CHAPTER 20

ATOMIC AND NUCLEAR PHYSICS

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- describe the structure of the atom [in terms of a positively charged nucleus and negatively charged electrons that go around the nucleus. This should include an understanding of the big ideas: These electrons do not go around in predictable circular paths in the way that planets go around the sun. The electrons behave as 'quantum particles' and their location and momentum at any point in time is governed by probability; one cannot predict the motion of an electron. The 'shells' in which electrons 'orbit' refer to the level of kinetic energy the electrons possess; the further the shell is from the nucleus, the more energy the electron has. If one were to 'look' at an atom, one would see a fuzzy 'cloud' of electrons with a very small nucleus in the centre.
- justify the findings of the alpha-particle scattering experiments, specifically that it provides evidence for: (a) a very small nucleus surrounded by mostly empty space, (b) a nucleus containing most of the mass of the atom, (c) a nucleus that is positively charged.
- define the terms proton number (atomic number) Z and nucleon number (mass number) A and be able to calculate the number of neutrons in a nucleus.
- recall the term nuclide and use the nuclide notation $^{A}_{Z}X$.
- explain what is meant by an isotope and state that an element may have more than one isotope.
- describe the emission of radiation from a nucleus as spontaneous and random.
- describe alpha-particles, beta-particles, and gamma-radiation.
- justify qualitatively the order of strength for alpha-particles, beta-particles, and gamma-radiation in terms of their (a) relative ionizing effects and (b) relative penetrating powers.
- describe the deflection of alpha-particles, beta-particles, and gamma-radiation in electric fields and magnetic fields.
- explain that radioactive decay is a change in an unstable nucleus that can result, most commonly, in the emission of alpha-particles or beta-particles and/or gamma-radiation.

(Other types exist but are not required at this level.)

- use decay equations, using nuclide notation, to show the emission of alpha-particles, beta-particles, and gamma-radiation.
- describe nuclear reactions (fission and fusion) with examples. (Fusion as the formation of a larger nucleus by combining two smaller nuclei with the release of energy, and recognize fusion as the energy source for stars.)
- recognize that matter can be converted to energy and vice versa (in this way the law of conservation of energy still holds).
- apply the equation; $E = mc^2$ to calculate the energy released in the process of nuclear reactions.
- describe the activity of a radioactive material in terms of counts per unit time.
- define and infer the half-life of materials. (Half-life is the time taken for half the nuclei of an isotope in any sample to decay. Use this definition in calculations, which may involve tables or decay curves.)
- explain and apply the concept of Carbon dating to solve problems.
- explain how the type of radiation emitted and the half-life of the isotope determine which isotope is used for applications, including: (a) household fire (smoke) alarms, (b) irradiating food to kill bacteria, (c) sterilization of equipment using gamma rays, (d) measuring and controlling thicknesses of materials using appropriate radiation, (e) diagnosis and treatment of cancer using gamma rays.
- state the effects of ionizing nuclear radiations on living things, including cell death, mutations, and cancer.

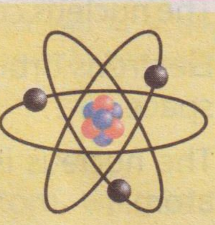
Atomic and nuclear physics are branches of science that help us to understand the smallest building blocks of matter. Atomic physics deals with the study of the structure of atoms, their constituents (electrons, protons, and neutrons), and how they interact with light and energy. Scientists have developed different models of the atom over time, from simple ideas to more advanced ones like the quantum model. Nuclear physics, on the other hand, focuses on the nucleus of the atom, which contains protons and neutrons. It explains important concepts like radioactivity, nuclear reactions, and how energy is released in nuclear power plants. Researches in these fields have led to important applications in medicine, energy, and technology. In this chapter, we will explore these basic ideas and understand how they shape the world around us.

20.1 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?

Atom is 99.9999999% empty space!



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 as shown in Fig.20.1.

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.

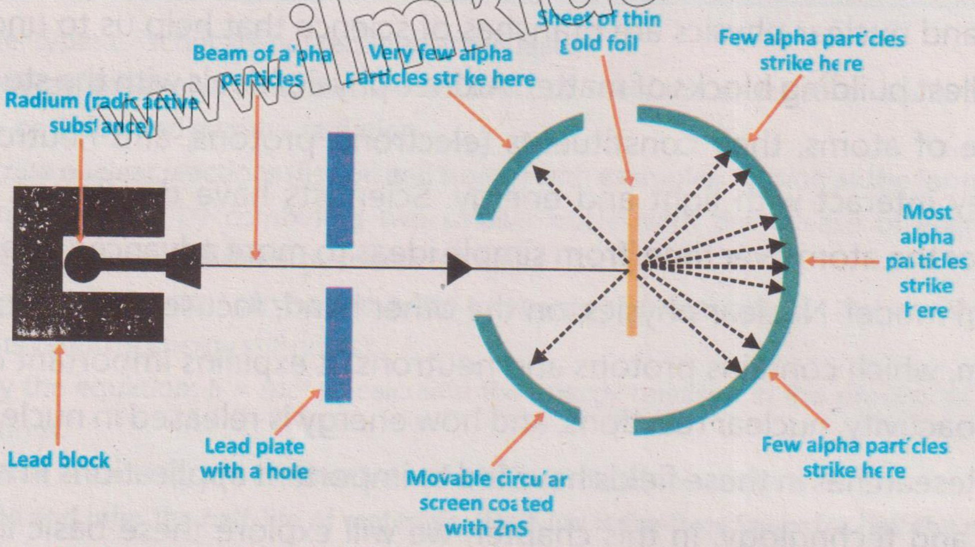


Fig. 20.1: Rutherford's gold foil experiment: scattering of alpha particles

Findings of Rutherford's Experiment

1. Atoms have a small, dense, and positively charged core called the nucleus.
2. The nucleus contains most of the mass of atoms.
3. Electrons orbit the nucleus at large distances, and the atom is mostly empty space.
4. The nucleus is extremely small, about 10,000 times smaller than the entire atom.

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.

20.2 Atomic Nucleus

Atomic nucleus is the central part of an atom which holds most of its mass (Fig. 20.2). 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.

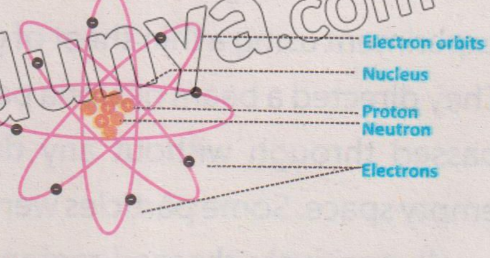


Fig. 20.2: Diagram of an atom showing the nucleus, protons, neutrons, and electron orbits

Charge Number and Mass Number

Atoms are made up of protons, neutrons, and electrons. The charge number Z tells us how many protons an atom has, which is unique for each element. It is also called atomic number. This number also determines an element's position in the periodic table and its chemical properties. The mass number A is the total count of protons and neutrons in an atom's nucleus. 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. A nuclide is represented by $^{A}_{Z}X$, where X is its chemical symbol, the superscript is mass number A and subscript is charge number Z.

Do You Know?

The number of protons in the nucleus is what defines an element. Change the number of protons, and we change the element itself!

Tidbit

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

Brain Teaser

If protons repel each other, how can so many of them stay packed in a tiny nucleus without flying apart? What holds them together?

To determine the number of neutrons in the nucleus of an atom, we use the formula:

$$N = A - Z$$

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 $^{15}_{7}N$.

20.3 Isotopes

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

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. A common example of isotopes is hydrogen, which has three isotopes as shown in Fig. 20.3.

$^{1}_{1}H$ contains 1 proton and 0 neutrons

$^{2}_{1}H$ contains 1 proton and 1 neutron.

$^{3}_{1}H$ contains 1 proton, 2 neutrons

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

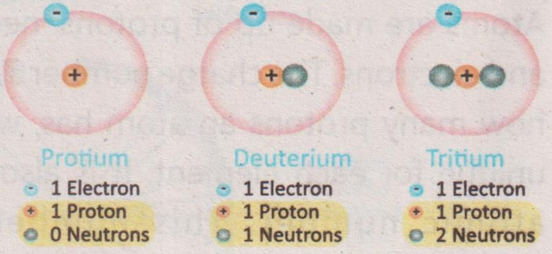


Fig. 20.3: Isotopes of hydrogen

20.4 Radioactivity

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, but in a large group of atoms, the decay follows a pattern.

Do You Know?

Marie Sklodowska-Curie, a French Physicist and chemist, was the first woman to receive a Nobel Prize and the only woman to receive two Nobel Prizes, while studying uranium's rays, she discovered new elements and named them 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.

Alpha particles (α) are helium nuclei, consisting of 2 protons and 2 neutrons each (Fig. 20.4). They carry a +2e charge ($e=1.6 \times 10^{-19}$ C), and are relatively large and

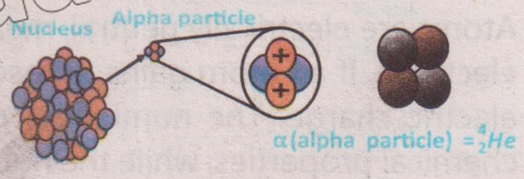


Fig. 20.4: Representing alpha particle

heavy [4 atomic mass units,u). 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. However, they have high ionizing power, meaning they strongly affect other atoms they come in contact with.

Beta particles (β) are high-energy electrons ($_{-1}^{0}e$) or positrons ($_{+1}^{0}e$) emitted from the nucleus (Fig.20.5) They carry a -1e charge (electrons) or +1e charge (positrons) and have a very small mass. Beta radiation has moderate penetration power. It can pass through paper but is stopped by a few millimetre of aluminum. Their ionizing power is moderate, meaning they cause less ionization than alpha particles but more than gamma rays.

Tidbit

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

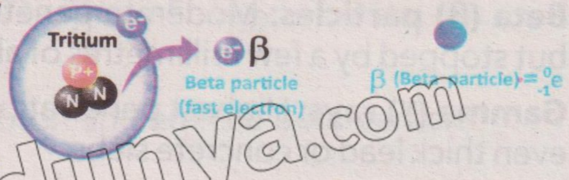


Fig. 20.5: Representing beta particles

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 (Fig. 20.6). Gamma rays have very high penetration power, allowing them to pass through thick materials like lead or concrete. However, they have low ionizing power, meaning they cause much less ionization compared to alpha and beta particles.

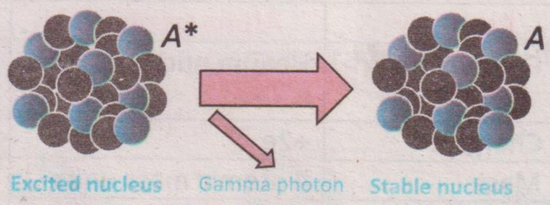


Fig. 20.6: Representing gamma radiation

Ionizing Effects and Penetrating Powers

Ionizing Effects

Ionization occurs when radiation removes electrons from atoms, turning them into ions. The ability of radiation to ionize atoms depends on its energy and charge.

Alpha (α) particles: Strongest ionizing power due to their large size and charge.

Beta (β) particles: Moderate ionizing

Do You Know?

Gamma rays are pure electromagnetic energy with no mass or charge. They are the most penetrating and require thick lead or concrete to shield against.

power, as they are smaller and faster than alpha particles.

Gamma (γ) rays: Weakest ionizing power, as they have no charge and no mass.

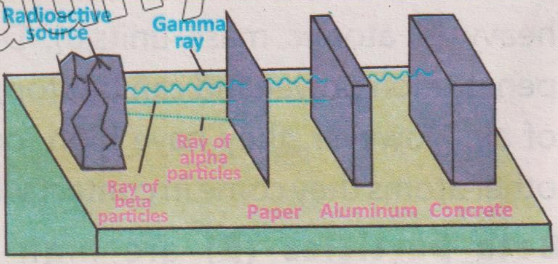


Fig. 20.7: Penetrating power of three types of radiations

Penetrating Powers

Penetration power refers to how far radiation can travel through materials before being absorbed. Penetration power of (α) ,(β) and (γ) rays are shown in Fig. 20.7.

Alpha (α) particles: Lowest penetration – stopped by a sheet of paper or a few centimetres of air.

Beta (β) particles: Moderate penetration – can pass through a sheet of paper but stopped by a few millimetres of aluminum.

Gamma (γ) rays: Highest penetration – can pass through paper, aluminum, and even thick lead or concrete slabs.

The other properties like composition, charge, mass, ionizing power, penetrating power and deflection in fields of these rays are shown in Table 20.1.

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 ($^{0}_{+1}e$)	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 both in electric and magnetic fields	Significant in electric and magnetic fields	No deflection

20.5 Radioactive Decay

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.

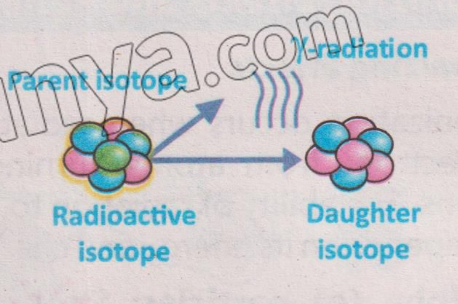


Fig. 20.8: Transformation of a parent isotope into a daughter isotope

Figure. 20.8 demonstrates a radioactive process in which transformation of parent isotope into daughter isotope takes place through the emission of radiations.

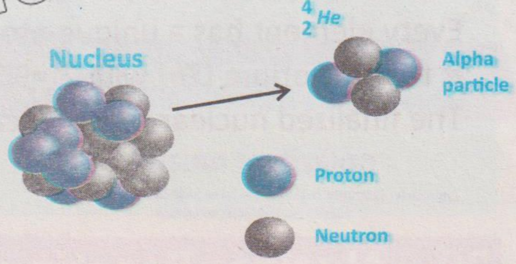


Fig. 20.9: Representing alpha decay

1. Alpha (α) Decay Equation

In alpha decay, an unstable nucleus emits an alpha particle (^4_2He), reducing its atomic number by 2 and mass number by 4 (Fig. 20.9)

General Equation: $^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + {}^4_2He$ .... (20.1)

Example (Decay of Uranium-238): $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^4_2He$ +Energy

2. Beta (β) Decay Equations

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

General Equation: $^A_ZX \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-}\beta$ + Energy .... (20.2)

Example (Decay of Carbon-14): $^{14}_6C \rightarrow {}^{14}_7N + {}^{0}_{-}\beta$ + 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 (Fig. 20.10).

General Equation: $^A_ZX^* \rightarrow {}^A_ZX + \gamma$ ....(20.3)

Example (Decay of Cobalt-60):

$^{60}_{27}Co^* \rightarrow {}^{60}_{27}Co + \gamma$

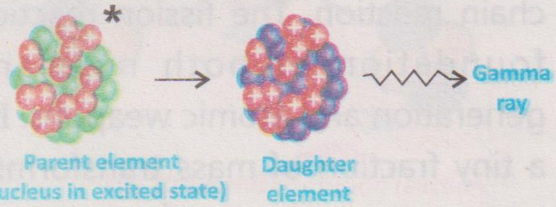


Fig. 20.10: Representing gamma decay

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

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: $^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + \alpha$ + Energy

For Uranium -238, the nuclear reaction will come: $^{238}_{92}U \rightarrow {}^{238-4}_{92-2}Y + {}^4_2He(\alpha)$ + Energy

or $^{238}_{92}U \rightarrow {}^{234}_{90}Y + {}^4_2He(\alpha)$ + Energy

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 witten as: $^{238}_{92}U \rightarrow \, ^{234}_{90}Th + \, ^{4}_{2}He(\alpha)$ + Energy

20.6 Nuclear Reactions

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.

We will discuss here two types of nuclear reactions:

1. Fission Reaction
2. Fusion Reaction

Fission Reaction

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. 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 (Fig. 20.11). 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.

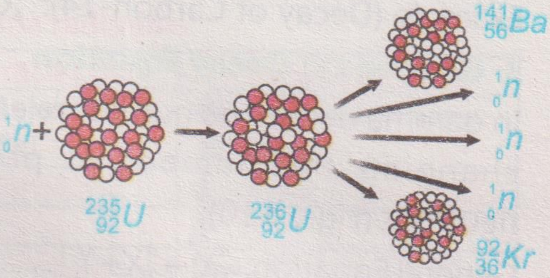


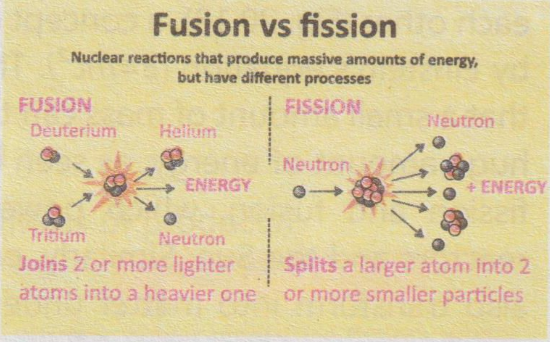
Figure 20.11: Nuclear fission reaction

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

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?



Nuclear Fusion

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). 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.

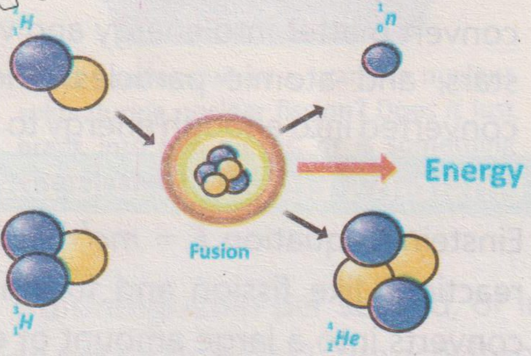


Fig. 20.12: Nuclear fusion reaction

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

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n + \text{Energy} \quad \ldots\ldots\ldots\ldots (20.5)$$

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.

20.7 Interconversion of Matter and Energy

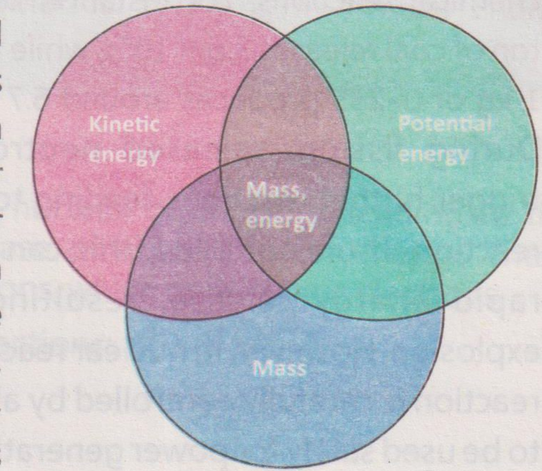


Fig. 20.13: Interconversion of different energies

Matter and energy can be converted into each other (Fig. 20.13), 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 to 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 ($3 \times 10^8\ \mathrm{m\,s^{-1}}$). In nuclear reactions, the total mass of the products is slightly less than the mass of the reactants. This missing mass is called mass defect (Δm). Using $E = mc^2$, we can find the energy released:

If $\Delta m = 1 \times 10^{-4}$ kg, then using $E = mc^2$:

$$E = (1\times10^{-4}\ \mathrm{kg}) \times (3\times10^{8}\ \mathrm{m\,s^{-1}})^2\ ;\ E = 9\times10^{12}\ \mathrm{J}$$

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.

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

Example 20.3: Energy Released in Nuclear Fission Reaction:

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

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 will be:

$$\Delta m = (\text{Mass of reactants}) - (\text{Mass of products})$$

$$\Delta m = (235.0439 + 1.0087) - (140.9144 + 91.9262 + 3.0261)$$

$$\Delta m = 236.0526 - 235.8667 = 0.1859 \text{ u}$$

Energy released will be:

$$E = \Delta m \times 931.5 \text{ MeV/ u}$$

$$E = 0.1859 \times 931.5 = 173.2 \text{ MeV}$$

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.

20.8 Half-Life

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), where 1 Bq = 1 disintegratoin per second, or in Curies (Ci), where 1 Ci = 3.7×10^{10} disintegration per second (dps). 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.

Brain Teaser

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

The half-life of a radioactive isotope is the time it takes for half of the radioactive atoms in a sample to decay into a more stable form.

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).

Table 20.2: Half-life of isotopes

Istope	Symbol	Half-Life	Application
Carbon-14	$^{14}_{6}C$	5,730 years	Radiocarbon dating of ancient artifacts and fossils.
Uranium-238	$^{238}_{92}U$	4.5 billion years	Dating rocks and Earth's age; used in nuclear reactors.
Potassium-40	$^{40}_{19}K$	1.25 billion years	Dating rocks and geological formations.
Thorium-232	$^{232}_{90}Th$	14 billion years	Used in nuclear reactors and dating.
Radon-222	$^{222}_{86}Rn$	3.8 days	Indoor air quality monitoring; health hazard.
Iodine-131	$^{131}_{53}I$	8 days	Medical treatment for thyroid cancer and imaging.
Cobalt-60	$^{60}_{27}Co$	5.27 days	Cancer treatment (radiotherapy) and industrial radiography.
Tritium (Hydrogen-3)	$^{3}_{1}H$	12.3 days	Used in luminous paints and as a tracer in biological studies.
Polonium-210	$^{210}_{84}Po$	138 days	Used in static eliminators and as a heat source in space probes.
Strontium-90	$^{90}_{38}Sr$	28.8 days	Used in medical treatment and as a radioactive tracer.

The amount of radioactive isotope in the given sample decreases with time as shown in Fig. 20.14. .The number of nuclei present at time $t=0$ is $N = N_o$, and the number present at time $t= T_{½}$ is $N = N_o/2$. The number present at time $t= 2T_{½}$ is $N = N_o/4$ and so on. In this example the amount N of the radioactive substance left after sometime t is given by

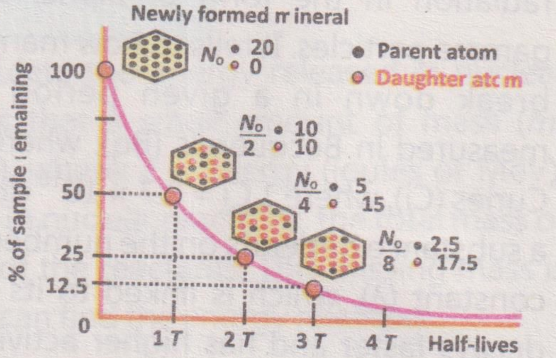


Fig. 20.14: Conversion of $^{99}_{43}Tc$ to $^{99}_{44}Ru$ by beta decay

After 1 half-Life: $N_1 = \frac{1}{2}N_0$

After 2 half-Life: $N_2 = \frac{1}{2} \times \frac{1}{2}N_0 = \left(\frac{1}{2}\right)^2 N_0$

After 3 half-Life: $N_3 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}N_0 = \left(\frac{1}{2}\right)^3 N_0$

After 4 half-Life: $N_4 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}N_0 = \left(\frac{1}{2}\right)^4 N_0$

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

$$\text{Number of half-lives} = \frac{\text{Total time passed}}{\text{Half-life}}$$

Therefore $$n = \frac{\Delt t}{T_{1/2}} \quad \text{..........} \quad (20.6)$$

Half-Life of Radioactive Isotopes

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 what ever may be the surrounding conditions.

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.

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.

Carbon Dating

Carbon dating is a scientific method used to determine the age of ancient organic materials like wood, bones, and shells, up to 50,000 years old. 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

Brain Teaser

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

Tidbit

Carbon-14 is constantly created in the upper atmosphere when cosmic rays hit nitrogen atoms — meaning the clock "starts ticking" the moment an organism dies.

Fun Fact

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

ancient remains, giving important insights into human history and environmental changes. The radioactive decay of carbon-14 shown in Fig. 20.15.

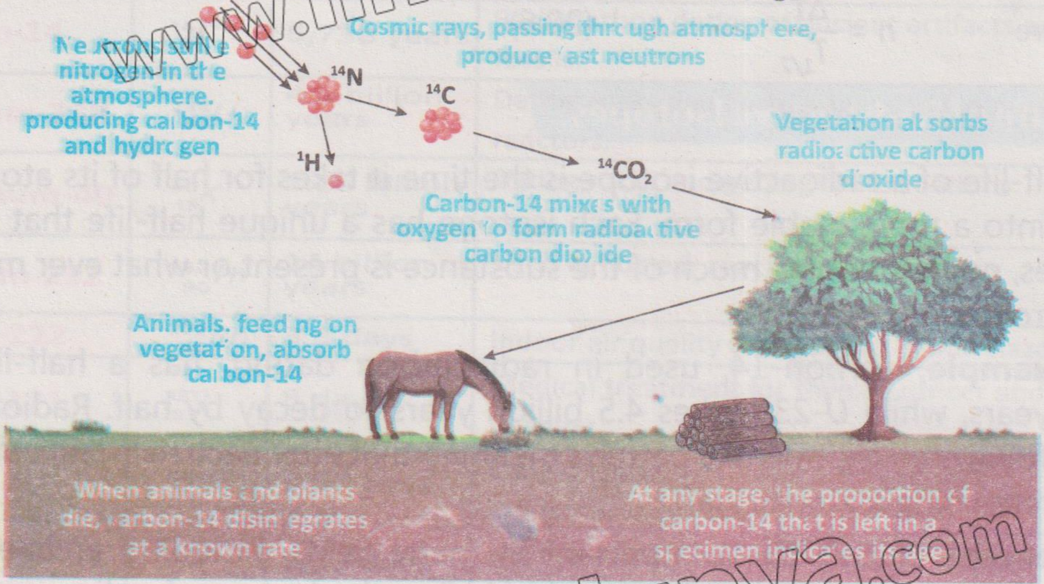


Fig. 20.15: Carbon dating

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 that;

initial quality of pure lead-212 N_o = 50 mg

Half-life of lead - 212 T - 10.6h

Total elapsed time Δt = 53 hours

To find; Quantity to be left N = ?

The number of half-lives n is given by $n = \frac{\Delta t}{T_{1/2}}$

Substituting the values: $n = \frac{53\ \text{h}}{10.6\text{h}}$

Therefore $n = 5$

Original sample remaining after n number of half-lives: $N = \left[\frac{1}{2}\right]^n N_o$

Substituting the values: $N = \left[\frac{1}{2}\right]^5 \times 50\ \text{mg}$

Therefore $N = 1.56$ mg

So, 1.56 mg of lead -212 will be present after 53 hours of 5 half-lives.

20.9 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.

Effects of Nuclear Radiation

1. High doses can kill cells by damaging their DNA, which is why radiation is used in cancer treatment (radiotherapy) to destroy cancer cells.

Do You Know?

High-energy gamma rays are used to target and destroy cancer cells in radiotherapy. Precision is key to avoid harming healthy cells.

2. 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.
3. 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.
4. Severe exposure over a short time can cause radiation sickness, leading to nausea, vomiting, organ failure, and even death in extreme cases.

Uses of Nuclear Radiation

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

1. **Medical Uses:** Short-lived isotopes are used in radiotherapy and imaging to minimize long-term radiation risks.
2. **Industrial Uses:** Isotopes with long half-lives are used in power generation, radiation detectors, and material testing, where long-term stability is important.

   Nuclear radiation plays a major role in medicine, industry, and scientific research, but it must be handled carefully to avoid harmful effects.
3. **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.
4. **Cobalt-60 in Sterilization:** Gamma radiation is used to sterilize medical equipments, killing bacteria and viruses without damaging the materials.

Radiation Source

1. **Americium-241 ($^{241}_{95}Am$) 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.

2. Cobalt-60 and Iodine-131 in Medicine:

Gamma rays from Cobalt-60 are used in radiotherapy to destroy cancer cells, while Iodine-131, with a short half-life (8 days), is used in thyroid diagnosis and treatment to minimize long-term radiation exposure.

Do You Know?

Even without nuclear power or medical scans, we are exposed to radiation from cosmic rays, rocks, and even bananas (which contain potassium-40).

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

20.1 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

20.2 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

20.3 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

20.4 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

20.5 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

20.6 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

20.7 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

20.8 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

B. Short Answer Questions

20.1 Define the atomic nucleus. What are its two main characteristics?
20.2 What is the structure of an atom according to Rutherford's model?
20.3 How does alpha radiation differ from beta radiation?
20.4 What is the primary energy source of the Sun and other stars?
20.5 Name the equation proposed by Einstein that relates energy and mass.
20.6 What is the principle behind carbon dating and its applications?
20.7 Define nuclear fusion with an example.
20.8 Americium-241 ($^{241}_{95}Am$) undergoes alpha decay and produces an alpha particle. Write down the chemical equation for it and name the nucleus formed.

C. Constructed Response Questions

20.1 If an atom is mostly empty space, why do not we fall through solid objects or pass through walls?
20.2 Imagine a new radioactive element is discovered. How could scientists estimate its half-life without waiting thousands 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?

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

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

D. 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?

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

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

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

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?

E. Numerical Problems

20.1 Find the number of protons and neutrons in the nuclide defined by $^{21}_{9}X$.
[Ans: 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? **[Ans: ≈ 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? **[Ans: 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? **[Ans: 192 months]**

20.5 In a nuclear reaction, 4 μg of mass is converted into energy. Find the energy. **[Ans. 360 MJ]**

20.6 In 420 days, one-eighth of polonium (Po) remains un-decayed. Calculate the half-life of polonium? **[Ans: 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? **[Ans: 30 min]**