This change is represented as

$$^{232}_{90}Th \longrightarrow ^{232}_{91}Pa + ^{0}_{-1}e$$

γ-decay

When a γ-ray is emitted out of nucleus then the mass number and charge number of nucleus does not under to any change. It is the fact γ-radiation is simply a photon that is either mass nor charge.

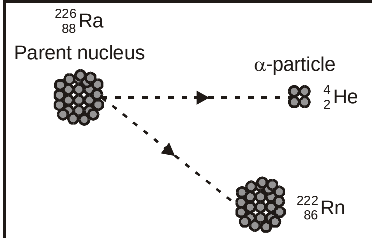
Like atom nucleus is also sometime excited to a higher state. This excited state of the nucleus is unstable state, in combing back to ground state γ-radiation is emitted.

The emission of γ-particle is represented as:

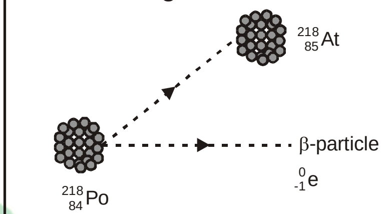
$$^{A}_{Z}X^* \longrightarrow ^{A}_{Z}X + \gamma\text{-radiation}$$

Here, $^{A}_{Z}X^*$ represents an excited nucleus and $^{A}_{Z}X$ represents a nucleus in ground state.

Do You Know?

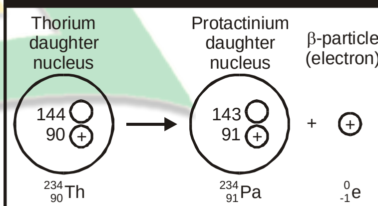


The emission of α-particle from Radium-226 results in the formation of Radon-222 gas.



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.

Q.8 What is meant by half life of radioactive element? How can it be determined from the decay of radioactive element?

Ans. **HALF LIFE**

Definition

"The half-life of radioactive element is that period in which half of the atoms decay".

Explanation

Whenever an α or β particle is emitted from a radioactive element it changes into some other element. This radioactive decay process is quite random this means that we cannot foretell about decay of any particular atom. 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.

Example: Suppose we have 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 said element is 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.

Conclusions

From above example we can deduce two conclusions:

(1) No radioactive element can completely decay. It is due to the reason that in any half period only half of the nuclei decay and in this way infinite time is required for all the atoms decay.

(2) 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 number of atoms present in the beginning is small then less atom will decay.

Results in Terms of Equation

These results can be represented 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.,

$$\Delta N \propto -N$$

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

Combing, we get:

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

$$\Delta N = -\text{Constant } N\Delta t$$

$$\Delta N = -\lambda N\Delta t \qquad \ldots\ldots (1)$$

where λ is the constant of proportionality, called the decay constant. The negative sign indicates the decrease in the number of atom N.

Decay Constant

Equation 1 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 decay constant λ is small then in that very interval less number of atoms will decay.

Eq. (1) can be written as:

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

Definition

"The ratio of the fraction of decaying atoms per unit time is called decay constant".

Unit

SI unit of decay constant is s^{-1}.

Decay Curve

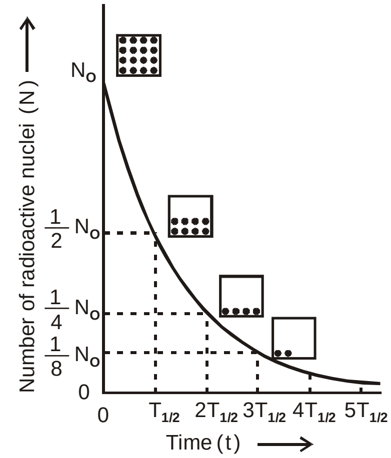


Fig. The half life $T_{1/2}$ of a radioactive decay is the time in which one-half of the radioactive nuclei disintegrates.

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

After one half life the remaining no. of atoms $= \frac{N_o}{2} = \frac{1}{2}(N_o)$

After 2nd half life the remaining no. of atoms $= \frac{1}{2}\left(\frac{1}{2}N_o\right) = \left(\frac{1}{2}\right)^2 N_o$

After 3rd half life the remaining no. of atoms $= \frac{1}{2}\times\left(\frac{1}{2}\right)^2 N_o = \left(\frac{1}{2}\right)^3 N_o$

Similarly;

After nth half life the remaining no. of atoms $= \left(\frac{1}{2}\right)^n N_o$

The graph shown in figure is general for all the radioactive elements.

Estimation of Half Life

But different elements have different values of half life. For example, half life of uranium 238 is 4.5×10^9 years while the half life of radium –226 is 1620 years.

Some elements have very small value of half life, for example, half life of radon is 3.8 days and that of uranium –239 is 23.5 minutes. This shows that the estimation of amount of a radioactive element can be made by the help of its half life (or by knowing its decay constant λ).

Relationship between λ and $T_{1/2}$

The following relation exist between the decay constant λ and the half life $T_{1/2}$:

$$\lambda \times T_{1/2} = 0.693$$

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

This equation shows that if 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.

Q.9 Write a notes on the interaction of alpha, beta and gamma rays with matter.

Ans.

INTERACTION OF α-PARTICLES WITH MATTER

(1) An α-particle travels a well defined distance in a medium before coming to rest. This distance is called range of the particle. As the particle passes through a solid, a 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 of α-particle with matter ionization this the main interaction with matter to detect the particle or to measure its energy. The range depends on:

(i) the charge, mass and energy of the particle

(ii) the density of the medium and ionization potentials of the atoms of the medium.

(2) Since α-particle is about 7000 times more massive than a electron so it is not deflected easily from its straight path. (Provided it does not approach to 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 to rest. It then captures two electrons from the medium and become a neutral helium atom.

(3) α-particle radiate energy as X-ray photons when they are slowed by the electric field of the charged particles in a solid material.

(4) α-particles produces florescence or glow on striking some substances like zinc sulphide, sodium iodide or barium platinocyanide coated screens.

Fluorescence

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

INTERACTION OF β-PARTICLES WITH MATTER

(1) β-particles loses 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 α-particles. Therefore, path of β-particle is not straight but shows much straggling scattering.

The range of β-particle is measured by effective depth of penetration into the medium not by the length of erratic path. The more dense the medium (material) the shorter its range will be.

(2) β-particle radiate energy as X-rays photons when they are slowed by the electric field of charged particles in a solid material.

(3) Charged particles ρ, produces fluorescence or glow on striking some substances like zinc sulphide, sodium iodide or barium platinocyanide coated screen.

INTERACTION OF γ-PARTICLES WITH MATTER

(1) Photons or γ-rays, being uncharged, causes very little ionization they interact matter in three different ways depending on their energy.

(i) A low energies (less than about 0.5 Mev), the γ-rays produce photoelectric effect.

(ii) At intermediate energies, the γ-rays produce compton effect.

(iii) At higher energies (more than 1.02 Mev), γ-rays produce pair production.

(2) In air γ-rays intensity falls off as the inverse square of the distance from the source, in much same manner as light from a lamp. In solids, the intensity decreases exponentially with increasing depth of penetration into the material.

The intensity I_o of a beam after passing through distance X in the medium is reduced to intensity I given by the relation

$$I = I_o e^{-\mu x}$$

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.

(3) γ-radiation produce florescence or glow on striking some substances like zinc sulphide, sodium iodide or barium platinocyanide coated screens.

INTERACTION OF NEUTRONS WITH MATTER

Neutrons, being neutral particles, are extremely penetrating particles. To be stopped or slowed down, a neutron must undergo a direct collision with nucleus or atom of comparable size (mass).

Materials such as water or plastics (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.

Note: If question is asked: Give brief account of interaction of radiation with matter then. You must not repeat the similar point separately rather you can say … α, β and γ produce fluorescence …

Table: The summary of the nature of α, β and γ radiation

Characteristics	α-particles	β-particles	γ-rays
1. Nature	Helium nuclei of charge 2e	Electrons or positrons from the nucleus of change i.e.,	E.M. waves from excited nuclei with no charge
2. Typical sources	Radon-222	Strontium-94	Cobalt-60
3. Ionization (ion pairs mm 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	-10^7 ms^{-1}	-1×10^6 ms^{-1}	-3×10^8 ms^{-1}

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.

Q.10 Describe the principle, construction and working of Wilson Cloud Chamber.

Ans.

WILSON CLOUD CHAMBER

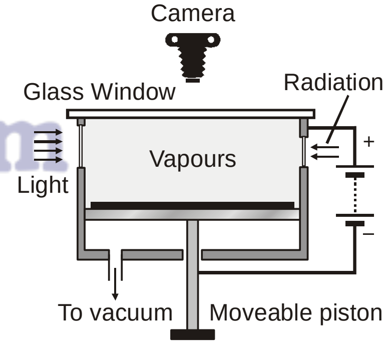
It is a device which shows the visible path of an ionizing particle.

Principle

It is based upon the principle that supersaturated vapours condense more readily on ions. The number of ions produced depends upon the ionizing power of the particles. If an ionizing particle passes through a region in which aloud droplets are about to form, the droplets will form first along the particle's path, showing the path as a trail of droplets.

Construction

It consists of a cylindrical chamber fitted with a piston at its bottom as shown in figure.



Wilson Cloud Chamber

The top of the chamber is made of transparent glass and a camera is fixed to take photographs above the glass top. A black felt pad soaked in alcohol is placed on a metal plate inside the chamber. The air soon becomes saturated with alcohol vapours.

Working

:d air (airWhen the piston is moved down quickly, mixed with vapours) expand adiabatically and so cools down the saturated vapours inside the chamber becomes supersaturated (i.e., they contain more liquid than they can hold). The supersaturated vapours condense in the form of tiny droplets on ions. They look like fog when viewed from the glass top and expansion is done at the time when the ionizing particles enter the chamber, the vapours condense on the ions. This will give a visible trail of droplets along the path followed by ionizating particles. By using a strong light, the camera mounted above the glass top is used to take the photograph of this path.

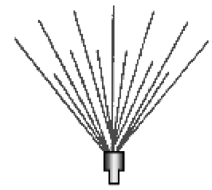
Clearance of Unwanted Ions

After taking photograph the piston is pushed back to its original position and a potential difference of order 1 KV is applied between top and bottom of chamber which clear away all the unwanted ions from the chamber to make it ready for use.

Track's of Particle

Tracks of α-particles

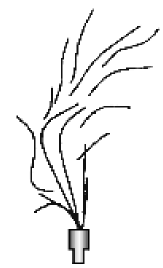
The tracks of α-particles are thick, straight and continuous due to high ionization by them as shown in figure (a).



(a) α- Particle

Tracks of β-particles

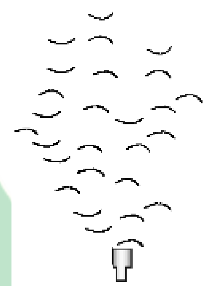
The tracks of β-particles are thin, discontinuous due to less ionization, and showing frequent deflections as shown in figure (b).



(b) β- Particle

Tracks of γ-rays

Gamma rays have no definite tracks along their paths. The length of track depends upon the energy of incident particles.



(c) γ-Rays

Q.11 What is G.M counter? Give its construction. How is it used to count the nuclear radiation?

Ans. **GEIGER MULLER COUNTER**

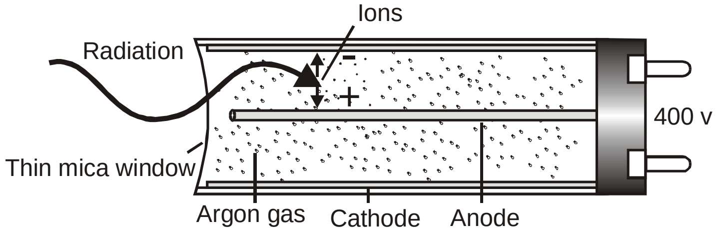
Geiger-Muller tube is a well known radiation detector.

Principle

The discharge in the tube results from the ionization produced by the incident radiation.

Construction

It consists of a stiff central wire acting as an anode in a hollow metal cylinder. The walls of the cylinder are acting as cathodes. The tube is 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 it carries connecting pins for the two electrodes. A high potential difference (about 400 v for neon bromine filled tube) but slightly less than that necessary to produce discharge through the gas is maintained between the electrodes.



Geiger - Muller Tube


G.M. tube with scaler unit

Working

When a radiation enters the tube through then mica window, the gas inside the tube is ionized. Positive ions and electrons are produced. These electrons and ions are accelerated by the electric field in opposite directions. They produce further ionization by suffering collisions with the atoms of the gas. As a result a cascade (group) of electrons is formed. At this stage a discharge occures and the gas becomes conducting, causing the current to flow in the external circuit. The voltage drop across resistance R produces a current pulse of short duration which is amplified and recorded by an electric counter. The counter which also provides the power, is called a scalar.

Quenching Effect

The cascade (group) of electrons produced by the entry of an ionizing particle is counted as single pulse (whatever the energy or size of the pulse may be). The entire pulse takes less than 1 μs. However, positive ions, being very massive than the electrons, take several hunder times longer 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 will disturb the counting. This is prevented by mixing a small amount of quenching gas with the principal gas.

Self Quenching

The quenching gas must have an ionization potential lower than that of principal gas (inert 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. For example, Bromine gas is added to neon gas. The bromine molecules absorb energy from the ions of 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.

Electronic Quenching

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 to output pulse.

Drawback of Geiger Counter

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 faster rate, not all of them will be counted since some will arrive during the dead time.

Uses

Geiger counter can be used to:

(1) Determine the range or peneteration power of ionizing particles.

(2) The reduction in the count rate by inserting metal plates of varying thickness between the source and the tube helps to estimate the peneteration power of the incident radiation.

(3) It is very small in size than any other detector and operates at low voltage.

(4) This type of detector is used for detecting α or β particles but a specially designed device can be used for γ-rays.

Q.12 What is solid state detector? Also discuss construction and working.

Ans. **SOLID STATE DETECTOR**

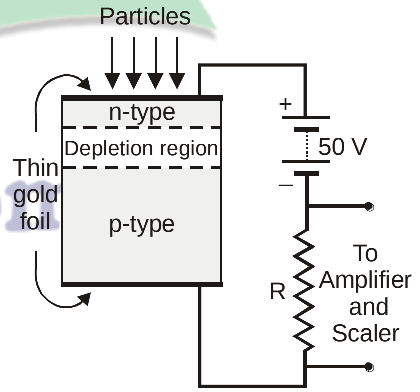
If a semi-conductor like p-n junction diode is used for the detection of nuclear radiations (α, β, γ-rays) it is called a solid state detector.

Principle

Its working principle is based upon the reverse bias. The applied reverse-bias enlarges the charge free-region in a p-n junction. In other words, when radiation is allowed to enter the depletion region, electron-hole pairs are produced by the incident radiation.

Construction

Solid state detector is basically a special designed p-n junction as shown in figure. 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 cooled 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 supposed to be placed at the front surface. This is known as the surface barrier type detector.



Working

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 enters the detector from n-side, it is absorbed in the depletion region and it produces electron-hole pairs. These mobile charge carriers move towards the respective sides due to applied electric field. It means that electrons move towards the positive side of the electrode and holes towards the negative side. These charges produce potential drop across the junction and a current pulse whose magnitude is proportional to the energy of the incident particle, is created through the external circuit. This current pulse is amplified and registered by a scalar unit (i.e., electronic counter).

The p-n junction again becomes non-conducting when the electrons and holes arrive at the specific ends. It becomes ready to receive the next incident particle for producing electron-hole pairs.

Its Uses

(1) The energy required to produce electron-hole pair is about 3 to 4 eV which makes the device useful for detecting low energy particles.

(2) The collection time of electrons and holes is much less than gas filled counters and hence a solid state detector can count very fast.

(3) It is very small in size than any other detector and operates at low voltage.

(4) It is more useful for the detection of α and β particles, whereas a special designed detector and an amplifier can also be used to detect for high energy γ-rays.

(5) It is more efficient and accurate.

Q.13 What are the nuclear reactions and conditions for the nuclear reactions?

Ans. **NUCLEAR REACTIONS**

When an α-particle is emitted from uranium −226, radon −222 is obtained. The nuclear reaction is represented by

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

This type of reaction takes place on its own accord. Rutherford first of all expressed his opinion that besides natural radioactive decay processes, other nuclear reactions can also occurs.

A particle x is bombarded on any nucleus X and this process yield a nucleus Y and a light object y as shown below:

$$ X + x \longrightarrow Y + y $$

Rutherford in 1918 bombarded an α-particle on nitrogen. He observed that as a result of this reaction, oxygen is obtained and a proton is emitted that is:

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

This reaction indicate that when an α-particle enters the nucleus of ${}^{14}_{7}\text{N}$ then an excitation is produced in it and as a result of it ${}^{17}_{8}\text{O}$ and a proton are produced.

Condition for Nuclear Reactions

For nuclear reactions to take place, the following conditions must be satisfied.

(1) Conservation of Mass

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 they can be created.

Consider the reaction:

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

Number of protons = 7 + 2 = 8 + 1

9 = 9

Number of neutrons = 7 + 2 = 9 + 0

$$= \quad 9 \quad = 9$$

(2) Conservation of Energy

A nuclear reaction can take place only when the total energy of reactants including rest mass energy is equal to the total energy of the products. In this case, we again consider the nuclear reaction.

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

Mass of reactants is:

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

Mass of $^{4}_{2}H$ = 4.0026 U

Total mass of reactants = 18.0057 U

Mass of product is:

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

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

Total mass of products = 18.0069 U

Difference between masses = (18.0069 – 18.0057) U

= 0.0012 U

This shows that total mass after reaction is greater than total mass before reaction by 0.0012 U.

We know that:

$$1\ u = 931\ Mev$$

$$\therefore \quad 0.0012\ u = 0.0012 \times 931 = 1.13\ Mev$$

This energy is required to be supplied in order to have the nuclear reaction given above. So an α-particle of 1.13 Mev energy is required to perform this nuclear reaction. Such an α-particle is emitted by Po-214, whose energy is 7.7 Mev, which is greater than 1.13 Mev, which makes this nuclear reaction possible.

The above conditions are called the before-test of a nuclear reaction which will enable us to know whether reaction will take place or not.

Nuclear Reaction in Reverse Direction

If we accelerate protons, with the help of cyclotron, and increase their velocities and then bombard these high velocity proton on $^{17}_{8}O$, the above given reaction will proceed in reverse direction as shown.

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

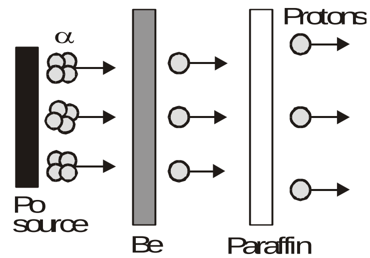
Discovery of Neutron

In 1932 James Chadwick discovered neutron. When $^{9}_{4}Be$ was bombarded with a-particle (emitted from $^{210}_{84}$ PO) then $^{12}_{6}C$ and neutron were obtained. The reaction is:

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

As neutron is neutral particle therefore, its identification was difficult. But when neutron were passed through a block of paraffin, fast moving protons were ejected out and these were easily identified.

Figure shows the experimental arrangement of Chadwick's apparatus used for the discovery of neutron.



Per Nucleon Energy

Fission reaction can be explained easily with the help of the study of binding energy. We know that 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 rigidity bound. For example the binding energy per nucleon for uranium is about 7.7 Mev and the product of fission reaction of uranium (barium and krypton) have total mass less than the mass of uranium. i.e.,

$$8.5 - 7.6 \quad = \quad 0.9 \text{ Mev per nucleon}$$

thus when a uranium nucleus breaks up (by fission reaction) into barium and krypton then energy at a rate of 0.9 Mev per nucleon is given out. This means that an energy $235 \times 0.9 = 211.5$ Mev is given out in the fission of one uranium nucleus.

Possible Uranium Reactions

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:

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

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

Hence in uranium fission reaction several products may be produced.

All 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 and plutonium-239, and slowly these two are used for fission purposes.

Q.14 Write a detailed note on nuclear fission. (OR) What is fission chain reaction? Describe uncontrolled and controlled chain reaction?

Ans. **NUCLEAR FISSION**

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

Explanation

Otto Hahn and Fritz Strassman of Germany while working upon nuclear reactions made a wonderful discovery. They observed that when slow moving neutrons are bombarded on ${}^{235}_{92}U$, then as a result of nuclear reaction ${}^{141}_{56}Ba$, ${}^{92}_{36}Kr$ and an average of three neutrons are obtained.

It may be remembered that mass of both Krypton and barium is less than that of mass of uranium. This nuclear reaction was different from earlier nuclear reactions by two ways:

(1) As a result of breakage of the nucleus two nuclei of almost equal size are obtained.

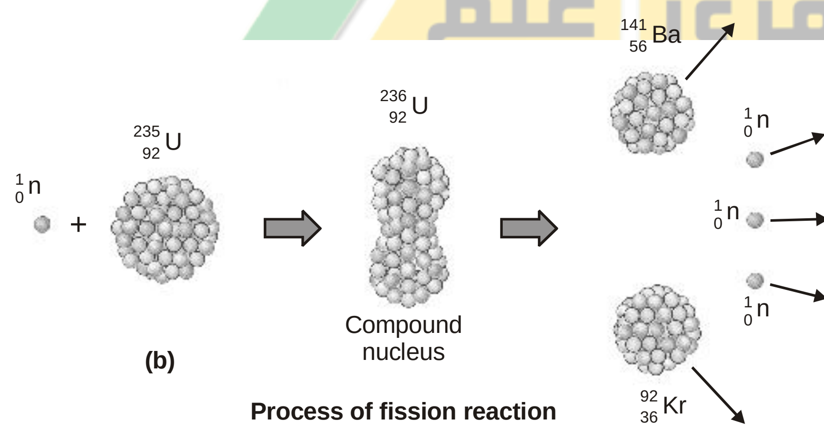
(2) A very large amount of energy is given out in this reaction Fission reaction of (uranium) ${}^{235}_{92}U$ can be represented by

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

where 'Q' is energy given out in this reaction.

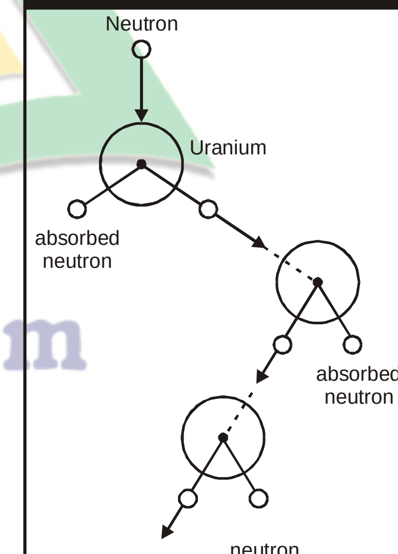
By comparing the total energy on the left side of the equation with total energy on the right-side, we find that in the fission of one uranium nucleus about 200 Mev energy is given out.

Fission reaction is shown in figure.



Process of fission reaction

Do You Know?



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.

Fission Chain Reaction

We know 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 using these neutrons properly 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.

There are two types of fission reaction:

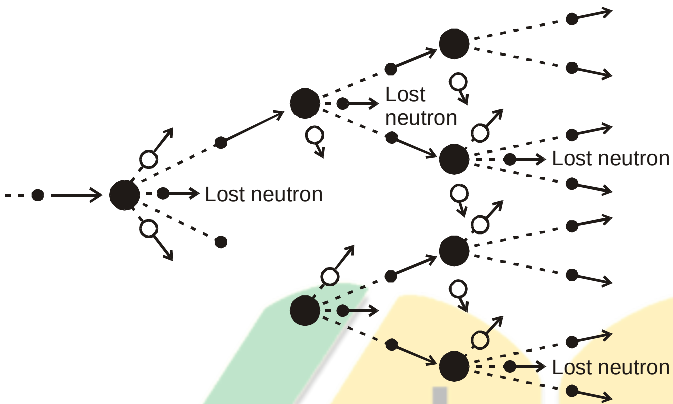
(i) Uncontrolled fission chain reaction

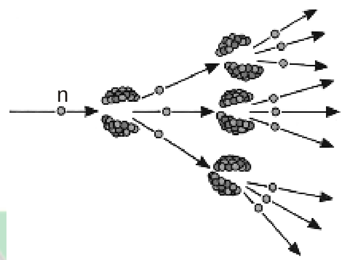
(ii) Controlled fission chain reaction

(i) Uncontrolled Fission Chain Reaction OR (Fission Chain Reaction)

Suppose we have a definite amount of ${}^{235}_{92}U$ and a slow neutron (originated from any source) produces fission reaction in one atom of uranium. During this fission three neutrons are produced. If conditions are appropriate these neutrons will produce fission in some more atoms of uranium and more neutrons will be emitted. In this way this process will rapidly proceed and in a very small time a large amount of energy along with huge explosion is produced.

The figure represents a (uncontrolled) fission chain reaction.

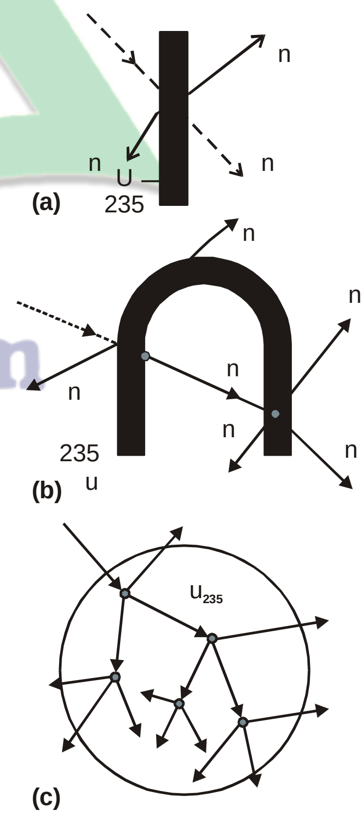




(ii) Controlled Fission Chain Reaction

It is possible to produce such condition in which only one neutron out of three 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.

Let us try to understand this by following figures:



(a) In figure (a) a thin sheet of uranium $\left({}^{235}_{92}U\right)$ is shown in which fission reaction is in progress. The resulting neutrons scattered in the air and they are unable to produce any fission chain reaction.

(b) In figure (b) a favourable condition for chain reaction is shown. In this case some of the neutrons produced in the first fission reaction produce only one more fission reaction but they do not produce any further fission, therefore, chain reaction is not possible.

(c) In figure (c) a sphere of ${}^{235}_{92}U$ is shown. If the sphere is big then most of the neutrons produced due to the fission reaction get absorbed in ${}^{235}_{92}U$ before escaping out of the sphere and produce chain reaction.

Critical Mass

Such a mass of uranium in which one neutron out of all the neutron produced in one fission reaction, produces further fission is called critical mass. The volume of this mass is called critical volume.

Mass of Uranium and Critical Mass

(i) If the mass of uranium is much greater than the critical mass, then the chain reaction proceeds at a rapid speed and huge explosion is produced. Atom bomb works at this principle.

(ii) If the mass of uranium is less than critical mass, the chain reaction does not proceed.

(iii) 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 on 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 with out 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 fission reaction is controlled.

Q.15 What is nuclear reactor? Describe the main function of its main parts.

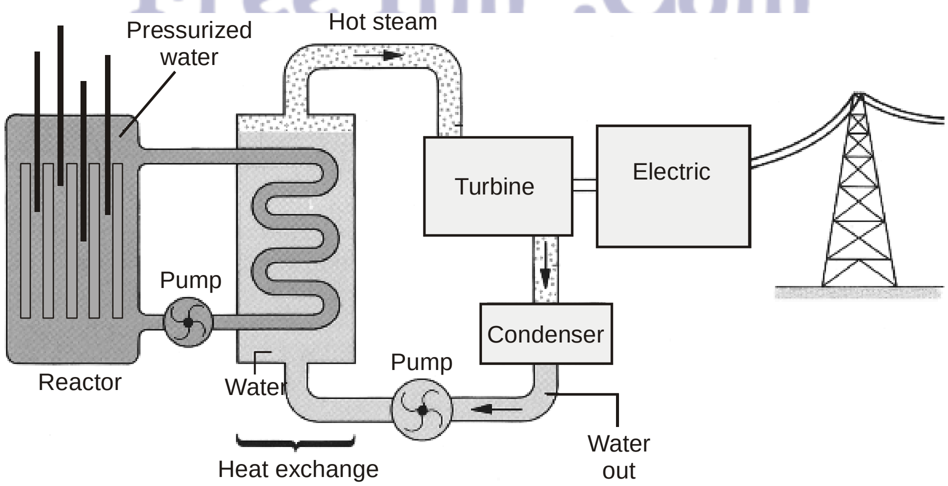
Ans. **NUCLEAR REACTOR**

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

Principle

The principle of nuclear reactor is based on controlled fission chain reaction.

Main Parts of Nuclear Reactor



(1) Core

It is the main part of nuclear reactor. Here the fuel is kept in the shape of cylindrical tubes. Reactor fuels are of various types.

Uranium was used 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 quantity of ${}^{235}_{92}U$ in naturally occurring uranium is only 0-7 percent. Now a days plotonium –239 and uranium –233 are also used as fuel.

(2) Moderator

The fuel rods are placed in a substance of small atomic weight, such as water, heavy water, carbon or hydrogen, 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 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 ${}^{235}_{94}Pu$ etc. For this purpose slow neutrons are more useful. To achieve this moderators are used.

(3) Absorbing Rods

There are neutrons absorbing rod which control the number of neutrons which produce nuclear fission reaction. For this purpose cadmium or boron materials are used. These materials have the property of absorbing fast moving neutrons. These control rods 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 Exchanger

Heat is produced due to fission chain reaction taking place in the core of the reactor. The temperature of the core, therefore, rises to about 1200°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 great pressure. In the heat exchanger this heat is used to produce steam from ordinary water. The steam is then used to run the turbine which 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.

KANUP

In Karachi Nuclear Power Plant (KANUP), heavy water is being used as a moderator and for transportation of heat also from the reactor core to heat exchanger, heavy water is used. To cool steam coming out of the turbine seawater is being used.

Disposal of Nuclear Waste

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 meter below the surface of the earth. Here they can remain and decay without polluting the environment.

Types of Reactors

There are two types of nuclear reactors:

(1) Thermal reactors (2) Fast reactors

(1) Thermal Reactors

The thermal reactors are called "thermal" because the neutrons are 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 generator.

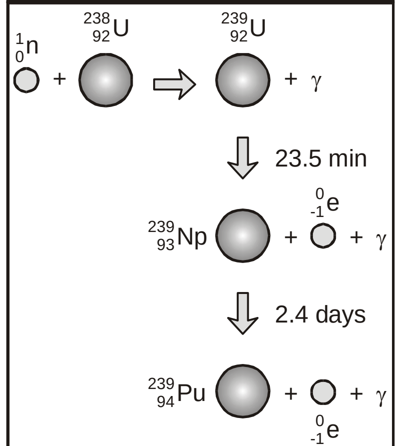
(2) Fast Reactor

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 plotonium-239.

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

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

Do You Know?



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

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 plotonium and uranium dioxide surrounded by a blanket of uranium –238.

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

Nuclear Fusion Reaction

Definition

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

Explanation

The nuclear energy per fission reaction is about 0.9 Mev. It is due to the fact that binding energy per nucleon of the fission fragments is greater than uranium. The nuclear energy is obtained from any nuclear reaction in which the binding energy per nucleon of the products increases.

The binding energy increases in the elements up to A = 50, hence when two light nuclei fuse together to form a heavy nucleus whose mass number (A) is less than 50, then energy is given out. In case of mass defect and binding energy, we have seen that when two protons and two neutrons fuse to form a helium nucleus, then about 28 Mev energy is given out.

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.,

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

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

$$ {}_{1}^{2}H + {}_{1}^{2}H \longrightarrow {}_{1}^{3}He + {}_{1}^{1}H + 4.0 \text{ Mev} $$

or

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

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

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

Different Methods for Production of Fusion Reaction

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

(1) By Using Accelerators

This high speed is given with the help of an accelerator. This method has been used in the research study of nuclear fusion of ${}_{1}^{2}H$ and ${}_{1}^{3}H$. But this methods of nuclear fusion for getting energy cannot be used on large scale.

(2) By Increasing Temperature

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 temperature of that substance. To start a fusion reaction the temperature at which the required speed of light nuclei can be obtained is about 10 million degrees celsius. At such extraordinarily high temperature the reaction that takes place is called thermonuclear reaction. Ordinarily such a high temperature cannot be achieved. However during the explosion of an atom bomb this temperature can be had for a very short time.

Until now the fusion reaction is taking place only in hydrogen bomb. That extraordinary high temperature is obtained during the explosion of an atom bomb due to this high temperature the fusion reaction between ${}_{1}^{2}H$ and ${}_{1}^{3}H$ 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 methods would be found to control this reaction as well.

Nuclear Reaction in the Sun

The sun is composed of hydrogen. It has a little amount of helium and slight amount of other heavy elements. A tremendous amount of energy keeps on releasing continuously at all times. The temperature of its core is about 20 million degree celsius. Its energy is due to fusion reaction called P-P reaction. During this process two hydrogen nuclei or two proton fuse to form 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, $^{3}_{2}He$ can isotope of helium is formed i.e.,

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

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

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

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

Ultraviolet radiations causes
(i) Sunburn, blindness and skin cancer
(ii) Severe crop damage
(iii) Decay of micro-organisms
(iv) Disrupt the ocean ecosystem

In this reaction six protons take part and finally a helium nucleus and protons are formed. That is the result of different stages of this reaction is that 4 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 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.

Q.16 Write a detailed note on radiation exposure and its damages.

Ans. **RADIATION EXPOSURE**

When a Geiger tube is used in any experiment, it records radiation even when a radioactive source is not there. 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.

Cosmic Rays

The cosmic radiations 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 to some chemicals in the atmosphere such as chloroflouro carbons (CFC) used in refrigeration, aerosol spray and plastic from industry. Its use is now being replaced by environmentally friendly chemicals.

Building Materials

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.

Medical Radiation Exposure

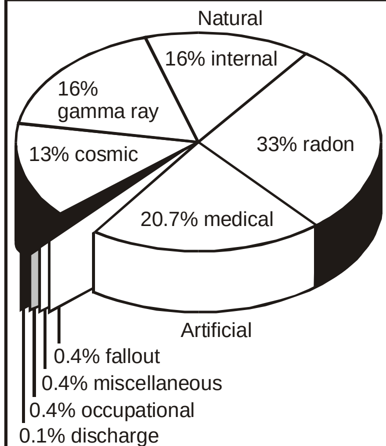
Some radiation in the environment is added by human activities. Medical practices, mostly diagnostic X-ray probably contribute the major portion to it. It is an unfortunate fact that may X-ray exposures such as routine chest X-ray and dental X-ray are made for no strong reason and may do more harm than good.

Every X-ray exposure should have a definite justification that outweighs the risks.

Other Sources

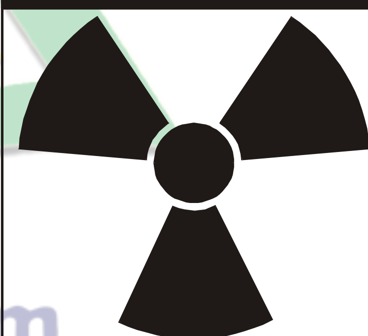
The other sources include radioactive waste from nuclear facilities, hospitals, research and industrial establishments, colour television, luminous watches and tobacco leaves. A smoker not only inhales toxic smoke but also hazardous radiation. Low level background radiation from natural sources is normally considered to be harmless. However, higher levels of exposure are certainly damaging. We cannot avoid exposure to radiation. However, the best advice to avoid unnecessary exposure to any kind of ionizing radiation.

For Your Information

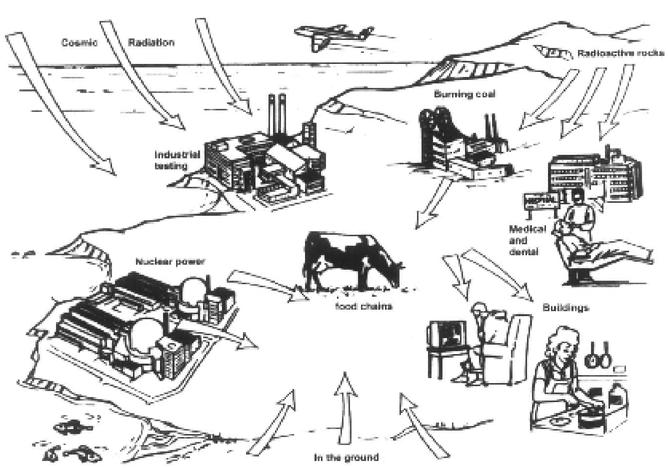


Pie-chart showing proportion of radiation from different sources absorbed by average person.

Do You Know?



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



TABLE

Relative Biological Effectiveness (RBE)

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

Biological Effects of Radiation

To study the effects of radiation, we need to define some of the units of radiation. The strength of radiation source is indicated by its measured in Becquerel (Bq) and Curie (Ci).

Becquerel (BQ): One disintegration per second is called becquerel.

Curie (C): 3.7×10^{10} disintegration per second is called curie.

Absorbed Dose: The energy absorbed from ionizing radiations per unit mass of absorbing body is called absorbed does.

It is expressed as:

$$D = \frac{E}{m}$$

Gray: The unit of absorbed does is gray (Gy). It is defined as one joule per kilogram i.e.,

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

Rad: The old unit of absorbed dose is rad (an acronym for radiation absorbed dose.

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

Biological Effects

It has been experimentally proved that equal dose of different radiations do not produce same biological effects. 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 quality factor known as relative biological effectiveness or RBE.

Equivalent Dose De

The equivalent dose (De) of any absorbed radiation is defined as:

"The product of absorbed dose and REB of the kind of radiation being absorbed".

The equivalent dose can be written as:

$$De = D \times RBE$$

Seivert

The SI unit of equivalent dose is Seivert (Sv)

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

An old unit of equivalent dose is rem

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

General Information about Biological Effects of Radiation

(1) The background radiation to which we are exposed, on average, is 2m Sv per year.

(2) Dose of about 3 Sv cause radiation burns to the skin.

(3) For the workers where nuclear facilities are provided or inside mines a weekly dose of 1m Sv is considered safe.

(4) The damage from α-particle is small unless the source enters the body.

(5) α and β particles can cause redness and sores on the skin.

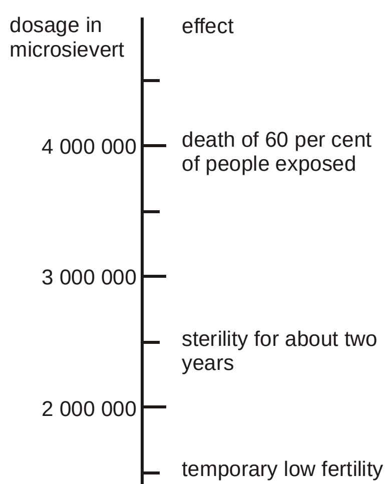
(6) The low level radiation effects are loss of hair, ulceration, stiffening of the lungs, and a drop in the white blood cells which is followed by a sickness pattern of diarrhea, vomiting and fever known as radiation sickness as shown figure.

(7) High levels dose of radiation may disrupt the blood cells seriously leading to diseases such as anemia and leukasemia.

(8) 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.

Table: 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



Table

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
Techneliu ^{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

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.

Uses of Radio Isotopes

(i) **In Complex Reaction:** Radioisotopes are used to find out what happens in many complex chemical reactions and how they proceed.

(ii) **In Biology:** 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.

(iii) 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.

(iv) 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.

For Your Information

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

Do You Know?

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

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.

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.

Uses of Tracers

(i) In Medicine

Tracers are widely used in medicine to detect malignant tumors.

(ii) In Agriculture

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.

(iii) In Understanding of Photosynthesis

This technique has helped to understand more elaborately the complex process of photosynthesis.

(iv) In Identification of Faults

The tracer technique was also used to identify faults in the underground pipes e.g., faults in fountain system of the historical Shalimar Gardens of Lahore are detected by the Scientists of Pakistan Atomic Energy Commission.

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.

(i) Diagnostic of Thyroid Gland

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.

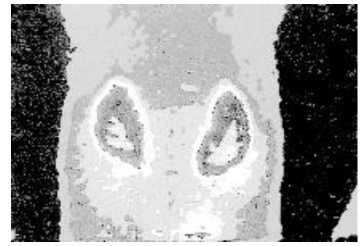
(ii) Study of Circulation of Blood

A similar method can be used to study the circulation of blood using radioactive isotope sodium-24.

(iii) Determination of Cancerous Cells and their Treatment

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 often used in the treatment of cancer. The γ-rays are carefully focused 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 fell ill, because the radiation also damages the healthy cells.

Radiography



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 figure, 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.

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 question 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) The strong force

Unification of Electric and Magnetic 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. 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

Strong nuclear force is effective only within sub-nuclear distances and therefore, confines the neutrons and protons within the nucleus.

Electromagnetic Force

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.

Weak Nuclear Force

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.

Gravitational Force:

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.

Unification of Electromagnetic and Weak Forces:

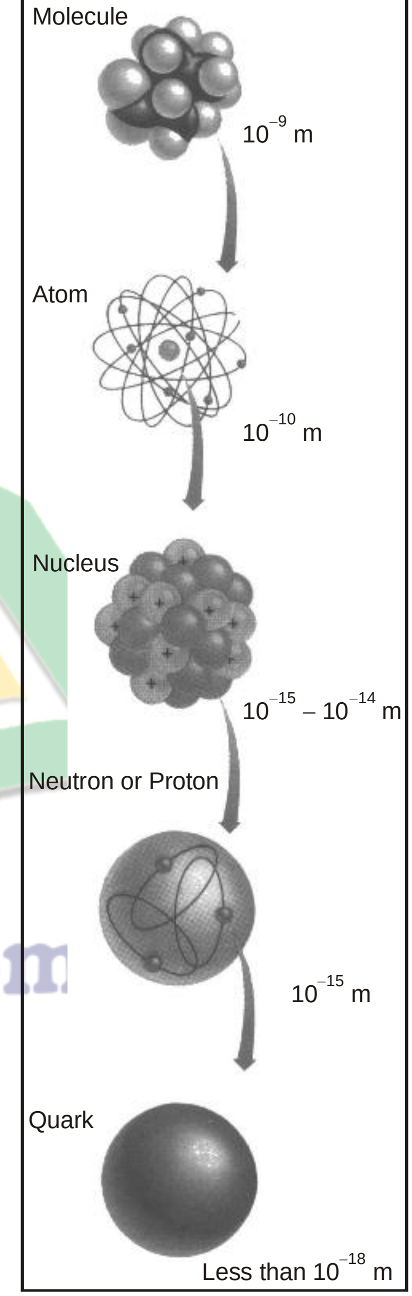
One hundred years after the unification of electric and magnetic forces into electromagnetic force, in 1979, the physics noble prize was conferred on Glashow, Weinberg and Abdus Slam for the unification of electromagnetic and weak forces.

Unification to Electro-

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

For Your Information

Composition of Matter



BUILDING BLOCKS OF MATTER

Subatomic particles are divided into three groups:

(1) Photons (2) Leptons (3) Hadrons

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.

Quarks and Antiquarks

Name	Symbol	Charges
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	$+\frac{1}{3}$ e
Bottom	b	$-\frac{2}{3}$ e

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 neutrons are leptons.

Quarks

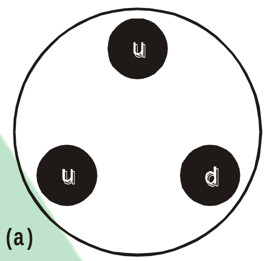
According to quark theory initiated by M. Gell-Mann and G. Zweig, the quarks are proposed as the basic building blocks of the mesons and baryons. A pair of quark and antiquark makes a meson and 3 quarks make a baryon. It is proposed that there are six quarks, the (1) up (2) down (3) strange (4) charm (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. (a). The neutron is assumed to be made of one up quark and two down quarks as shown in Fig. (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.

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
$\bar{t}$	$+\frac{1}{3}$ e
$\bar{b}$	$+\frac{1}{3}$ e

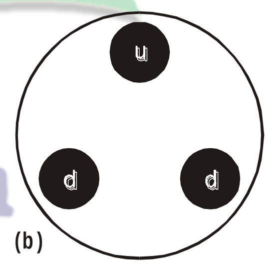
Proton



(a)

Charge
2/3 + 2/3 - 1/3 = 1

Neutron



(b)

Charge
2/3 - 1/3 - 1/3 = 0

SOLVED EXAMPLES

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

Mass defect can be calculated as:

$$m = (m_p + m_n) - m_2$$
$$= 1.6726 \times 10^{-27} + 1.6749 \times 10^{-27} - 3.3435 \times 10^{-27}$$
$$= 3.9754 \times 10^{-30} \text{ kg}$$

Now Binding energy can be calculated as:

$$B.E = mc^2 = (3.9754 \times 10^{-30})\ 9 \times 10^{16}$$
$$B.E = 3.5729 \times 10^{-13} \text{ J}$$
$$B.E = \frac{3.5729 \times 10^{-13}}{1.6 \times 10^{-19}} = 2.33 \times 10^{6} \text{ ev} = 2.33 \text{ Mev}$$

Result

Mass defect = m = 3.9754×10^{-30} kg

Binding energy = 2.23 MeV

EXAMPLE 21.2

Iodine –131 is an artificial radioactive isotope. Δt 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	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.

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

RBE factor = 10

D_e = 400 rem = 400×0.01 Sv = 4 Sv , D = ?

Using equation:

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

Since 1 Gy is 1 J kg^{-1}, hence total energy absorbed by the whole body

$$= mD = 80 \times 0.4\ Gy = 32\ J$$

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.