UNIT 18

ATOMIC AND NUCLEAR PHYSICS

After studying this unit, the students will be able to:

- **a.** Describe the structure of an atom in terms of a nucleus and electrons,
- **b.** Describe the composition of the nucleus in terms of protons and neutrons.
- **c.** Explain that number of protons in a nucleus distinguishes one element from the other
- **d.** Represent various nuclides by using the symbol of proton numbers z nucleon number
- **e.** A and the nuclide notation x.
- **f.** Explain that some nuclei are unstable, give out radiation to get rid of excess energy and are said to be radioactive. '
- **g.** Describe that the three types of radiation are α, β, γ
- **h.** State, for radioactive emissions:
- **i.** Their nature
- **j.** Their relative ionizing effects.
- **k.** Their relative penetrating abilities.
- **l.** Explain that an element may change into another element when radioactivity occurs
- **m.** Represent changes in the composition of the nucleus by symbolic equations when alpha or beta particles are emitted.
- **n.** Describe that radioactive emissions occur randomly over space and time.
- **o.** Explain the meaning of half-life of a radioactive material.

p. Describe what are radioisotopes. What makes them useful for various applications?

q. Describe briefly the processes of fission and fusion.

r. Show an awareness of the existence of background radiation and its sources.

s. Describe the process of carbon dating of estimate the age of ancient objects.

t. Describe hazards of radioactive materials.

Q.1 Differentiate between atomic number and atomic mass?

Answer

Atomic number

"The number of protons in the nucleus is called atomic number. It is written by the symbol 'Z'."

Number of neutrons in the nucleus is called neutron number, written by the symbol N.

For your understanding
The word atom is derived from the Greek work "otomos", meaning "indivisible". At one time, atoms were thought to be the smallest particles of matter. Today we know that atoms are composite systems and contain even smaller particles; protons, neutrons and electons.

Atomic mass number

"Number of nucleons (protons + neutrons) in the nucleus is called atomic mass number."

The term "nucleons" means protons and neutrons collectively in the nucleus.

Isotopes

"Isotopes are atoms of an element which have same number of protons but different number of neutrons in their nuclei." Three isotopes of hydrogen are shown in the figure 18.2.

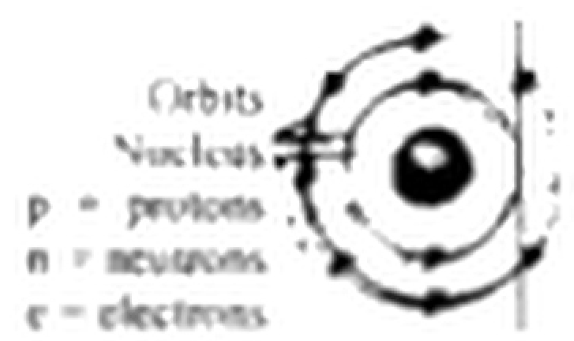


Fig. 18.1 The nucleus of an atom consists of protons and neutrons.

Fig.18.2 Three isotopes of hydrogen
Protium (^1_1H) Deutrium (^2_1H) and Tritium (^3_1H)

1) Protium (^1_1H) contains one proton in the nucleus and one electron revolving around the nucleus.

2) Deuterium (^2_1H) contains one proton, one neutron and one electron.

3) Tritium (^3_1H) contains one proton, two neutrons and one electron.

Q.2 What do you mean by the term (natural) radioactivity?

Answer

Natural Radioactivity

"The spontaneous emission of radiation by unstable nuclei is called natural radioactivity."

The elements which emit such radiations are called radioactive elements.

Explanation

In 1896, Becquerel accidently discovered that uranium salt crystals emit an invisible radiation that can darken a photographic plate. He also observed that the radiation had the ability to ionize a gas.

Subsequent experiments by other scientist showed that other substances also emitted radiations.

Do you know?
The positively charged protons in a nucleus have huge electrical forces of repulsion between them. Why don't they fly apart in response to this force? Because there is an attractive force between the nucleons called the strong force. This force acts over only a very short distance. Without this strong nuclear force there would be no atoms beyond hydrogen.

Marie Curie and Pierre discovered two new elements called Polonium" and "radium."

Decay process

"Emission of radiations due to disintegration of unstable nuclei 15 called decay process."

Three types of radiations are usually emitted by a radioactive substance. They are: alpha (α) particles beta (β) particles; and gamma (γ) rays.

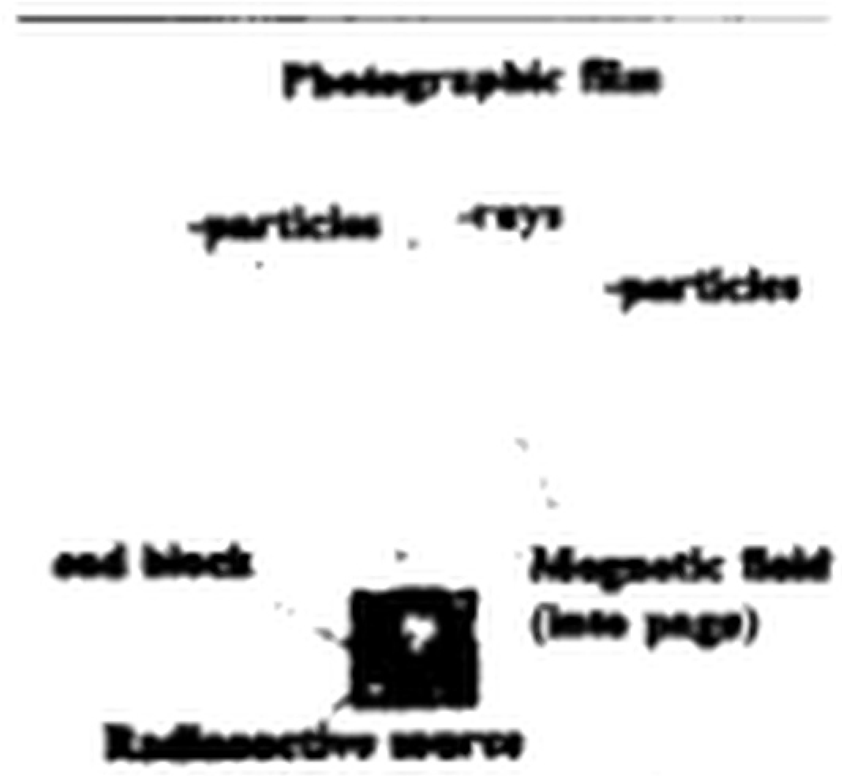


Fig. 18.3 Three types of radiations can be distinguished from their path followed in an external magnetic field

The radiation emitting from the radioactive source splits into three components when placed in a magnetic field, α and β radiations bend in opposite direction while γ radiations does not change its direction in the magnetic field.

Q.3 What are background radiations?

Answer

Background radiations

"Radiations present in atmosphere due to different radioactive substances are called background radiations."

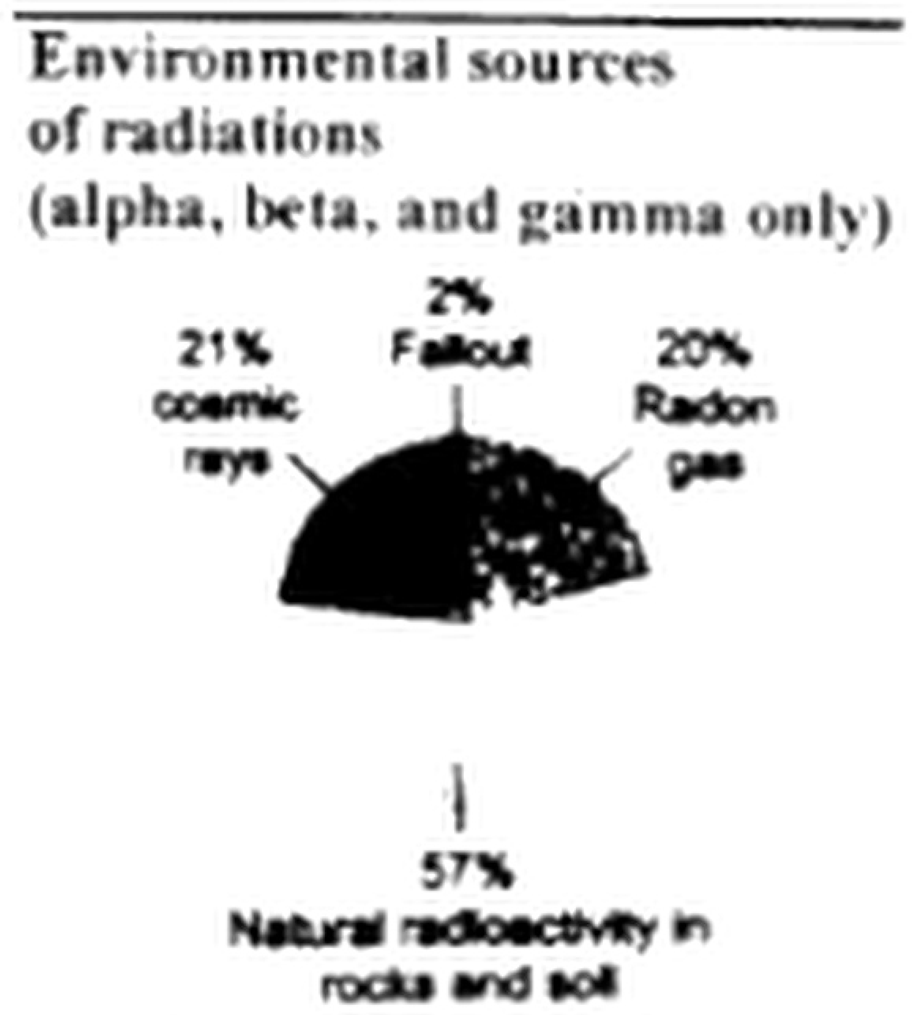


Fig. 18.4 The sources of background radiation from the environment

Everywhere in rocks, soil water, and air of our planet are traces of radioactive elements. This natural radioactivity is called the background radiations.

It is as much part of our environment as sunshine and rain. Fortunately, our bodies can tolerate it. Only places where radiation is very high can be injurious to health

Cosmic radiations

"The earth, and all living things on it also receive radiation from outer space. This radiation is called Cosmic radiation."

Cosmic radiation primarily consists of protons, electrons, alpha particles and larger nuclei. The cosmic radiation interacts with atoms in the atmosphere to create shower of secondary radiation, including X-rays, muons, protons, alpha particles, electrons, and neutrons.

Q.4 What are the three basic radioactive decay processes and how do they differ from each other?

Answer

Nuclear transmutation

"The spontaneous process in which 'a parent unstable changes into a more stable daughter nuclide with the emission of radiations is called transmutation." Radioactive decay can be in the form of equation in which an unstable parent nuclide X changes into a daughter nuclide Y with the emission of an alpha particle or gamma particle.

Physics Insight
When alpha and beta particles are slowed down by collisions they become harmless, in fact, they combine to form neutral helium atoms.

For your information
The SI unit of radioactivity is the Becquerel, Bq. In SI base units, 1 Bq = 1disintegration per second (dps). This is very small unit. For example, 1.0 g of radium has an activity of 3.7 × 10^{10} Bq. Therefore, the kilobecquerel (kBq) and the megabecqurel (MBq) are commonly used. The acitivity of 1.0 g of radium is 3.73 × 10^{4} MBq.

Alpha (α) decay

General equation: ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + energy$

(parent nuclide) (daughter nuclide) (alpha nuclide)

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

(radium) (radon)

It means in 'alpha decay, the proton number or atomic number Z of the parent nuclide reduces by 2 and its mass number or nucleon number A decreases by 4.

Beta (β) -decay

General equation: $^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}^{0}_{-1}e + energy$

(parent nuclide) (daughter nuclide) (alpha nuclide)

Example

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e + energy$$
$$(carbon)(nitrogen)(betaparticle)$$

In beta (β) decay, the parent nuclide has its proton number Z increased by I, but its mass number or nucleon number A remains unchanged.

3) Gamma (y) –decay

Example $^{A}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma + energy$

(parent nuclide) (daughter nuclide) (gama rays)

Example

$$^{60}_{27}CO \rightarrow {}^{60}_{27}CO + {}^{0}_{0}\gamma + energy$$
$$(cobalt)(cobalt)(gamma, rays)$$

Gamma rays are usually emitted at the same moment as either an alpha or beta particle, is emitted.

Q.5 Describe the nature and properties of radioactive radiations?

Answer

Nature of radiations

1) Alpha particle is a helium nucleus comprising of two protons and two neutrons with a charge of 26.

An unstable nucleus with large protons and neutrons may decay by emitting alpha radiations

2) Beta radiation is a stream of high energy electrons.

An unstable nucleus with excess of neutrons may eject beta radiations.

3) Gamma radiations are fast moving light photons.

They are electromagnetic radiations of very high frequency emitted by unstable excited nuclei.

Properties of radiations

I) Ionizing effect

The phenomenon by' which radiations split matter into positive and negative ions is called ionization All three kinds of radiations i.e. Alpha, beta and gamma can ionize the matter.

However alpha particles have the greatest power of ionizations compared to beta particles and gamma rays.

It is due to large positive charge and large mass of alpha particles. Beta particles ionize a gas much less than alpha particles do. The ionization power of gamma rays is even less than that of beta particles Ionization of three radiations in gas is shown in figure 18.5.

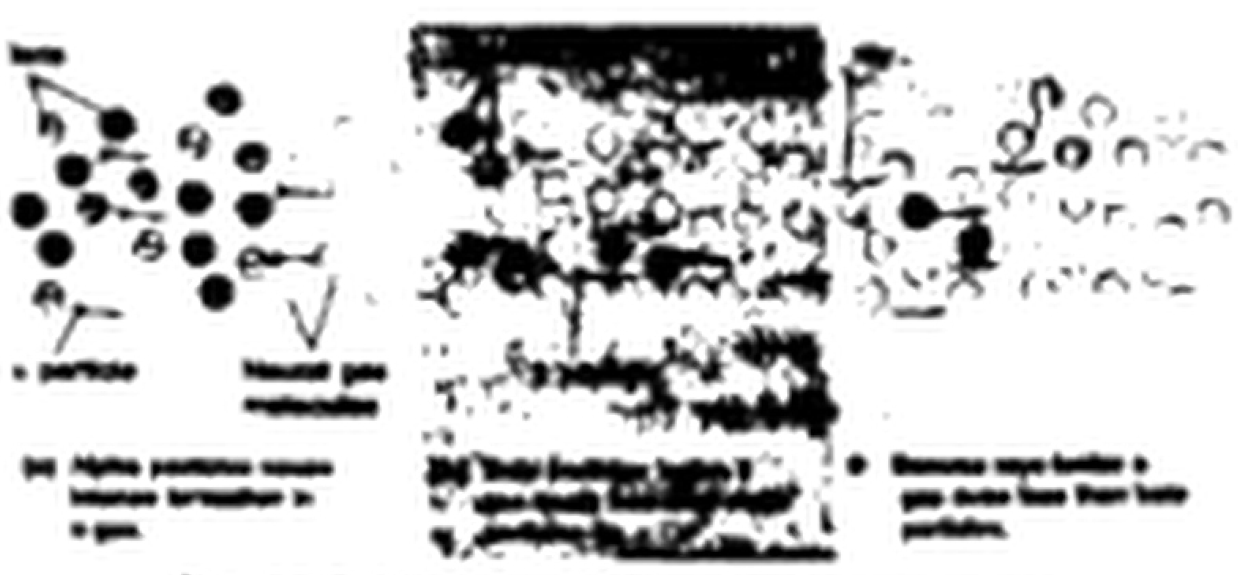


Fig 18.5 Ionization effect of radiations in gas

For your information

i) Nuclear radiation is measured in unit of roentgen equivalent mean (rem) i.e., unit of equivalent dose.

ii) Patient should be exposed to X-rays with the limit of 0.1 to 1.0 rem.

iii. Safe limit of radiation exposure is 5.0 rem per year.

Characteristics of Radiations

Alpha (α) Particles

Positively charged particles (helium nuclei) ejected at high speed with a range of only a few centimetres in air. They can be stopped by an ordinary sheet of thin aluminium foil.

Penetrating ability

The strength of radiations to penetrate a certain material is called penetrating power.

The alpha particles have the shortest range because of its strong interacting or ionizing power.

I) The gamma rays can penetrate a considerable thickness of wavelength. Their concrete. It is due to their large speed and neutral nature wavelengths and

2) The beta radiations strongly interact with matter due its energies charge and has short range as compared to gamma radiations.

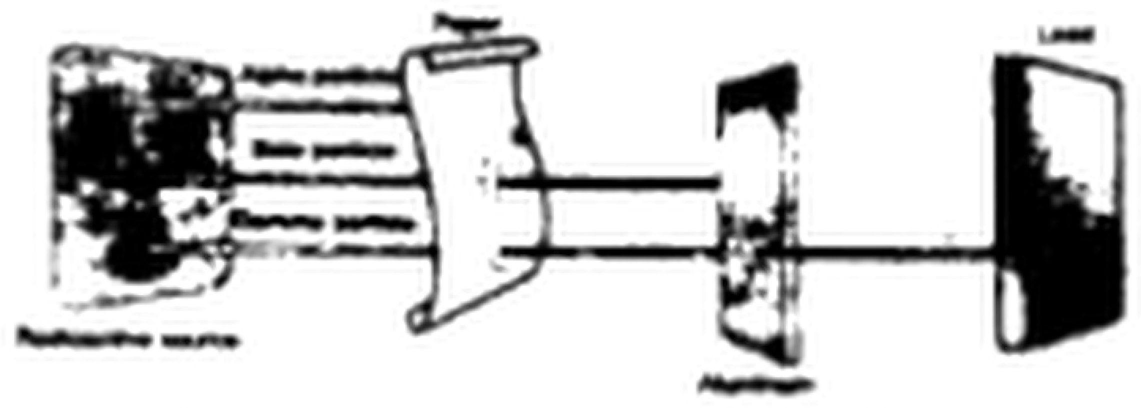


Fig. 18.6 Penetrating power of radiations in different materials

3) Alpha particle has range of only a few centimeters in air. Beta particles have range of several meters in air. However, gamma rays have a range of several hundred meters in air.

Q.6 What do you understand by half-Life of a radioactive element?

Answer

Half-life and its measurement

"The time during which half of the unstable radioactive nuclei disintegrate is called the half-life of the sample of radioactive element."

Remember		
Three types of Radiations		
Alpha Particle	**Beta Particle**	**Gamma Ray**
Charge + 2	Charge -1	No charge
Least penetration	Middle energy	Highest penetration
Tansmutes nucleus	Tansmutes nucleus	Change only energy

$A \longrightarrow A-4$ $Z \longrightarrow Z-2$ $N \longrightarrow N-2$	$A \longrightarrow A$ $Z \longrightarrow Z+1$ $N \longrightarrow N-2$	$A \longrightarrow A$ $Z \longrightarrow Z$ $N \longrightarrow N$

Measurement

Process of radio activity is random and the rate of radioactive decay is proportional to the number of unstable nuclei present.

In the process, a constant fraction of large number of unstable radioactive nuclei decays in a certain time. So, the life time of the unstable nuclei is unlimited and is difficult to measure. Every radioactive element has its own characteristic half—life.

Physics insight

Half-Life

Remaining atoms = original atoms × $\frac{1}{2}$

The amount of a radioactive isotope remaining in a sample equals the original amount times ½ to the power t, where t is the number of half-lives that have passed.

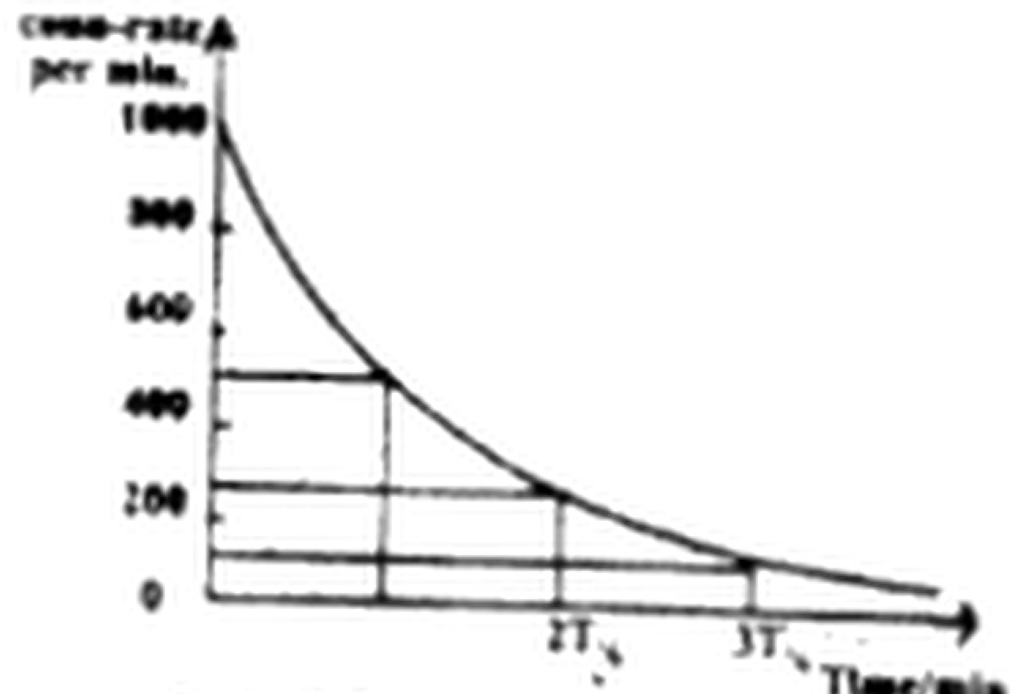


Fig. 18.8: Decay of unstable element

For example, radium -226 has a half-life of 1620 years, which means that half of a radium -226 sample will be converted to other elements by the end of 1620 years. In the next 1620 years, half of the remaining radium will decay, leaving only one-fourth the original amount of radium. If the half-life of the radioactive element is Tm.

Two half-Lives Don't Make a Whole Life!
A half-life is the time a radioactive element takes for half of a given number of nuclie to decay. During a second half-life, half of the remaining nuclei decay, so in two half-lives, three-quarters of the original material has decayed, to all of it.

Then at the end of this time the number of atoms in the sample will become half i.e. 1/2.

After a time 2 $T_{1/2}$ i.e. after second half life period, the number of remaining atoms will become 1/2, 1/2= $(1/2)^2$ =1/4, after a time $3T_{1/2}$, the number of remaining atoms will be 1/2, 1/2 , 1/2= $(1/2)^2$ = 1/8 and at the end of 't' half-lives number of atoms that remain will be $1/2^t$

$$N = N_o \times 1/2^t$$

It means that if No is the original number of atoms in the sample of radioactive element, then after 't' half-lives number of atoms left in the sample can be determined by using the relation,

The process of radioactivity does not depend upon the chemical combinations or reactions.

It is also not affected by any change in physical conditions like temperature, pressure, electric or magnetic fields.

Q.7 What are the radioisotopes?

Answer

Radioisotopes

"The stable and non-radioactive elements can also be changed into radioactive elements by bombarding them with protons, neutrons or alpha particles. Such artificially produced radioactive elements are called radioactive isotopes or radio isotopes.

Few examples of production of radio isotopes are given below;

$${}_{0}^{1}n + {}_{11}^{23}Na \rightarrow {}_{11}^{24}Na + gamma(\gamma) - rays$$

(neutron) (stable (a sodium radioisotope)

Sodium

Nuclide)

$${}_{2}^{4}He + {}_{13}^{27}Al \rightarrow {}_{15}^{30}P + {}_{0}^{1}n$$

(alpha (stable aluminum nuclide) (a phosphorous radioisotope)

Particle

Q.8 Describe two uses of radioisotopes in medicine, industry or research?

Answer

Uses of radioisotopes: 1: Traces

Radioactive tracers are chemical compounds containing some quantity of radioisotopes. They can be used to explore the metabolism of chemical reactions inside the human body, animals or plants.

Fig 18.9 To check the action of fertilizer researchers combine a small amount of radioactive material with the fertilizer and then apply the combination to a few plants. The amount radioactive fertilizer taken up by the plants can be easily measured with radiation detectors.

Radioisotopes are used as tracers in medicine, industry and agriculture. For example:

1) Radio iodine-131 readily accumulates in thyroid gland and can be used for of thyroid functioning.

2) For the diagnosis of brain tumor phosphorous —32 can be easily measured with is used. The malignant part of the body absorbs radium more quantity of isotopes, and this helps in tracing the affected part of the body.

3) In industry tracers can be used to locate the wear and tear of the moving parts of the machinery.

4) They can be used for the location of leaks in underground pipes. By introducing a suitable radioactive tracer into pipe, the leak can be conveniently traced from higher activity in the region of crack in the pipe.

5) In agriculture radio phosphorous —32 is used as tracer to find out how well the plants are absorbing the phosphate fertilizer which are crucial to their growth.

Radiation Treatment

Gamma radiations destroy both cancerous cells and healthy cells, therefore the beam of radiations must be directed only at cancerous cells.

For your Information

During brain radiotherapy patient is carefully positioned in the helmet to ensure that the gamma rays coverage at the desired point in the brain. A lead apron protects the body from exposure to radiation.

2) Medical treatment

Radioisotopes are also used in nuclear medicines for curing various diseases. For example, radioactivecobalt-60 is used 'for curing cancerous tumors and cells. The radiations kill the cell of the malignant tumor in the patient.

3) Carbon dating

Radioactive carbon — 14 is present in small amount in the atmosphere. Live plants use carbon-dioxide and therefore becomes slightly radioactive.

When a tree dies, the radio carbon —14 present inside the plant starts decaying. Since the half-life of carbon — 14 IS 5730 years, the age of a dead tree can be calculated by comparing the activity of carbon — 14 in the live and dead tree. The activity of the live tree remains almost constant as the carbon — 14 IS being replenished while the carbon-14 in the dead tree is no more replenished.

Also, some rocks contain the unusable potassium isotope K- 40.

This decays to the stable on nuclide Ar — 40 with half-life of 2.4 x 108 years. The age of rock sample can be estimated by comparing the concentrations of K—40 and Ar-40.

Q9. Write in detail about fission reaction.

Answer

Fission reaction

Nuclear fission takes place when a heavy nucleus, such as U — 235, splits, or fissions, into two smaller nuclei by absorbing a slow moving (low energy) neutron

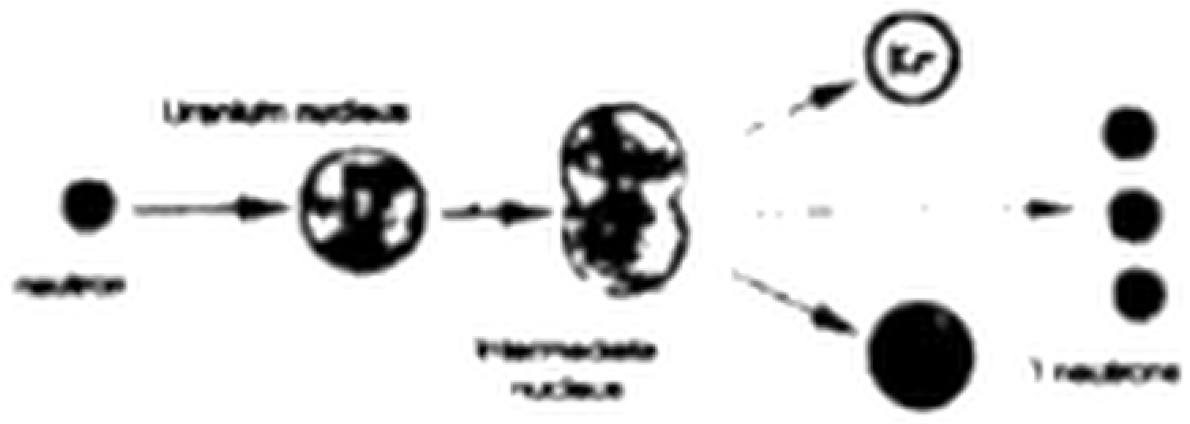


Fig. 18.11 Nuclear fission reaction

as represented by the equation.

${}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{92}^{236}U^{*} \rightarrow X + Y +$neutrons where U* —> 236 is an intermediate state that lasts only for a few seconds before splitting into nuclei X and Y, called "fission fragments." Nuclear fission was first observed in 1939 by Otto Hahn and Fritz.

Half-lives of selected isotopes			
Element	**Isotope**	**Half-Life**	**Radiation Produced**
Hydrogen	${}_{1}^{3}H$	12.3 years	β
Carbon	${}_{6}^{14}C$	5730 years	β
Cobalt	${}_{27}^{60}Co$	30 years	β, γ
Iodine	${}_{53}^{131}I$	8.07 years	β, γ
Lead	${}_{82}^{212}Pb$	10.6 years	β
Polonium	${}_{84}^{194}Po$	0.7 seconds	α
Polonium	${}_{84}^{210}Po$	138 days	α, γ
Uranium	${}_{92}^{235}U$	7.1×10^{8} years	α, γ
Uranium	${}_{92}^{238}U$	4.51×10^{9} years	α, γ
Plutonium	${}_{94}^{236}Pu$	2.85 years	α
Plutonium	${}_{91}^{242}Pu$	3.79×10^{5} years	α, γ

The Uranium nucleus was split into two nearly equal fragments after absorbing a slow moving (low energy) neutron.

The process also resulted in the production of typically two or three neutrons per fission event. On the average, 2.47 neutrons are released per event as represented by the expression;

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

Fig. 18.12 fission chain reaction in U - 235

In nuclear fission, the total mass of the' products is less than the original mass of the heavy- nucleus. Measurements showed that about 200 MeV of energy is released in each fission event.

This is a large amount of energy relative to the amount released in chemical processes.

For example, if we burn 1 tone of coal then about 36 x 10^{10} J of energy is released, but, during the fission of 1 kg of Uranium — 235 about 67 x 10^{10} J of energy is released.

We know that neutrons are emitted when U-235 undergoes fission. These neutrons can in turn trigger other nuclei to undergo fission with the possibility of a chain reaction.

Calculations Show that if the chain reaction is not controlled, it will proceed too rapidly and possibly result in the sudden release of an enormous amount of energy (an explosion).

This fission chain reaction is controlled in nuclear reactors.

Q10 What is nuclear fusion?

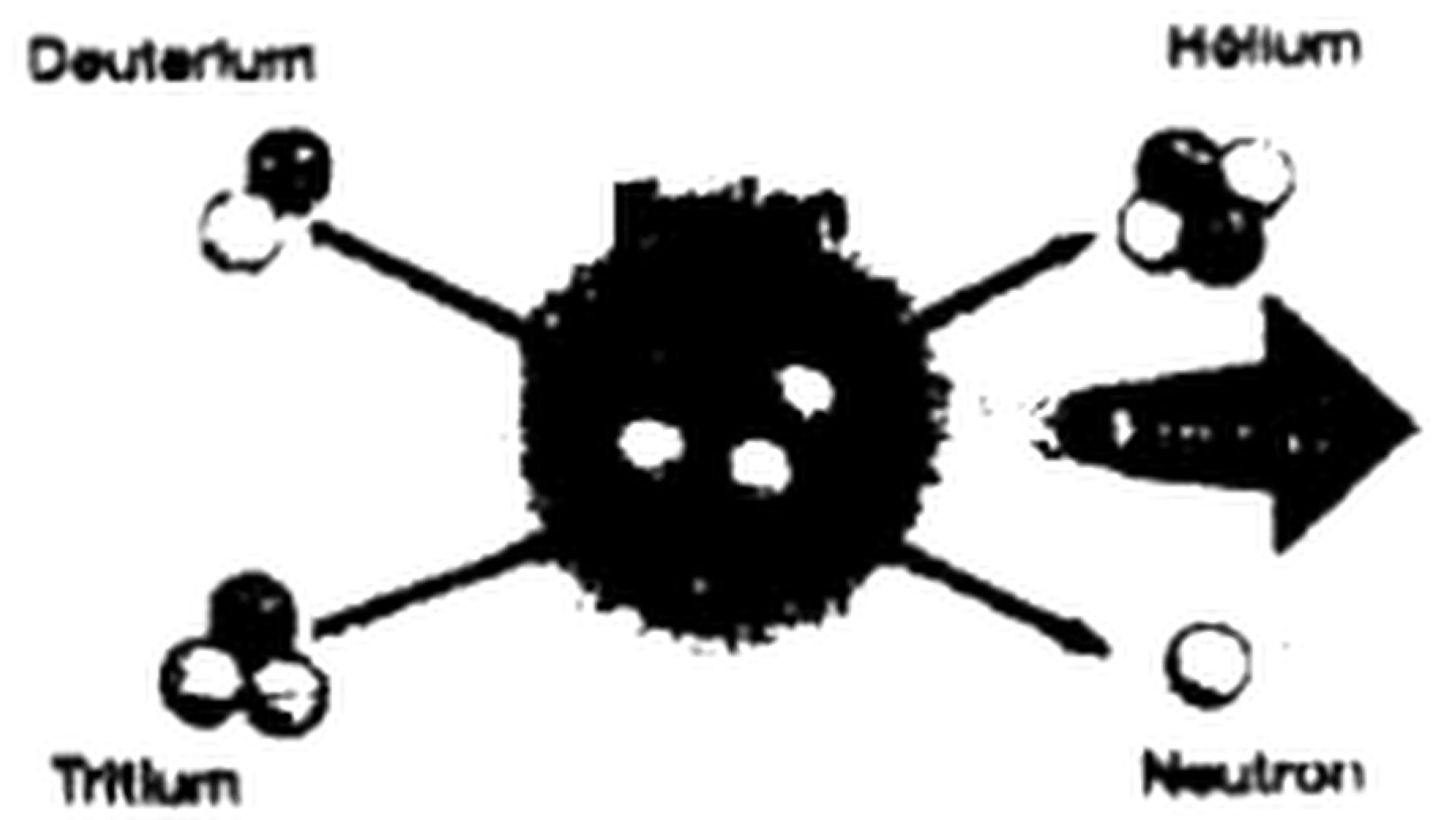
Answer

Nuclear fusion

"When two light nuclei combine to from a heavier nucleus, the process is called nuclear fusion."

The mass of the final nucleus is always less than the masses of the original nuclei.

According to mass energy relation this loss of mass converts into energy. If an atom of Deuterium is fused with an atom of Tritium, then a helium nucleus or alpha panicle is formed as given by:



$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He \rightarrow {}^{1}_{0}n + energy$$

Pictorially fusion reaction is shown in the figure.

Energy coming from the sun and stars is supposed to be the result of fusion of hydrogen nuclei into helium nucleus with release of energy.

The temperature at the centre of the sun is nearly 20 million Kelvin which makes the fusion favorable.

According to this reaction four hydrogen nuclei fuse together to form a helium nucleus along with two positrons, three alpha particles and 25.7 MeV of energy,

Q.11 What are the common radiation hazards? Briefly describe the precautions that are taken against them?

Answer

Radiation Hazards

1) Radiation burn, mainly due to beta and gamma radiations, which may cause redness and sores on the skin.

2) Sterility (i.e. inability to produce children).

3) Genetic mutations in both humans and plants. Some children are born with serious deformities.

4) Leukemia (cancer of the blood cells.

5) Blindness or formation of cataract in the eye.

Precautions

I) The sources should only be handled with tongs and forceps.

2) The user should use rubber gloves and hands should be washed carefully after the experiment.

3) All radioactive sources should be stored in thick lead containers.

4) Never point a radioactive source towards a person.

5) Frequent visits to the radiation sensitive areas should be avoided.