PHYSICS – 10

Chapter 20

ATOMIC AND NUCLEAR PHYSICS

Atomic physics deals with the study of the structure of atoms, their constituents (electrons, protons, and neutrons), and how they interact with light and energy. Nuclear physics, on the other hand, focuses on the nucleus of the atom, which contains protons and neutrons.

Key Concepts

- 1. Atomic structure
- 2. Atomic nucleus
- 3. Isotopes
- 4. Radioactivity
- 5. Radioactive Decay
- 6. Nuclear Reactions
- 7. Interconversion of matter and energy
- 8. Half-life
- 9. Effects and uses of nuclear radiation

Q.1 Describe the structure of an atom briefly.

Atomic Structure

- All matter is made up of tiny particles called atoms, was first suggested by Dalton.
- In 1897, J. J. Thomson proposed that atoms contain positively charged matter and negatively charged electrons.

Do You Know? — How much of an atom is empty space?

An atom is approximately 99.9999999% empty space. The nucleus, which contains most of the mass, is extremely small compared to the overall size of the atom. The electrons exist in a diffuse "cloud" around the nucleus, leaving vast empty regions.

Structure of an Atom

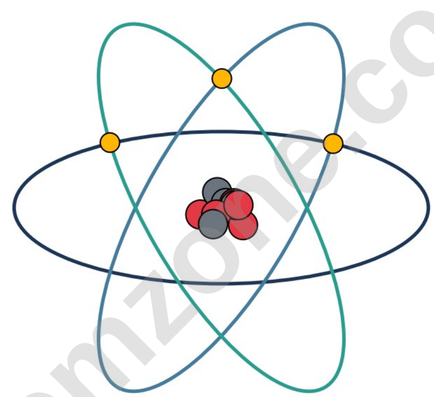

Fig 20.2: Diagram of an atom showing the nucleus, protons, neutrons, and electron orbits.

Q.2 Describe Rutherford's alpha particle scattering experiment briefly and discuss finding of the experiment.

Rutherford's Alpha Particle Scattering Experiment

- In the early 20th century, scientists were studying radioactivity, a process in which unstable atoms release radiation.
- One type of radiation they discovered was alpha (α) particles. These particles were positively charged and have a small mass, similar to atoms like helium. They moved with high velocities.
- In 1911, Rutherford, along with Hans Geiger and Ernest Marsden, conducted another experiment using a thin sheet of gold foil.
- They directed a beam of alpha particles at the foil and noticed that most particles passed through without any deflection, suggesting that the atom is mostly empty space. Some particles were slightly deflected, indicating the presence of a small, positively charged region.

- A few particles bounced back at large angles, meaning that all the positive charge and most of the mass of atoms was concentrated in a tiny central part called nucleus.

Findings of Rutherford's Experiment

- (i) Atoms have a small, dense, and positively charged core called the nucleus.
- (ii) The nucleus contains most of the mass of atoms at large distances, and the atom is mostly empty space.
- (iii) The nucleus is extremely small, about 10,000 times smaller than the entire atom.

Draw Backs / Disadvantages

- Later studies revealed that electrons do not follow fixed orbits like planets around the Sun.
- Instead, they exist in regions called electron clouds, where their exact position cannot be known.
- This "fuzzy cloud" represents the probability of finding an electron in a certain area around the nucleus.
- The cloud is denser where the electron is more likely to be and thinner where it is less likely.
- This model reflects the quantum nature of electrons where they behave as both particles and waves, and their motion is uncertain.

Q.3 Define: 1. Atomic nucleus 2. Charge number 3. Mass number 4. Nuclide

1. Atomic Nucleus

- Atomic nucleus is the central part of an atom which holds most of its mass.
- It is made up of protons and neutrons, which together known as nucleons.
- Protons and neutrons are held together by the strong nuclear force.
- The size of the nucleus is very small in comparison to the entire size of the atom.

2. Charge Number or Atomic Number

Definition: The total number of protons in the nucleus of an atom is called its atomic number or charge number.

- It is represented by Z.
- It also determines the position of an element in the periodic table and its chemical properties.

Tidbit: Electrons are nearly 1,836 times lighter than protons, yet they move extremely fast — almost at the speed of light in their orbits.

3. Mass Number

Definition: The mass number is the total count of protons and neutrons in an atom's nucleus.

$$A = Z + N$$

- It is represented by A.
- Since electrons have very little mass, they are not included in the mass number.
- Scientists use the mass number to understand an atom's size, stability, and structure.

4. Nuclide

A nuclide is represented by ^{A}ZX , where X is its chemical symbol, the superscript is mass number A and subscript is charge number Z. (OR) The representation of a nucleus in terms of expressing charge number and mass number with symbol of a nucleus is called a nuclide.

Brain Teaser — If protons repel each other, how can so many of them stay packed in a tiny nucleus without flying apart?

Protons are positively charged and repel each other electrically. However, an even stronger attractive force called the strong nuclear force acts between nucleons (protons and neutrons) at very short ranges inside the nucleus. This force overcomes the electrostatic repulsion and holds the nucleus together.

Q.4 Define isotope of an element. Give examples.

Isotopes

Definition: Isotopes are atoms of an element that have the same number of protons but different numbers of neutrons.

1. Explanation

- Atoms are electrically neutral, meaning they have equal number of protons and electrons.
- If an atom gains or loses electrons, it becomes an ion and carries an electric charge.
- The number of protons and electrons determines an atom's chemical properties, while the number of neutrons affects its nuclear properties, like stability and radioactivity.

2. Examples

A common example of isotopes is hydrogen, which has three types:

Isotope	Symbol	Protons	Neutrons	Electrons
Protium	${}_{1}^{1}H$	1	0	1
Deuterium	${}_{1}^{2}H$	1	1	1
Tritium	${}_{1}^{3}H$	1	2	1

- Even though these hydrogen isotopes have different masses, they still behave chemically in the same way.
- Similarly, carbon has three isotopes ${}^{12}C$, ${}^{13}C$, ${}^{14}C$ containing 6, 7 and 8 neutrons, respectively.

Q.5 Define and explain radioactivity.

Radioactivity

Definition: Radioactivity is the process in which unstable atoms release energy to become stable. This energy is given off as radiation, which can be in the form of particles or waves.

- Some elements are naturally radioactive, while others can be made radioactive in laboratories.
- Henri Becquerel discovered radioactivity in 1896, and later, Marie Curie and Ernest Rutherford studied it further.
- Atoms have a nucleus made of protons and neutrons, surrounded by electrons.
- Some nuclei become unstable due to an imbalance of protons and neutrons or excess energy inside.
- To become stable, the nucleus breaks down and gives off radiation in a process called radioactive decay. This happens naturally and cannot be controlled. It is spontaneous and random.
- While we cannot predict when a single atom will decay, in a large group of atoms, the decay follows a pattern.

Do You Know? — Who was Marie Sklodowska-Curie and what did she discover?

Marie Sklodowska-Curie was a French physicist and chemist. She was the first woman to receive a Nobel Prize and the only woman to receive two Nobel Prizes. While studying radiation from uranium, she discovered the new radioactive elements polonium and radium.

Emission of α, β and γ Radiations

Radioactive decay releases three types of radiation: Alpha (α), Beta (β), and Gamma (γ) radiation, each with different properties.

1. Alpha particles (α)

Alpha particles (α) are helium nuclei, consisting of 2 protons and 2 neutrons. They carry a +2e charge ($e = 1.6 \times 10^{-19}$ C), and are relatively large [4 atomic mass units - amu (u)].

2. Beta particles (β)

- Due to their size, alpha particles have low penetration power and can be stopped by a sheet of paper or a few centimetres of air.
- They have high ionizing power, meaning they strongly affect other atoms they come in contact with.
- Beta particles (β) are high-energy electrons ${}^{0}_{-1}e$ or positrons ${}^{0}_{+1}e$ emitted from the nucleus.

Tidbit: Alpha particles are the heaviest and slowest of the three common radiation types. They cannot penetrate a sheet of paper but can cause severe damage if inhaled or ingested.

3. Gamma radiation (γ)

- Gamma radiation (γ) consists of high energy electromagnetic waves (photons), making them massless and neutral (0 charge).
- Gamma rays are emitted out due to de-excitation of nucleus.
- Their ionizing power is moderate, meaning they cause less ionization than alpha particles but more than beta particles.
- Beta radiation has moderate penetration power. It can pass through paper but is stopped by a few millimetres of aluminium.
- Beta particles carry a −1e or +1e charge, meaning they cause ionization by a few millimetres of aluminium.
- Gamma rays have very high penetration power, allowing them to pass through thick materials like lead or concrete.

Ionizing Effects and Penetrating Powers

1. Ionizing Effects

Ionization is the ability of radiation to ionize atoms depends on its energy and charge, turning them into ions.

- a. Alpha (α) particles: Strongest ionizing power due to their large size and charge.
- b. Beta (β) particles: Moderate ionizing power, as they are smaller and faster than alpha particles.
- c. Gamma (γ) rays: Weakest ionizing power, as they have no charge and no mass.

Do You Know? — What are gamma rays and how can they be shielded?

Gamma rays are high-energy electromagnetic waves (photons) with no mass or charge. They have the highest penetrating power among common radiation types. To shield against them, very dense materials like thick lead or concrete are required.

2. Penetrating Powers

- Penetration power refers to how far radiation can travel through materials before being absorbed.
- a. Alpha (α) particles: Lowest penetration – stopped by paper or a few centimetres of air.
- b. Beta (β) particles: Moderate penetration – can pass through paper but stopped by a few millimetres of aluminium.
- c. Gamma (γ) rays: Highest penetration – can pass through paper, aluminium, and even thick lead or concrete.

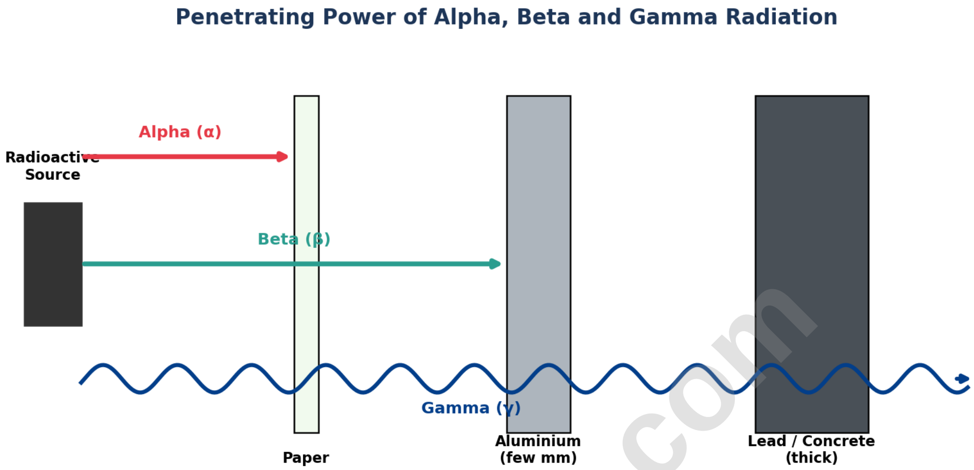

Fig 20.7: Penetrating power of alpha, beta and gamma radiation

Table 20.1: Comparison of Alpha, Beta, and Gamma Radiation

Property	Alpha Particles (α)	Beta Particles (β)	Gamma Rays (γ)
Composition	Helium nuclei ($^{4}{}_{2}He$)	Electrons $^{0}{}_{-1}e$ or positrons	Electromagnetic waves (photons)
Charge	+2e	−1e or +1e	0
Mass	4 atomic mass units	Very small	0
Ionizing power	High	Moderate	Low
Penetrating power	Low	Moderate	High
Deflection in fields	Slight in electric and magnetic fields	Significant in electric and magnetic fields	No deflection

Q.6 What is a radioactive decay? Explain the decay of α, β and γ decay with related equations.

Radioactive Decay

Definition: Radioactive decay is the process in which unstable atoms release radiation to become stable.

- This radiation can be in the form of particles (alpha and beta) or waves (gamma rays).
- Some atoms have too many or too few neutrons in their nucleus, making them unstable.
- To become stable, they release energy in the form of radiation.
- This process demonstrates a transformation of a parent isotope into a daughter isotope, through the emission of radiations.

1. Alpha (α) Decay Equation

In alpha decay, an unstable nucleus emits an alpha particle ($^{4}_{2}He$), reducing its atomic number by 2 and mass number by 4.

General Equation: $^{A}{}_{Z}X \rightarrow {}^{A-4}{}_{Z-2}Y + {}^{4}_{2}He$ .... (20.1)

Example (Decay of Uranium-238): $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He + Energy$

2. Beta (β) Decay Equations

In beta decay, a neutron converts into a proton and emits a beta particle (electron or positron).

General equation: $^{A}{}_{Z}X \rightarrow {}^{A}{}_{Z+1}Y + \beta^{-} + Energy$ ... (20.2)

Example (Decay of Carbon-14): $^{14}_{6}C \rightarrow {}^{14}_{7}N + \beta^{-} + Energy$

3. Gamma (γ) Decay Equation

In gamma decay, the nucleus releases excess energy as a gamma ray (γ) without changing the number of protons or neutrons.

General equation: $^{A}{}_{Z}X^{*} \rightarrow {}^{A}{}_{Z}X + \gamma$ .... (20.3)

Example (Decay of Cobalt-60): $^{60}_{27}Co^{*} \rightarrow {}^{60}_{27}Co + \gamma$

These equations represent the fundamental processes of radioactive decay, helping us to understand how unstable atoms transform into stable ones.

Q.7 Define nuclear reaction. Name its types. Define and explain nuclear fission.

Nuclear Reactions

Definition: Nuclear reactions involve changes in the nucleus of an atom, leading to the transformation of elements and the release or absorption of energy. These reactions are different from chemical reactions, which only involve electrons.

1. Types

- (i) Fission Reaction
- (ii) Fusion Reaction

2. Fission Reaction

Definition: In fission reaction, a heavy nucleus (like Uranium-235) splits into two smaller nuclei when bombarded by a neutron. This process releases a large amount of energy and additional neutrons, which can cause a chain reaction.

Explanation

- The fission reaction is the foundation of both nuclear power generation and atomic weapons.
- In fission, a tiny fraction of mass transforms into an enormous amount of energy.
- Nuclear fission was first discovered in 1939 by Otto Hahn and Fritz Strassman. They observed that a uranium nucleus splits into two nearly equal fragments after absorbing a slow-moving neutron.
- This process also releases extra neutrons, typically two or three per fission event, with an average of 2.5 neutrons per reaction.
- This chain reaction plays an important role in nuclear power generation and atomic bombs.

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U^{*} \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + Energy \quad \text{...........} \ (20.4) $$

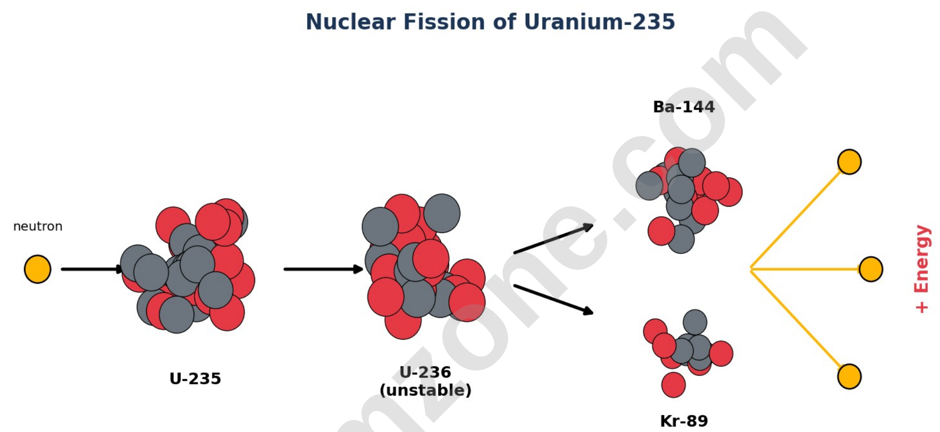

Fig 20.11: Nuclear fission reaction

- In nuclear fission reaction, the total mass of the products is slightly less than the original heavy nucleus.
- This lost mass is converted into energy, releasing about 200 MeV (1 eV = 1.6×10^{-19} J) per fission event, which is far greater than energy from chemical reactions.
- For instance, burning 1 ton of coal releases 3.6×10^{9} J, while fission of 1 kg of U-235 produces around 6.7×10^{13} J.
- During fission, released neutrons can trigger further reactions, leading to a chain reaction. If uncontrolled, this can cause a rapid energy release, resulting in an explosion.
- However, in nuclear reactors, this reaction is carefully controlled by absorbing extra neutrons, allowing the energy to be used safely for power generation.

Do You Know? — What is the difference between nuclear fusion and fission?

- Nuclear fusion is the process where two or more light nuclei (like hydrogen) combine to form a heavier nucleus, releasing energy.
- Nuclear fission is the process where a heavy nucleus (like uranium) splits into two or more smaller nuclei, also releasing energy.
- Fusion powers the sun, while fission is used in nuclear power plants.

Q.8 Define and explain nuclear fusion.

Nuclear Fusion

Definition: Nuclear fusion is a process where two or more light nuclei (like hydrogen isotopes) combine to form a heavier nucleus, releasing huge amount of energy.

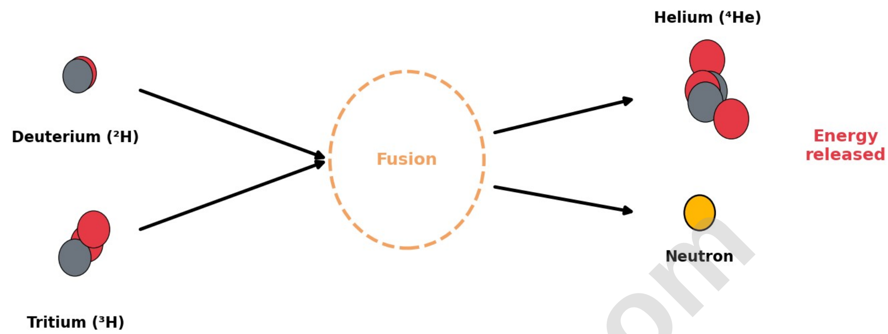

Fig 20.12: Nuclear fusion reaction

1. Explanation

- This occurs at extremely high temperatures and speeds, where some mass is converted into energy.
- The final nucleus is always lighter than the total mass of the original nuclei, and the lost mass turns into energy.

2. Example

For example, when deuterium and tritium fuse, they form helium (alpha particle) and release energy.

$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + energy \;\; .... (20.5) $$

3. Applications

The Sun and stars shine because of fusion reactions, where four hydrogen nuclei fuse into one helium nucleus, releasing about 25.7 MeV of energy. The Sun's core, at nearly 20 million kelvin, provides the perfect conditions for fusion to occur.

Q.9 Explain Einstein's mass energy equation.

Interconversion of Matter and Energy

Definition: Matter and energy can be converted into each other, a concept explained by Einstein's equation ($E = mc^2$).

- This means that a small amount of mass can turn into a huge amount of energy, as seen in nuclear fission and fusion, which power nuclear reactors and the Sun.
- Similarly, energy can also transform into matter under extreme conditions, such as in particle accelerators, where high-energy photons create particle-antiparticle pairs (pair production).
- This process follows the law of conservation of energy, which states that total energy, including mass-energy, remains constant in an isolated system.

- The ability to convert matter into energy and vice versa is key to understanding the universe, stars, and atomic particles.
- Theoretically a single gram of matter can be converted into enough energy to power a city for days.

Einstein's Equation and Energy Calculation

- Einstein's equation $E = mc^2$ helps calculate the energy released in nuclear reactions like fission and fusion. It states that a small amount of mass (m) converts into a large amount of energy (E), where: E = Energy (joules or MeV), m = Mass, c = Speed of light ($3 \times 10^8\ ms^{-1}$).
- In nuclear reactions, the total mass of the products is slightly less than the mass of the reactants. This lost mass is called mass defect (Δm). Using $E = mc^2$, we can find the energy released.

$$\text{If } \Delta m = 1 \times 10^{-4}\ kg, \text{ then } E = mc^2 = (1\times10^{-4}\ kg) \times (3\times10^8\ ms^{-1})^2\ ;\ \ E = 9 \times 10^{12}\ J$$

Tidbit: Nuclear power plants use fission, where heavy nuclei like uranium split into smaller parts, releasing energy. Fusion is safer and cleaner, but hard to control.

Uniform Mass Scale (u)

The term uniform mass scale (u) refers to atomic mass unit (u) being used as a standardized unit to measure the mass of atoms and molecules.

$$1u = 1/12 \text{ the mass of carbon-12 atom} \approx 1.66605 \times 10^{-27}\ kg$$

Q.10 Define and explain term half-life of a radioactive element.

Half-Life of Radioactive Isotopes

Definition: The half-life of a radioactive isotope is the time it takes for half of its atoms to decay into a more stable form. Each isotope has a unique half-life that never changes, no matter how much of the substance is present or whatever may be the surrounding conditions.

1. Example

For example, carbon-14, used in radiocarbon dating, has a half-life of 5,730 years, while U-238 takes 4.5 billion years to decay by half. Radioactive decay follows an exponential pattern, meaning that after each half-life, only half of the remaining material is left.

2. Explanation

- The activity of a radioactive material is the rate at which its atoms decay, releasing radiation in the form of alpha, beta, or gamma particles.
- It tells us how many atoms break down in a given period and is measured in Becquerels (Bq).
- 1 Bq = 1 decay per second, or in Curies (Ci), where 1 Ci = 3.7×10^{10} decays per second.
- The activity of a substance depends on the number of radioactive atoms present and the decay constant (λ), which is linked to its half-life.
- A material with a shorter half-life decays faster and has higher activity, while one with a longer half-life decays slower and has lower activity.
- Scientists measure radioactivity using tools like Geiger counters and scintillation detectors, which help in monitoring radiation levels, ensuring safety, and studying radioactive decay in fields like medicine, archaeology, and nuclear physics.
- This concept helps scientists predict how long a radioactive substance remains active and is essential for its use in nuclear power, medical treatments, and radiocarbon dating.

Table 20.2: Half-life of Isotopes

Isotope	Symbol	Half-life	Applications
Carbon-14	^{14}C	5,730 years	Radiocarbon dating of ancient artifacts and fossils.
Uranium-238	^{238}U	4.5 billion years	Dating rocks and Earth's age; used in nuclear reactors.
Potassium-40	^{40}K	1.25 billion years	Dating rocks and geological formations.
Thorium-232	^{232}Th	14 billion years	Used in nuclear reactors and dating.
Radon-222	^{222}Rn	3.8 days	Indoor air quality monitoring; health hazard.
Iodine-131	^{131}I	8 days	Medical treatment for thyroid cancer and imaging.
Cobalt-60	^{60}Co	5.27 days	Cancer treatment (radiotherapy) and industrial radiography.

Isotope	Symbol	Half-life	Applications
Tritium (Hydrogen-3)	^{3}H	12.3 years	Used in luminous paints and as a tracer in biological studies.
Polonium-210	^{210}Po	138 days	Used in static eliminators and as a heat source in space probes.
Strontium-90	^{90}Sr	28.8 years	Used in medical treatment and as a radioactive tracer.

Brain Teaser — What happens when a uranium nucleus splits during nuclear fission? Does it just break into two pieces, or is something else released?

When a uranium-235 nucleus splits during fission, it does not just break into two smaller nuclei (called fragments). The process also releases additional neutrons and a large amount of energy. These released neutrons can go on to trigger fission in other uranium nuclei, leading to a chain reaction.

3. Mathematical Expression

- The amount of radioactive isotope in the given sample decreases with time.
- The number of nuclei present at time t = 0 is N = No and number present at time t = T½ is N = No/2. The number present at time t = 2T½ is N = No/4 and so on.

$$\text{After 1 half-life: } N_1 = \tfrac{1}{2}\, No$$

$$\text{After 2 half-lives: } N_2 = \tfrac{1}{2} \times \tfrac{1}{2}\, No = (\tfrac{1}{2})^2\, No$$

$$\text{After 3 half-lives: } N_3 = (\tfrac{1}{2})^3\, No$$

$$\text{After 4 half-lives: } N_4 = (\tfrac{1}{2})^4\, No$$

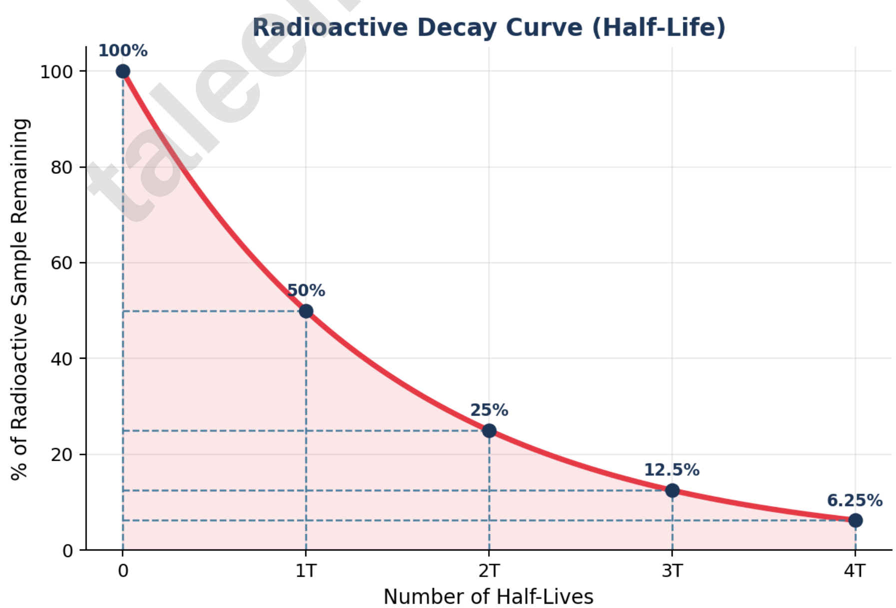

Fig 20.14: Conversion of ^{99}Tc to ^{99}Ru by beta decay — radioactive decay curve

Number of half-lives (n) can be found by the following relation:

$$\text{Number of half-lives} = \text{Total time passed} / \text{Half-life}, \quad \text{i.e.} \quad n = \Delta t / T_{1/2}$$

4. Importance

- The concept of half-life is important in many fields, including archaeology (dating ancient artifacts), medicine (using radioactive isotopes for diagnosis and treatment), and nuclear energy (handling radioactive waste).
- By knowing the half-life of a substance, scientists can predict how long it will stay radioactive and how fast it will decay.

Q.11 Explain carbon dating for determination of age of ancient objects.

Carbon Dating

Definition: Carbon dating is a scientific method used to determine the age of ancient organic materials like wood, bones, and shells.

- This technique is based on the radioactive decay of carbon-14, a type of carbon found in the atmosphere.
- Living organisms constantly absorb carbon-14 while they are alive, maintaining a steady balance with carbon-12.
- However, when an organism dies, it stops absorbing carbon, and the carbon-14 starts to decay at a fixed rate, with a half-life of about 5,730 years.
- By measuring the remaining carbon-14 in a sample and comparing it to its original amount, scientists can estimate how long ago the organism died.
- Carbon dating is an essential tool in archaeology, geology, and anthropology, helping researchers determine the age of artifacts, fossils, and ancient remains, giving important insights into human history and environmental changes.

Fun Fact: Carbon-14 is constantly being created in Earth's atmosphere!

Brain Teaser — If two fossils found in the same layer of rock have nearly the same amount of carbon-14 left, but one belongs to a fast-living animal and the other to a slow-living one, which one is older or are they the same age?

They would be approximately the same age. Carbon-14 dating measures the time since the organism died, based on the fixed decay rate of carbon-14. The metabolism or lifespan of the organism does not affect this radioactive clock, which starts ticking the moment it stops absorbing carbon from the atmosphere.

Q.12 Explain the effects and uses of nuclear radiations.

Nuclear Radiations

1. Effects and Uses of Nuclear Radiation

- Ionizing radiation (such as alpha, beta, and gamma rays) can affect living organisms because it can alter or damage atoms and molecules, including DNA.
- The impact of radiation depends on the dose, exposure time, and type of radiation.

2. Effects of Nuclear Radiation

- (i) High doses can kill cells by damaging their DNA, which is why radiation is used in cancer treatment (radiotherapy) to destroy cancer cells.
- (ii) Radiation can cause DNA mutations, breaking chemical bonds and altering genetic codes, which may lead to genetic disorders or hereditary diseases if reproductive cells are affected.

- (iii) Long-term exposure to low doses increases the risk of cancer by mutating normal body cells. For example, too much UV radiation from the Sun can lead to skin cancer.
- (iv) Severe exposure over a short time can cause radiation sickness, leading to nausea, vomiting, organ failure, and even death in extreme cases.

Do You Know? — How are gamma rays used in cancer treatment?

- High-energy gamma rays are used in radiotherapy to target and destroy cancer cells.
- The precision of the radiation beam is key to damaging the DNA of cancer cells while minimizing harm to the surrounding healthy tissues.

3. Uses of Nuclear Radiation

The selection of a radioactive isotope depends on its type of radiation and half-life:

- (i) Medical Uses: Short-lived isotopes are used in radiotherapy and imaging to minimize long-term radiation risks.
- (ii) Industrial Uses: Isotopes with long half-lives are used in power generation, radiation detectors, and material testing, where long-term stability is important.
- (iii) Cobalt-60 and Cesium-137 in Food Preservation: Gamma rays from these isotopes kill bacteria in food, increasing shelf life without affecting quality. Cobalt-60, with a moderate half-life (5.27 years), is commonly used in the food industry.
- (iv) Cobalt-60 in Sterilization: Gamma radiation is used to sterilize medical equipment, killing bacteria and viruses without damaging the materials.

4. Radiation Source

- (i) Americium-241 (^{241}Am) in Smoke Detectors — Used in fire alarms, where alpha particles ionize air molecules, creating an electric current. When smoke enters, the current is disrupted, triggering the alarm. Its long half-life (432 years) makes it ideal for long-term use.
- (ii) Cobalt-60 and Iodine-131 in Medicine — Gamma rays from Cobalt-60 are used in radiotherapy to destroy cancer cells. Iodine-131, with a short half-life (8 days), is used in thyroid diagnosis and treatment to minimize long-term radiation risk.

Do You Know? — What are some natural sources of radiation exposure in daily life?

Even without human-made sources, we are constantly exposed to low levels of natural background radiation. This comes from cosmic rays from space, radioactive materials in rocks and soil (like radon), and even from foods such as bananas, which contain a small amount of radioactive potassium-40.

Formula Sheet

#	Formula	Description
1	Z = number of protons	Atomic number
2	A = number of protons + number of neutrons (A = Z + N)	Atomic mass (mass number)
3	$E = mc^2$	Einstein's mass energy equation
4	$n = \Delta t / T_{1/2}$	Number of half-lives
5	$N / N_o = 1 / 2^n$	Fraction of sample remaining

Solved Examples

Example 20.1: Find the number of protons and neutrons in the nuclide defined by $^{15}_{7}X$.

Solution: From the symbol, we have atomic number (Z) = number of protons = 7, mass number (A) = number of protons + number of neutrons = 15.

But number of protons are 7, so number of neutrons will be 8. So, the element is an isotope of nitrogen-7, and is written as $^{15}_{7}N$.

Example 20.2: Find the atomic mass and atomic number of the nuclei that come after alpha decay of Uranium (U-238).

Solution: Alpha decay nuclear reaction is given by: $^{A}ZX \rightarrow {}^{A-4}Z_{-2}Y + \alpha$

For Uranium-238, the nuclear reaction will become: $^{238}_{92}U \rightarrow {}^{238-4}_{92-2}Y + {}^{4}_{2}He(\alpha)$ or $^{238}_{92}U \rightarrow {}^{234}_{90}Y + {}^{4}_{2}He(\alpha)$

So, atomic number of the required nucleus is 90 and mass number is 234. Every element has a unique atomic number. From periodic table, the new element is to be Thorium (Th) with Z = 90.

The finalized nuclear reaction can now be written as: $^{238}_{92}U \rightarrow {}^{234}_{90}Y + {}^{4}_{2}He(\alpha)$

Example 20.3: Find the mass defect (Δm) and energy released in the following nuclear fission reaction: $^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n$ + Energy

Solution: Consider the fission of uranium-235, where:

- Mass of ($^{235}_{92}U$) = 235.0439 u
- Mass of neutron ($^{1}_{0}n$) = 1.0087 u
- Mass of ($^{141}_{56}Ba$) = 140.9144 u
- Mass of ($^{92}_{36}Kr$) = 91.9262 u
- Mass of 3 neutrons = 3 × 1.0087 = 3.0261 u

Mass defect: Δm = (Mass of reactants) − (Mass of products)

$$\Delta m = (235.0439 + 1.0087) - (140.9144 + 91.9262 + 3.0261) = 236.0526 - 235.8667 = 0.1859\ u$$

Energy released:

$$E = \Delta m \times 931.5\ MeV/u = 0.1859 \times 931.5 = 173.2\ MeV$$

Example 20.4: We have a 50 mg sample of lead-212. It decays by beta and gamma emission with a half-life of 10.6 hours. How much of the pure sample is left after 53 hours?

Solution — Given: Initial quantity of pure lead-212 $N_o = 50$ mg; Half-life of lead-212 = $T_{½} = 10.6$ h; Total elapsed time t = 53 hours. To find: Quantity left N = ?

$$n = \Delta t / T_{½} = 53h / 10.6h = 5$$

Original sample remaining after n number of half-lives:

$$N = (½)^n N_o = (½)^5 \times 50\ mg = (1/32) \times 50\ mg$$

Result: N = 1.56 mg of lead-212 will be present after 53 hours (5 half-lives).

Multiple Choice Questions Exercise

#	Question	Options
1	What did Rutherford's alpha particle scattering experiment reveal about the structure of the atom?	(a) Electrons are distributed evenly throughout the atom (b) Protons and electrons are located in the nucleus (c) Atoms are indivisible and indestructible (d) The nucleus is small, dense, and positively charged
2	The atomic number of an element represents:	(a) number of neutrons in the nucleus (b) number of protons in the nucleus (c) total number of protons and neutrons (d) number of electrons and neutrons
3	Which type of radiation is positively charged and consists of two protons and two neutrons?	(a) Alpha (α) (b) Beta (β) (c) Gamma (γ) (d) Neutron emission
4	The process by which an unstable nucleus emits radiation and transforms into a more stable nucleus is called:	(a) nuclear fusion (b) nuclear fission (c) radioactive decay (d) isotopic exchange
5	Nuclear fission involves:	(a) combining light nuclei to form heavier ones (b) splitting heavy atomic nuclei into smaller ones (c) absorbing gamma radiation to increase stability (d) none of the above
6	What does Einstein's equation, $E = mc^2$, explain?	(a) The energy released in chemical reactions (b) The equivalence of mass and energy (c) The rate of radioactive decay (d) The conversion of mass into momentum
7	Which of the following is a practical application of nuclear radiations?	(a) Cooking food in microwave ovens (b) Medical imaging and cancer treatments (c) Solar energy generation (d) Airplane navigation systems
8	What are the potential effects of ionizing nuclear radiation on biological tissues?	(a) Increased cellular regeneration (b) DNA damage and cancer (c) Enhanced immune system response (d) Improved metabolic activity

Answer Key: 1-d, 2-b, 3-a, 4-c, 5-b, 6-b, 7-b, 8-b

SLO Based Additional MCQs + Past Papers MCQs of Punjab Boards

#	Question	Options
1	What was the primary conclusion drawn from the fact that most alpha particles passed straight through the	(a) Atoms are solid spheres (b) The atom is mostly empty space (c) Electrons orbit in fixed paths (d) The nucleus is negatively

#	Question	Options
	gold foil in Rutherford's experiment?	charged
2	According to the quantum model, what does the "fuzzy cloud" around the nucleus represent?	(a) The exact path of an electron (b) The probability of finding an electron (c) A shell of fixed energy (d) The strong nuclear force
3	In the nuclide notation $^{23}_{11}Na$ what does the number 23 represent?	(a) Atomic number (b) Number of protons (c) Mass number (d) Number of electrons
4	An atom has 12 protons and 13 neutrons. What is its mass number (A)?	(a) 12 (b) 13 (c) 24 (d) 25
5	Isotopes of an element have the same number of ___ but different numbers of ___:	(a) protons, neutrons (b) neutrons, protons (c) electrons, protons (d) protons, electrons
6	Which of the following are isotopes of carbon?	(a) $^{23}_{11}C$ and $^{14}_{7}N$ (b) $^{12}_{6}C$ and $^{13}_{6}C$ (c) $^{14}_{7}N$ and $^{16}_{8}O$ (d) $^{1}_{1}H$ and $^{2}_{1}H$
7	Which type of radiation consists of high-energy electromagnetic waves with no mass or charge?	(a) Alpha (α) (b) Beta (β) (c) Gamma (γ) (d) Neutron (n)
8	Which type of radiation has the highest ionizing power but the lowest penetrating power?	(a) Alpha (α) (b) Beta (β) (c) Gamma (γ) (d) X-rays
9	A radioactive source is placed in an electric field. Which type of radiation would be deflected the most towards the positive plate?	(a) Alpha (α) (b) Beta (β) (c) Gamma (γ) (d) All equally
10	In alpha decay, what happens to the atomic number (Z) of the parent nucleus?	(a) Increases by 2 (b) Decreases by 2 (c) Increases by 1 (d) Remains unchanged
11	What is emitted from the nucleus during beta-minus (β^-) decay?	(a) A helium nucleus (b) A high-energy electron (c) A high-energy photon (d) A proton
12	Which process involves the splitting of a heavy nucleus into two lighter ones, releasing neutrons and energy?	(a) Nuclear Fusion (b) Nuclear Fission (c) Radioactive Decay (d) Gamma Emission
13	What is the primary energy source of the Sun?	(a) Nuclear Fission of uranium (b) Nuclear Fusion of hydrogen (c) Chemical burning of gases (d) Radioactive decay of carbon
14	Einstein's famous equation $E = mc^2$ explains that:	(a) Mass and energy are unrelated (b) A small amount of mass can be converted into a large amount of energy (c) Energy can be destroyed (d) Mass can be created from nothing

#	Question	Options
15	In a nuclear reaction, if a mass defect (Δm) of 1 u is converted to energy, approximately how much energy is released?	(a) 1 Joule (b) 931.5 MeV (c) 3×10^{8} J (d) 1.6×10^{-19} J
16	The half-life of a radioactive isotope is the time it takes for:	(a) All of its atoms to decay (b) Half of its atoms to decay (c) Its activity to double (d) Its mass to increase by half
17	Carbon-14 dating is used to determine the age of:	(a) Any rock sample (b) Ancient organic materials (c) Metal artifacts (d) Living plants only
18	Which isotope, with its alpha radiation, is commonly used in household smoke detectors?	(a) Carbon-14 (b) Iodine-131 (c) Americium-241 (d) Cobalt-60
19	High doses of ionizing radiation can kill cells. This principle is used in which medical application?	(a) X-ray imaging (b) Radiotherapy for cancer (c) MRI scans (d) Ultrasound
20	Long-term exposure to low doses of radiation increases the risk of:	(a) Faster healing (b) Genetic mutations and cancer (c) Stronger bones (d) Improved eyesight

Answer Key: 1-b, 2-b, 3-c, 4-d, 5-a, 6-b, 7-c, 8-a, 9-b, 10-b, 11-b, 12-b, 13-b, 14-b, 15-b, 16-b, 17-b, 18-c, 19-b, 20-b

Exercise Short Questions

20.1 Define the atomic nucleus. What are its two main characteristics?

The atomic nucleus is the central part of an atom that contains most of its mass. Characteristics: It is positively charged due to protons. It contains protons and neutrons called nucleons. It is extremely small compared to the size of the atom. Almost all mass of the atom is concentrated in the nucleus.

20.2 What is the structure of an atom according to Rutherford's model?

An atom has a small, dense, positively charged nucleus at the center. Most of the atom is empty space. Electrons revolve around the nucleus at large distances.

20.3 How does alpha radiation differ from beta radiation?

Alpha radiation consists of helium nuclei with +2 charge and has low penetration but high ionization power and relatively large mass. Beta radiation consists of fast-moving electrons or positrons, has moderate penetration power, moderate ionization power, and relatively small mass.

20.4 What is the primary energy source of the Sun and other stars?

Nuclear fusion is the primary energy source of the Sun and other stars. In the Sun's core, four hydrogen nuclei fuse together to form one helium nucleus, releasing approximately 25.7 MeV of energy. The Sun's core maintains a temperature of nearly 20 million kelvins, providing perfect conditions for continuous fusion reactions.

20.5 Name the equation proposed by Einstein that relates energy and mass.

Formula: $E = mc^2$. Where E is energy (joules or MeV), m is mass (kilograms), and c is the speed of light (3×10^8 m/s). This equation shows that a small amount of mass can convert into enormous amounts of energy, as seen in nuclear fission and fusion.

20.6 Describe the principle behind carbon dating and its application.

Principle: Carbon dating is based on carbon-14 radioactive decay. Living organisms absorb carbon-14 from the atmosphere, maintaining a steady balance with carbon-12. When an organism dies, it stops absorbing carbon, and carbon-14 decays at a fixed rate (half-life of 5,730 years) and comparing it to the original amount, scientists calculate the organism's age. Application: Carbon dating determines the age of ancient organic materials like wood and bones (up to 50,000 years old). It is essential in archaeology and anthropology for dating artifacts and fossils.

20.7 Define nuclear fusion with an example.

Nuclear fusion is a process where two or more light nuclei combine to form a heavier nucleus at extremely high temperatures and speeds, releasing huge amounts of energy. Example: Deuterium and tritium combine to form helium. A large amount of energy is released: ${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$ + Energy

20.8 Americium-241 undergoes alpha decay and produces an alpha particle. Write down the chemical equation for it and name the nucleus formed.

General equation: ${}^{A}Z X \rightarrow {}^{A-4}Z_{-2}Y + {}^{4}_{2}He$. For Americium-241: ${}^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^{4}_{2}He$. Nucleus formed: Neptunium-237 (Np-237). The atomic number decreases by 2 (95 to 93) and mass number decreases by 4 (241 to 237).

SLO Based Additional Short Questions + Past Papers Short Questions of Punjab Boards

Q.1 What were the key observations made during Rutherford's alpha particle scattering experiment?

During Rutherford's experiment, most alpha particles passed through the gold foil without deflection, indicating atoms are mostly empty space. Some particles were slightly deflected, suggesting a small positively charged region. Very few particles bounced back at large angles, showing the nucleus is small, dense, and positively charged. These observations proved atoms have a tiny central nucleus containing most of the mass.

Q.2 Why is an atom said to be mostly empty space?

Rutherford's experiment showed that most alpha particles passed through the atom undeflected. This indicates that the nucleus occupies a very small volume. Electrons are far from the nucleus. Therefore, most of the atom consists of empty space.

Q.3 What force holds protons and neutrons together inside the nucleus?

Protons and neutrons are held together by the strong nuclear force. This force acts over very short distances. It overcomes the electrostatic repulsion between protons. Without it, the nucleus would break apart.

Q.4 What information does nuclide notation provide about an atom?

Nuclide notation ^{A}ZX provides complete information about an atom's nucleus. The subscript Z (atomic number) shows the number of protons. The superscript A (mass number) shows total protons plus neutrons. The symbol X identifies the chemical element. From this notation, number of neutrons can be calculated as $N = A - Z$.

Q.5 Why do isotopes have similar chemical properties?

Chemical properties depend on the number of electrons. Isotopes have the same atomic number. Hence, they have the same electronic configuration. Therefore, their chemical behavior is similar.

Q.6 What causes some atomic nuclei to become unstable and radioactive?

Atomic nuclei become unstable due to imbalance of protons and neutrons or excess energy. Too many or too few neutrons relative to protons makes the nucleus unstable. This instability causes spontaneous radioactive decay to achieve stability. The process releases radiation (alpha, beta, or gamma) randomly from individual atoms but follows statistical patterns in large samples.

Q.7 Why do alpha particles have high ionizing power?

Alpha particles have large mass and +2 charge. They collide strongly with atoms in matter. This causes removal of many electrons. Hence, they have high ionizing power.

Q.8 Why do gamma rays have very high penetrating power?

Gamma rays have no mass and no charge. They interact weakly with matter. Thus, they can pass through thick materials. Lead or concrete is required to stop them.

Q.9 Arrange alpha, beta, and gamma radiation in order of increasing penetrating power.

Alpha radiation has lowest penetrating power (stopped by paper or few cm of air), beta has moderate penetrating power (stopped by few mm of aluminium), and gamma has highest penetrating power (requires thick lead or concrete). Penetrating power depends on particle mass, charge, and energy. Alpha particles are heavy and highly charged, gamma rays are massless electromagnetic waves.

Q.10 How does nuclear fission create a chain reaction?

In nuclear fission, a heavy nucleus like U-235 splits when hit by a neutron, releasing 2-3 additional neutrons plus energy. These neutrons strike other U-235 nuclei, causing more fissions. Each fission produces more neutrons than consumed, creating an exponential chain reaction. In nuclear reactors, control rods absorb excess neutrons to prevent uncontrolled chain reaction and explosions.

Q.11 Why is half-life independent of external conditions?

Half-life depends on nuclear structure. It is unaffected by temperature or pressure. Chemical state does not change nuclear decay. Hence, half-life remains constant.

Q.12 Why is carbon-14 suitable for dating ancient fossils?

Carbon-14 has a long half-life of 5730 years. It is present in all living organisms. After death, it decays at a known rate. This makes it suitable for age determination.

Constructed Response Questions

20.1 If an atom is mostly empty space, why do we not fall through solid objects or pass through walls?

Even though an atom is mostly empty space, we do not fall through solid objects. Reason: Atoms contain electrons around their nucleus. When two solid objects come close, the electrons of one object push away the electrons of the other object. This pushing force is called an electromagnetic force. This strong force prevents atoms from passing through each other, so solids feel hard and we cannot pass through walls.

20.2 Imagine a new radioactive element is discovered. How could scientists estimate its half-life without waiting thousands of years?

Scientists can estimate half-life by measuring the decay rate using a Geiger counter or scintillation detector over a short period (days, weeks, or months). Method: By recording decays at different time intervals, they plot a decay curve showing how activity decreases with time. The time taken for activity to reduce to half its initial value represents one half-life. Mathematical analysis of decay data determines the decay constant, which is related to half-life. This method allows scientists to determine half-lives ranging from fractions of a second to billions of years.

20.3 If gamma rays do not change the number of protons or neutrons in a nucleus, why are they still considered dangerous?

Gamma rays are dangerous because of their high penetrating power and ability to cause ionization in living tissues. Reason: Gamma rays have extremely high penetration power and pass through thick materials like lead or concrete, penetrating deep into organs and cells. When gamma rays interact with cells, they ionize atoms and molecules including DNA by removing electrons, damaging cellular structures and causing DNA mutations. High doses kill cells directly, and long-term exposure increases cancer risk. The combination of penetration power and ionization ability makes them extremely dangerous.

20.4 If carbon-14 stopped forming in the atmosphere today, how would that affect the use of carbon dating in the future?

Carbon dating would become unreliable and eventually unusable if carbon-14 stopped forming in the atmosphere. Reason: Carbon dating relies on the constant ratio of carbon-14 to carbon-12 in living organisms. If carbon-14 formation stopped, all organisms would lose carbon-14 at constant rates, making samples appear to have different ages based on death time. Without new carbon-14 production, the atmospheric baseline would constantly change, and scientists could not establish original carbon-14 concentrations. This fundamental assumption would become invalid, making the technique unreliable.

20.5 What is the difference between nuclear fission and nuclear fusion in terms of process and energy release?

Nuclear Fission	Nuclear Fusion
In nuclear fission, a heavy nucleus (like U-235) splits into smaller nuclei when bombarded by a neutron.	Light nuclei combine to form a heavier nucleus at extremely high temperatures.
Low temperatures required for fission reaction.	Extremely high temperatures required for fusion reaction.
It creates uncontrolled chain reactions, causing explosions.	It does not produce chain reaction; difficult to control.

Nuclear Fission	Nuclear Fusion
It releases about 200 MeV per fission event.	It releases huge amounts of energy (25.7 MeV for deuterium-tritium).
It is used in nuclear power plants and atomic weapons.	It occurs in stars including the Sun; potential clean energy source.

Comprehensive Questions

20.1 How does the structure of an atom determine its chemical properties? Explain with reference to the arrangement of protons, neutrons, and electrons?

See Q.#3 of theory.

20.2 Explain Einstein's equation, $E=mc^2$, and its significance. How does this equation relate to nuclear reactions?

See Q.#9 of theory.

20.3 Describe the process of radioactive decay and how it leads to the emission of alpha, beta, and gamma radiation?

See Q.#5 of theory.

20.4 Why do different isotopes of the same element have similar chemical properties but different physical properties? Explain.

See Q.#4 of theory.

20.5 Explain how carbon dating uses carbon-14 to estimate the age of artifacts. Discuss its reliability, considering the influence of carbon-14's half-life?

See Q.#11 of theory.

Numerical Problems

20.1 Find the number of protons and neutrons in the nuclide defined by ${}^{21}_{9}X$.

Given: Mass number A = 21, Atomic number Z = 9.

Solution: Number of protons = Atomic number = Z = 9. Number of neutrons = N = A − Z = 21 − 9 = 12.

Result: 9 protons and 12 neutrons.

20.2 A fossil is found to have 25% of the carbon-14 compared to a living sample. How old is the fossil?

Given: Fraction remaining N/No = 25% = 0.25; Half-life of carbon-14 = $T_{½}$ = 5730 years.

$$N/No = 1/2^n \implies 0.25 = 1/2^n \implies 2^n = 4 = 2^2 \implies n = 2$$

$$\Delta t = n \times T_{½} = 2 \times 5730 = 11460 \text{ years}$$

Result: 11460 years.

20.3 A sample initially contains 400 g of a radioactive isotope with a half-life of 10 years. How much remains after 30 years?

Given: Initial mass No = 400 g; Half-life $T_{½}$ = 10 years; Time elapsed Δt = 30 years.

$$n = \Delta t / T_{½} = 30/10 = 3$$

$$N = No \times (½)^n = 400 \times (½)^3 = 400 \times 1/8 = 50 \text{ g}$$

Result: 50 g.

20.4 A radioactive substance has a half-life of 64 months. In how much time, one-eighth of the substance will be left?

Given: Half-life $T_{½}$ = 64 months; Fraction remaining N/No = 1/8.

$$1/8 = 1/2^n \implies 2^n = 8 = 2^3 \implies n = 3$$

$$\Delta t = n \times T_{½} = 3 \times 64 = 192 \text{ months}$$

Result: 192 months.

20.5 In a nuclear reaction, 4 μg of mass is converted into energy. Find the energy.

Given: Mass converted m = 4 μg = 4×10^{-6} g = 4×10^{-9} kg; Speed of light c = 3×10^8 ms^{-1}.

$$E = mc^2 = 4\times10^{-9} \times (3\times10^8)^2 = 4\times10^{-9} \times 9\times10^{16} = 36\times10^7 \text{ J} = 360 \text{ MJ}$$

Result: 360 MJ.

20.6 In 420 days, one-eighth of polonium (Po) remains un-decayed. Calculate the half-life of polonium.

Given: Time elapsed Δt = 420 days; Fraction remaining N/No = 1/8.

$$2^n = 8 = 2^3 \implies n = 3$$

$$\Delta t = n \times T_{½} \implies 420 = 3 \times T_{½} \implies T_{½} = 420/3 = 140 \text{ days}$$

Result: 140 days.

20.7 Three-fourth of the initial mass of a certain radioactive isotope decay after one hour. Find half-life of isotope in minutes.

Given: Fraction decayed = 3/4; Fraction remaining N/No = 1/4; Time elapsed Δt = 1 hour = 60 minutes.

$$1/4 = 1/2^n \implies 2^n = 4 = 2^2 \implies n = 2$$

$$\Delta t = n \times T_{1/2} \implies 60 = 2 \times T_{1/2} \implies T_{1/2} = 60/2 = 30 \text{ minutes}$$

Result: 30 minutes.

Important Questions of Board Examination

- (i) What is difference between atomic number and atomic mass number? Give a symbolic representation of nuclide.
- (ii) Define isotopes. Give three isotopes of hydrogen atom.
- (iii) Define natural radioactivity.
- (iv) Define nuclear transmutation.
- (v) What do you understand by half-life of a radioactive element? Explain.
- (vi) What are radio isotopes? How radio isotopes help us in our daily life.
- (vii) What is nuclear fission process? Explain in detail.
- (viii) What is nuclear fusion process. Explain in detail.

Important Short Questions of Board Examination

- (i) Define nuclear fission and nuclear fusion.
- (ii) Write chemical equation for nuclear fusion.
- (iii) What is difference between atomic number and atomic mass number.
- (iv) Define isotope.
- (v) Define half-life.
- (vi) Write two characteristic of α-particles.
- (vii) Write two characteristic of β particles.
- (viii) Define carbon dating.
- (ix) What do you mean by ionization and penetration ability?
- (x) Why isotope of an element have identical properties?
- (xi) Three isotopes of oxygen are $^{16}{}_{8}O$, $^{17}{}_{8}O$ and $^{18}{}_{8}O$. Give the number of protons, nucleons and neutrons in each case.
- (xii) How will you represent the emission of a beta particle using nuclide notation?
- (xiii) Why does γ radiations not experience deflection in electric and magnetic fields, unlike α particles and β particles?
- (xiv) Describe the process of nuclear fission and give an example of practical application where fission is used.
- (xv) What are changes in nuclide during all three decay processes?
- (xvi) Write nuclear equation for fission of uranium.
- (xvii) What is mass defect?