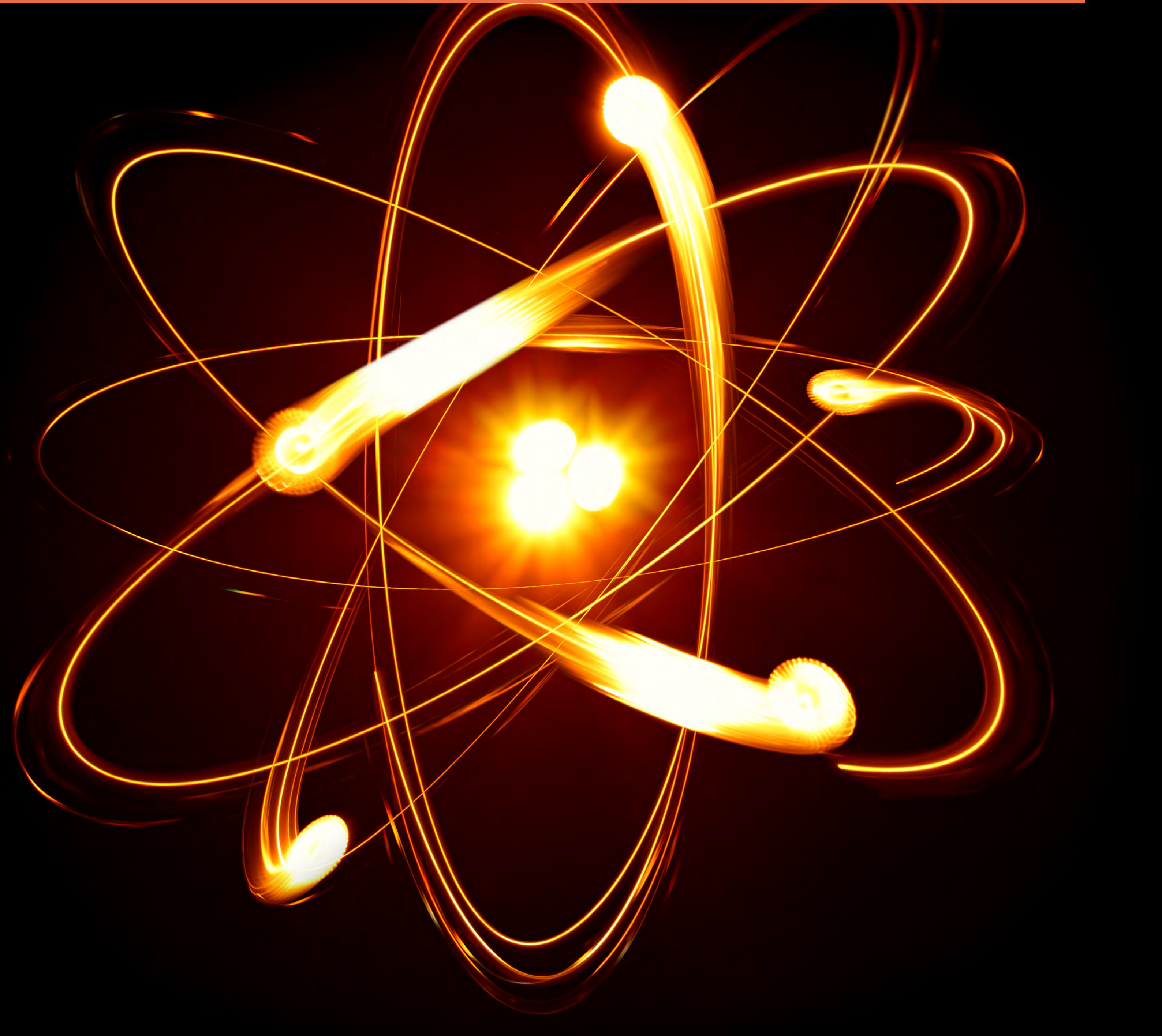
Physics

Year 1

SECTION

8

FUNDAMENTAL CONCEPTS IN ATOMIC AND NUCLEAR PHYSICS



ATOMIC AND NUCLEAR PHYSICS

1. Atomic Physics

2. Nuclear Physics

INTRODUCTION

Welcome to the attractive world of atomic structure! In this topic, we'll explore the various atomic models that have been proposed to explain the behaviour of atoms. You'll also learn how to calculate the energy of a photon produced during an electron's transition between energy levels.

You will learn how to compute simple nuclear equations. Nuclear reactions involve changes to the nucleus of an atom, resulting in a new element or isotope. These reactions can be either natural or artificial and have numerous applications in fields like medicine, energy, and industry. Balancing nuclear reactions is crucial to understand the changes that occur during these reactions. It helps us to identify the reactants and products, to determine the number of atoms involved, and to understand the conservation of mass and energy.

By the end of this section, you will be able to:

- Explain various atomic models and their limitations.
- Calculate the energy of a photon during a transition.
- Describe the structure of the nucleus of the atom.
- Explain radioactivity.
- Balance basic nuclear reactions.

KEY IDEAS

- Dalton's Atomic Model (1803): Atoms are indivisible, indestructible particles.
- Thompson's Atomic Model (1897): Atoms have a positive nucleus surrounded by electrons.

- Rutherford's Atomic Model (1911): Atoms have a small, dense nucleus with electrons orbiting around it. Bohr's Atomic Model (1913): Electrons occupy specific energy levels around the nucleus.
- One piece of evidence of Bohr's atomic model is the emission and absorption spectra of different elements, produced when electrons excite and de-excite, either absorbing or emitting a photon.
- The nucleus of the atom can undergo changes that make it more stable, which involves the emission of an alpha particle, beta particle, or gamma photon. In this section we will study this effect, known as nuclear radioactivity, in more detail.

ATOMIC MODELS AND THEIR LIMITATIONS

Atomic Physics

Atomic physics is the field of physics that studies the structure of an atom, atomic models, and the constituent particles in an atom.

Atoms

An atom is the smallest particle of an element that retains the properties of that element. All pure (uncombined) elements are composed of atoms. For example, iron is composed of iron (Fe) atoms, helium gas is composed of helium (He) atoms, etc.

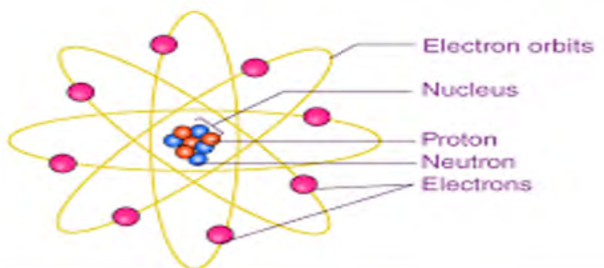


Fig. 8.1: The structure of the atom

The figure above gives a simplified artist's impression of our modern understanding of the structure of the atom, although it is much more complicated!

We have not always believed that the atom is built this way. The model of the atom has developed significantly since Dalton's model in 1803. Read the dialogue below to gain insight as to the contribution of three very important scientists.

Activity 8.1: A debate on atomic models

Participants:

- Emmanuella (representing J.J. Thompson)
- Love (representing Ernest Rutherford)
- Nana Poku (representing Niels Bohr)

Moderator: Welcome everyone to today's debate about atomic models! Each participant will explain their ideas and respond to each other. Let's start with Emmanuella.

Fig. 8.2: High School Debate Competition

Round 1: ***Opening Statements***

Emmanuella (Thompson):

"Thank you! I want to present J.J. Thompson's atomic model, known as the 'plum pudding model.' This model suggests that atoms are made up of a positively charged 'soup' with negatively charged electrons mixed throughout. This idea helps explain how atoms can be neutral and shows that they contain smaller particles."

Love (Rutherford):

"Thank you, Emmanuella. While I appreciate your contributions, I believe the 'plum pudding model' lacks a clear structure. My gold foil experiment demonstrated that atoms have a small, dense centre called the nucleus, which contains most of the atom's mass. Electrons orbit around this nucleus, showing that atoms are mostly empty space. This was a significant advancement in understanding atomic structure."

Nana Poku (Bohr):

"Thank you, Love. While I respect Rutherford's findings, his model doesn't explain why electrons stay in their orbits without spiralling into the nucleus. My Bohr model introduces energy levels, meaning electrons can only occupy certain paths or orbits. This explains why atoms are stable and how they emit light when they gain energy."

Round 2: Responses and Critiques

Emmanuella (Thompson):

"Love, your model shows a nucleus, which is a great step forward. However, it doesn't explain how electrons can stay in orbit without losing energy. My model introduces subatomic particles, which is essential for understanding atomic structure."

Love (Rutherford):

"Emmanuella, your 'soup ' analogy is interesting, but it doesn't account for the concentrated mass in the nucleus. Nana Poku, your fixed orbits are groundbreaking, but they can be misleading since electrons don't follow set paths. They exist in areas of probability around the nucleus."

Nana Poku (Bohr):

"Love, I appreciate your emphasis on the nucleus. My model explains electron behaviour more accurately. The fixed orbits represent areas where we are likely to find electrons, addressing some limitations of earlier models."

Round 3: Closing Statements

Moderator: Thank you all for your insightful arguments! This debate highlights the evolution of atomic models and how each contribution has shaped our understanding of atoms.

Modern atomic structure Discovery

An atom consists of a positive nucleus, which is found at its centre and surrounded by negative electrons that orbit (move around) the nucleus. The nucleus also contains protons and neutrons.

Most great scientists have contributed in various ways that led to the discovery of the modern atomic structure. The contributions of some of these scientists are highlighted below.

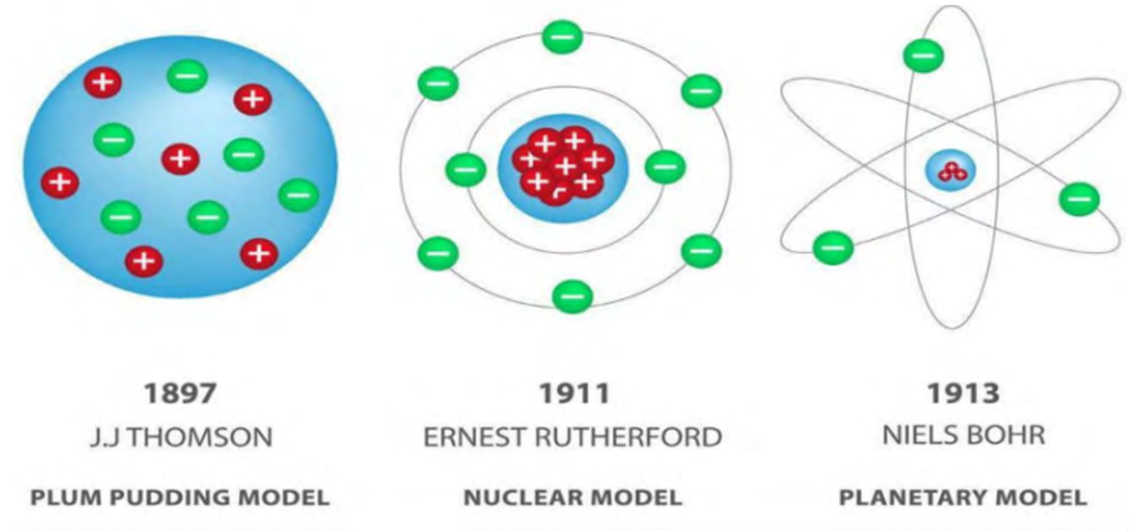


Fig. 8.3: Evolution of Atomic Models by J.J. Thomson, Ernest Rutherford, and Niels Bohr

J. J. Thompson's description of the atom is that an atom is a solid sphere of positive charge with the negative electrons stacked uniformly in it. The positive charges occupy the greatest volume, while the electrons occupy the smallest volume, and the whole atom becomes neutral. I.e. the electron charge balanced the positive charge.

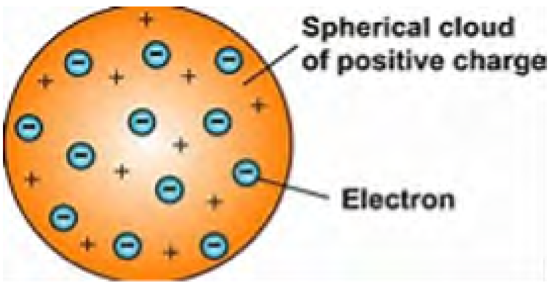


Fig. 8.4: J. J. Thompson's description of the atom

Limitations of Thompson's Model of the Atom

An experiment designed some years later by Ernest Rutherford heralded results that disagreed with Thompson's model. Complete Activity 3 to learn more about this experiment, and be sure to review the solutions in Annex 1.

Activity 8.2: Constructing a 3D Plum Pudding Atomic Model

Create a 3D model of the plum pudding, labelling its key features.

Rutherford's Alpha Scattering Experiment

In 1909, Ernest Rutherford came up with a new model of the atom based on observations he made in his alpha scattering experiment, which were:

1. Most of the alpha particles went through the thin metal foil without any change in path.
2. A few alpha particles were deflected through small angles.
3. Very few alpha particles were deflected backwards.

Activity 8.3: Simulating Rutherford's Gold Foil Experiment

Use the simulation linked above to replicate Rutherford's experiment, and explain how he came to the following conclusions:

1. The atom is mostly made up of empty space.
2. The atom holds at its centre a small, positively charged nucleus, which contains the majority of the mass of the atom.
3. Electrons orbit the atom very distantly.

You should also explain how Rutherford's observations disagreed with Thompson's Plum Pudding model.

Ernest Rutherford's Model of the Atom (The Nuclear Model)

Rutherford proposed that the atom has a positively charged nucleus, which contains most of the mass of the atom. The nucleus is surrounded by electrons in orbit, just as the planets orbit the sun in our solar system. He said that the nucleus, together with the electrons, constitutes an electrically neutral unit.

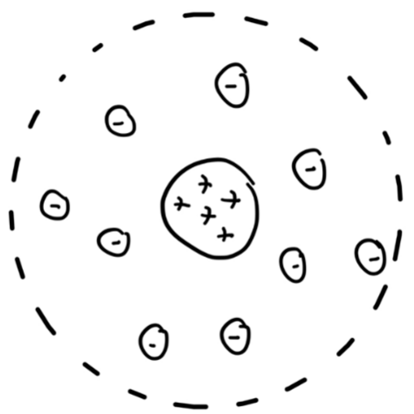


Fig. 8.5: Ernest Rutherford's Model of the Atom

Rutherford proposed the following:

1. **Nucleus:** The atom has a centre called the nucleus, which contains positively charged particles called protons. Most of the atom's mass is in the nucleus.
2. **Electrons:** Around the nucleus there are small, negatively charged particles called electrons. These electrons move in orbits at a relatively large distance from the nucleus.
3. **Orbits and Forces:** Electrons move in circular paths around the nucleus due to an attractive force between the positively charged protons and the negatively charged electrons.
4. **Empty Space:** Most of the atom is empty space, which is why many particles can pass through materials like gold foil without being deflected.
5. **Deflection:** When an alpha particle (a type of positive particle) gets close to the nucleus, it can experience a strong repulsive force, causing it to change direction or bounce back if it's heading straight toward the nucleus.

This model helped us understand that atoms are mostly empty space with a dense centre and electrons orbiting around it.

Limitations of Rutherford's Model of the Atom

1. Electrons Should Spiral In: Rutherford's model shows electrons moving in orbits around the nucleus. However, when charged particles like electrons move, they should lose energy and spiral into the nucleus, which would destroy the atom. But we don't observe atoms being destroyed this way; they stay stable.
2. Radiation Emission: If electrons were continuously emitting radiation as they moved, we would expect them to produce a mix of different frequencies of light. Instead, studies show that atoms only emit light at specific frequencies, meaning they have fixed energy levels.
3. Surprising Deflections: Rutherford's experiments with alpha particles (which are much heavier than electrons) showed that these particles were sometimes deflected at very large angles when passing through gold atoms. This was unexpected because, based on earlier models, we would expect only small deflections. Rutherford compared it to firing a cannonball at a piece of tissue paper and having it bounce back!'

Activity 8.4 Constructing a 3D Model of Rutherford's Atomic Structure

Create a 3D model of Rutherford's atom, labelling its key features.

Neils Bohr's Atomic Model

Niels Bohr proposed a new model of the atom in 1913 that built on Rutherford's ideas but addressed some of the limitations highlighted above. Here are the key points of Bohr's model:

1. Electrons in Orbits: Electrons move in specific circular paths or "orbits" around the nucleus. Each orbit corresponds to a specific energy level.
2. Quantized Energy Levels: Electrons can only occupy certain energy levels and cannot exist between these levels. When an electron jumps from a higher energy level to a lower one, it emits energy in the form of light.
3. Stable Orbits: Electrons in these orbits do not lose energy and spiral into the nucleus. They remain stable due to the balance between the attractive force of the nucleus and the motion of the electrons.
4. Emission of Light: When electrons move between energy levels, they absorb or release energy, resulting in the emission or absorption of light. This explains how atoms emit specific colours of light.

5. Hydrogen Atom: Bohr's model was particularly successful in explaining the hydrogen atom's spectrum, where the light emitted corresponds to specific energy transitions of electrons.

Protons and the neutrons are found in nucleus and the electrons move round the nucleus **in selected orbits**.

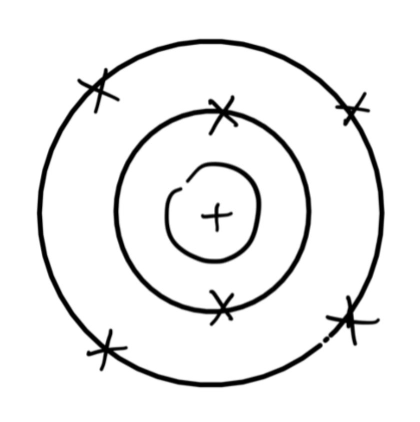


Fig. 8.6: Neils Bohr's Atomic Model

Let's observe the fluorescent light bulb…

Fig. 8.7: Fluorescent light bulb

Did you know that a fluorescent bulb works by excitation and subsequent de-excitation of mercury atoms to produce light? Read on for more information!

Energy Levels

An atom's energy levels are the different energy states that electrons can have within an atom; any other magnitudes of energy are forbidden! The energy levels are often represented as a series of parallel lines, a little like a ladder, with the lowest energies at the bottom and the highest at the top. An example of this is shown below.

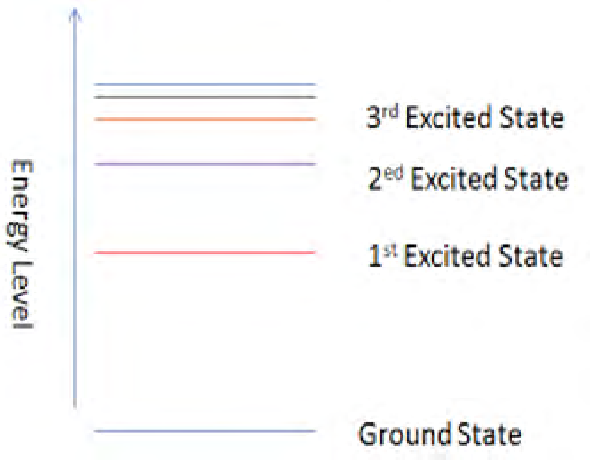


Fig. 8.7: Energy Levels

"Ground state"

The ground state is defined as the lowest allowed energy state of an atom, molecule, or ion. In other words, the ground state represents the most stable configuration.

Excited states

A particle in an excited state is an atom, ion, or molecule in which an electron is at a higher energy level than its ground state.

Transitions of electrons

Excitation

Electrons can move from one energy level to another. When an electron absorbs energy, it can jump from a lower energy level (orbit) to a higher energy level. This process is called excitation. The energy can come from various sources, such as photons of electromagnetic radiation, particle collisions or electrical energy.

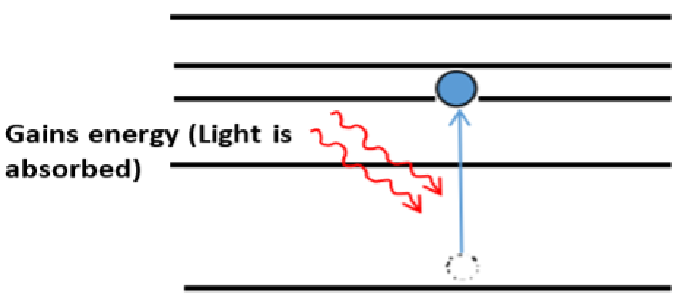


Fig. 8.8: Electron excitation due to energy absorption

De-excitation

After an electron has been excited to a higher energy level, it is unstable and eventually returns to a lower energy level. This process is called de-excitation. As it loses energy, it releases it in the form of a photon. This may be a visible light photon or may be a photon belonging to another region of the electromagnetic spectrum.

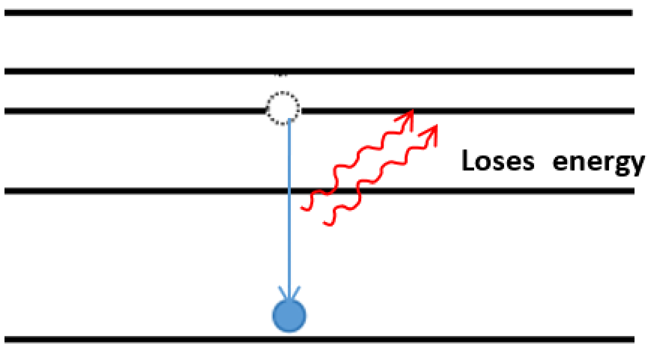


Fig. 8.9: Electron De-excitation due to energy emission

Activity 8.5: Exploring the Electromagnetic Spectrum

List the seven types of electromagnetic wave and research their corresponding frequencies and wavelength.

Table 8.1: Table to complete activity 8.5

Wave	Frequency range	Wavelength range

Calculating the frequency of photons absorbed or emitted during electron energy transitions

The figures below represent the movement of an electron from a low to a higher energy level (left) and vice versa (right).

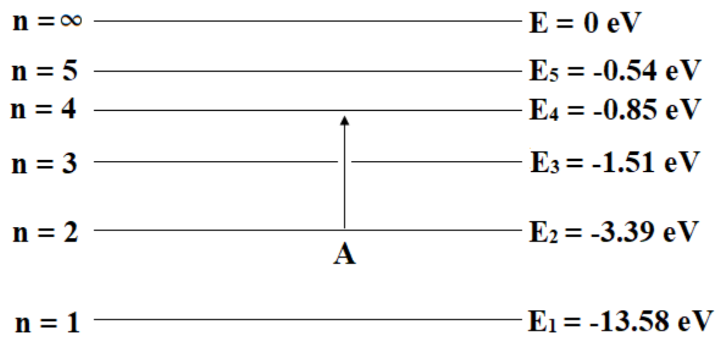


Fig. 8.10a: Electron from a low to a higher energy level

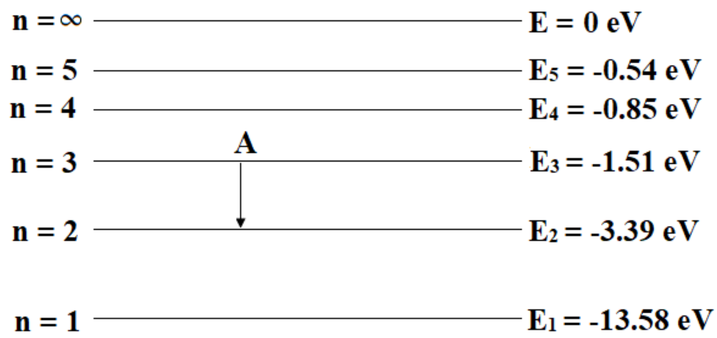


Fig. 8.10b: Electron from a high to a lower energy level

The energy carried by a photon is calculated using the formula:

$$E = hf = \frac{hc}{\lambda}$$

Where:

E is the energy of the photon (J)

h is Planck's constant (Js^{-1})

f is the frequency of the photon (Hz)

c is the speed of light (ms^{-1})

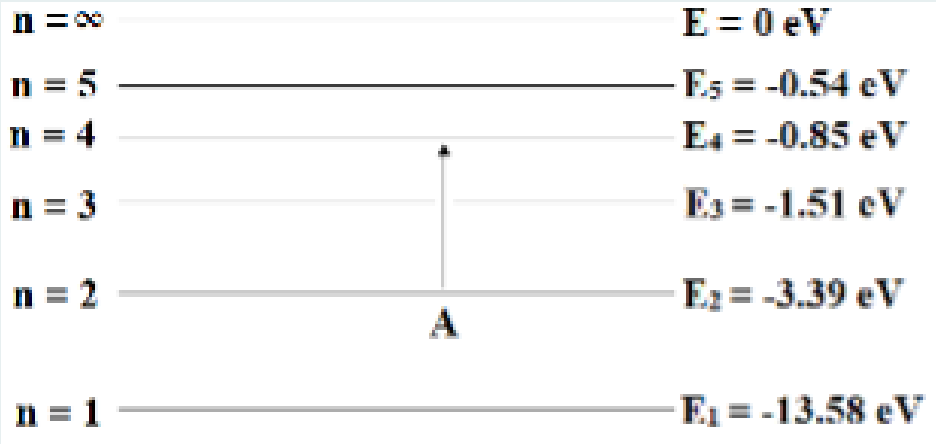
λ is the wavelength of the photon (m)

By using this equation, we can calculate the frequency or wavelength of a photon absorbed or emitted by an electron when it transitions from one energy to another.

First, we need to find the change in energy of the electron by reading values form the diagrams and converting electron volts (eV) to Joules (J).

$1eV = 1.6 \times 10^{-19}J$

Activity 8.6: Energy Transitions



From the diagram show that when an electron jumps from orbit $n = 3$ to orbit $n = 2$ it produces a photon of red light with an energy of **1.89 eV** and a wavelength of **656m.**

Activity 8.7: Calculation involving the use of the formula E = hf

1. What is the energy of a photon of frequency 3.2×10^{10} **Hz**?

   ($\boldsymbol{h} = 6.63 \times 10^{-34}$ **J s**)

2. What is the wavelength of a photon of energy 6.5×10^{-19} **J**?

3. Find the energy of a photon of wavelength 550 **nm**. $h = 6.63 \times 10^{-34}$ J s, $c = 3.0 \times 10^{8}$ m s^{-1}

4. Calculate the frequency of radiation emitted when electrons in hydrogen atom lose 10.21eV.

   ($h = 6.63 \times 10^{-34}$Js, leV = 1.6**x** 10^{-19}J)

Activity 8.8: Challenge questions

1. What is meant by the term 'ionisation energy'?

2. What is the frequency of radiation emitted when electrons in hydrogen atom moves from n=2 to n =1 states. Given the information:

$(\boldsymbol{E}_n = -\frac{13.6}{n^2}$ eV, h= 6.5×10^{-34}Js)

leV = 1.6 x10^{-19}J; c = 3.0 x10^{8}ms^{-1}

3. The energy levels of hydrogen atom are given by the expression

$E_n = -\frac{2.16 \times 10^{-18}}{n^2}$ J

What is the wavelength of radiation, which arises from transitions between n = 3 and n = 2 levels? (h = 6.5×10^{-34}Js; leV = 1.6×10^{-19}J; c = 3.0×10^{8}ms^{-1})

NUCLEAR PHYSICS

Welcome to the fascinating world of atomic structure! Today, we're going to explore the nucleus, the tiny centre of the atom, and learn about radioactivity.

The Structure of The Nucleus

The nucleus consists of the following components:

1. **Protons.** Protons are particles with a positive charge. The number of protons in an atom's nucleus determines its atomic number, which identifies the element (e.g., hydrogen has 1 proton, helium has 2 as shown in figure 1 and carbon has 6). Each proton carries a charge of +1 and has a mass of about 1.67×10^{-27} kg.
2. **Neutrons.** Neutrons are neutral particles, meaning they have no electric charge. Their mass is slightly greater than that of protons, also around 1.67×10^{-27} kg. Neutrons help stabilise the nucleus by reducing the repulsive forces between the positively charged protons.
3. **Strong Nuclear Force**. The strong nuclear force is responsible for holding protons and neutrons together. It operates over extremely short distances (about 10^{-15} meters) and is much stronger than the electromagnetic force that causes repulsion between protons, ensuring nucleons remain bound within the nucleus.

The nucleus forms the core of an atom, comprising protons and neutrons, collectively referred to as nucleons. These nucleons are held together by the strong nuclear force, which is one of the fundamental forces of nature and significantly stronger than the electromagnetic force that causes repulsion between the positively charged protons. Here's a summary of its structure:

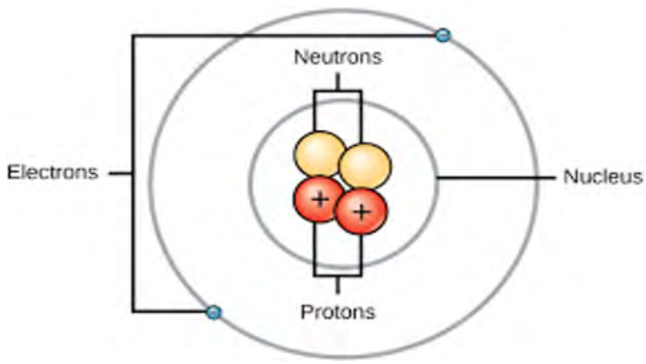


Fig 8.12: A Structure of a Helium-4 atom Nuclear Stability

Nuclear stability depends on the balance between protons and neutrons. If this balance is disrupted, with too many or too few neutrons relative to protons, the nucleus may become unstable and undergo radioactive decay to achieve a more stable state.

Identifying the number of protons and neutrons in different nuclei

The **atomic number** (symbol Z) of an element refers to the number of protons in the nucleus of each atom of that element. In a neutral atom, the atomic number also equals the number of electrons. For example, in a neutral helium atom $^{4}_{2}He$ as shown in figure 1, the atomic number is 2, indicating 2 protons and 2 electrons.

Note that in the case of an **ion**, for example the chloride ion $^{35}_{17}Cl^{-}$, the atomic number remains 17 (indicating 17 protons), but there are 18 electrons due to the additional negative charge.

The mass number (symbol A) represents the total number of protons and neutrons in the nucleus. It is also known as the nucleon number. For example, in a helium atom, the mass number is 4, indicating 4 nucleons in the nucleus.

The relationship between the mass number (A), atomic number (Z), and neutron number (N) is expressed as **A = Z + N.**

Activity 8.9: Identifying Protons and Neutrons in Atomic Nuclei

1. Calcuim $^{40}_{20}Ca$
2. Chlorine $^{35}_{17}Cl$
3. Oxygen $^{16}_{8}O$
4. Helium $^{4}_{2}He$

From the mass and atomic numbers, identify the number of protons and neutrons in the following nuclei:

Isotopes: isotopes are atoms of the same element having the same atomic number but different mass numbers due to differences in the number of neutrons.

For example:

$^{23}_{11}Na$ and $^{24}_{11}Na$ are isotopes of sodium

${}^{1}_{1}H$, ${}^{2}_{1}H$ and ${}^{3}_{1}H$ are isotopes of hydrogen

${}^{12}_{6}C$ and ${}^{13}_{6}C$ are isotopes of carbon

${}^{16}_{8}O$, ${}^{17}_{8}O$, and ${}^{18}_{8}O$ are isotopes of oxygen

${}^{35}_{17}Cl$ and ${}^{37}_{17}Cl$ are isotopes of chlorine

All elements have a number of isotopes. Hydrogen has the fewest number of isotopes with only three. The elements with the most isotopes are **caesium** and xenon, with 36 known isotopes

Table 8.2: Proton-Neutron Composition and Nuclide Notation of Sodium Isotopes

Element	No. of protons	No. of Neutrons	No. of Nucleons	Nuclide notation
Sodium-23	11	12	23	${}^{23}_{11}Na$
Sodium-24	11	13	24	${}^{24}_{11}Na$

Activity 8.10: Modelling Atomic Nuclei and Isotopes

Objective: Understanding the structure of atomic nuclei and isotopes through a hands-on model-building activity.

Materials needed:

- Modelling clay or beads in two colours (e.g., red for protons, blue for neutrons)
- Magnets (optional for bonding)
- A periodic table for reference

Instructions:

1. **Assigning Colours**:
    - Red clay/beads represent protons.
    - Blue clay/beads represent neutrons.
2. **Choosing an Element**: Select an element from the periodic table (e.g., carbon-12, oxygen-16).
3. **Building the Nucleus**:
    - Use the correct number of protons (same as the atomic number) and neutrons (varies for different isotopes) to create a nucleus model.

- For Carbon-12, you will use 6 red beads (protons) and 6 blue beads (neutrons).

4. **Creating Isotopes**: Modify your model by adding or removing neutrons to represent different isotopes of the same element. For example, you can change Carbon-12 to Carbon-14 by adding two neutrons.

5. **Discussion**:
   a. After building models, discuss how changing the number of neutrons affects the isotope but not the chemical element.
   b. Explain why isotopes have different atomic masses but the same number of protons.

6. **Presentation**: Present your nucleus models and explain the element and isotope you have created.

Activity 8.11: Understanding Radioactivity Through Dialogue

Read the dialogue from Nana Poku, Okuapeman school and Khairy, Aburi Girls

Nana Poku: Hey Khairy, have you heard about the Chernobyl accident?

***Khairy Nhyira**:* Yes, I have! It's a tragic event that happened in 1986 in Ukraine. What really struck me was how dangerous radioactivity can be.

Fig 8.13: An aerial view of the Chernobyl Disaster

***Nana Poku**:* Exactly! The explosion at the nuclear power plant released a massive amount of radioactive materials into the environment.

Khairy Nhyira: Right. So, what exactly is radioactivity?

Nana Poku: Radioactivity is when unstable atomic nuclei lose energy by emitting radiation. This can be in the form of alpha particles, beta particles, or gamma rays.

Khairy Nhyira: And that radiation can be harmful, right? Especially to living organisms?

Nana Poku: Yes, it can damage cells and even lead to cancer. That's why the areas around Chernobyl are still largely uninhabited.

RADIOACTIVITY

Radioactivity refers to the spontaneous or induced breakdown of unstable atomic nuclei, releasing energy in the form of particles like alpha (a), beta (b), and gamma radiation (g). Unstable isotopes undergo this process to become stable, a phenomenon called radioactive decay. Isotopes that exhibit radioactivity are termed radioisotopes or radionuclides, while those that don't decay are called stable isotopes. For instance, Carbon-14 is radioactive, whereas Carbon-12 and Carbon-13 are stable. There are 339 naturally occurring nuclides, with 286 classified as primordial, existing since the formation of the Solar System.

Alpha, beta, and gamma radiation all originate from the atomic nucleus (hence the name, nuclear radiation).

When an **alpha** particle is emitted, the nucleus loses 2 protons and 2 neutrons, altering its composition and turning it into a different element entirely.

When a **beta** particle is emitted, a neutron has spontaneously turned into a proton **and** an electron inside the nucleus. The electron is emitted at high speed (this is the beta particle), but the proton remains. This also means that the nucleus has turned into that of a different element.

When a **gamma** particle is emitted, the nucleus loses energy, but its structure is unchanged.

Activity 8.12: Investigating the Properties of Alpha, Beta, and Gamma Radiation

1. Research and use the chart below to record information about alpha, beta, and gamma radiation.

2. Fill in each cell with the appropriate information regarding the particle's nature, charge, mass, ionisation power, and penetrating power.

Table 8.3 Table to complete activity 8.12

	α	β	γ
Nature			
Charge			
Mass			
Penetration			
Electric and Magnetic Effect			
Ionisation			
Fluorescence			
Velocity			
Stopping Material			

Natural and Artificial Radioactivity

Nuclear radiation is emitted by multiple sources, and there is always some level of background radiation, wherever you live or work.

Natural radioactivity is the spontaneous disintegration of unstable nuclei without an external source with an emission of particles or radiation.

Artificial radioactivity is the spontaneous disintegration of unstable nuclei produced by bombarding nuclei with another nucleus with an emission of particles or radiation.

Activity 8.13: Categorising Sources of Background Nuclear Radiation

Create a Venn diagram of sources of background nuclear radiation, sorting the following into 'natural' or 'artificial':

1. Radon gas
2. Rocks, buildings and materials
3. Medical (x-ray machines, radiotherapy machines, etc)

4. Food
5. Cosmic rays
6. Nuclear power plants
7. Any others that you research!

Activity 8.14: Exploration Through Simulations and Videos

Instructions:

1. Visit the following links to explore the ionisation and penetrating power of alpha, beta, and gamma radiation.
2. Take notes on the key differences in their properties and effects.

Resources:

PhET Interactive Simulations: [PhET Radioactive Dating Game]

https://phet.colorado.edu/en/simulations/category/physics

BBC Bitesize: [Types of Radiation]

https://www.bbc.co.uk/bitesize/guides/z8j4mnb/revision/1

YouTube: Crash Course Physics: [Radiation and Radioactivity]
https://www.youtube.com/watch?v=Z5x9eU4gWwM

Activity 8.15: Exploring Applications of Radioactivity

Research the use of radioactivity. Create a poster presentation about your chosen application, explaining whether an alpha, beta, or gamma source is chosen and why. You should also discuss the 'half-life' of the isotope used, defining this term.

NUCLEAR DECAY EQUATIONS

Nuclear equations represent the **reactants and products in radioactive decay, nuclear fission, or nuclear fusion**. Instead of chemical equations, where we see that the number of atoms of a particular element is conserved in a reaction, in a nuclear reaction the atomic mass and proton numbers are conserved.

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

Nuclear reactions can be represented by equations. Such equations are known as nuclear equations. Two laws governing nuclear equations are

1. The law of conservation of mass numbers states that the total atomic numbers on both sides of the equation (left and right) must be the same or equal.

E.g. $^{a}_{b}Li + ^{c}_{d}Cl = ^{e}_{f}LiCl, \textit{ then } a + c = e$

2. Law of conservation of atomic numbers states that the total atomic numbers on both sides of the equation must be the same.

For example, if $^{a}_{b}Li + ^{c}_{d}Cl = ^{e}_{f}LiCl$ then $b + d = f$

We use the above laws to find out the missing or left-out values by equating the sum of the atomic or mass numbers at the left side of the equation to the right side of the equation.

Worked example

$^{y}_{82}Pb \rightarrow ^{214}_{83}Bi + ^{0}_{x}e + \text{energy}$

Balancing the mass numbers left and right: $y = 214 + 0 = 214$

Balancing the atomic numbers left and right: $82 = 83 + x$, therefore $x = -1$.

Activity 8.16: Balancing Nuclear Reactions

A nuclear reaction is found to be

$^{14}_{x}N + ^{4}_{2}He \rightarrow ^{y}_{8}O + ^{1}_{1}H$

Find the values of x and y in the nuclear equation given above.

Radioactive decay

Radioactive decay is the process by which an unstable atomic nucleus loses energy by emitting radiation.

This decay can occur in several forms**,** including**:**

Alpha particle decay (α)

Alpha particle emission is an emission that has alpha particles involved at the product side of the nuclear equation to produce other nuclides. E.g., if an **α** particle is emitted, the process is described as **α-decay**. In that case, the parent nuclide **loses** atomic number by **2** and mass number by **4**. This is demonstrated below:

Alpha decay of Uranium-235.

$$^{235}_{92}U \longrightarrow ^{4}_{2}He + ^{231}_{90}Th$$

Beta-decay (β)

Beta emission is an emission that has beta particles involved at the product side of the nuclear equation to produce other nuclides. If a **b particle** is emitted, the process is described as b-decay. In such a case, the parent nuclide gains an atomic number of 1 while there is **no change in mass number**. Hence, a beta particle is described as an electron with high speed.

Beta decay of Uranium-235.

$$^{235}_{92}U \longrightarrow ^{0}_{-1}e + ^{235}_{93}Np$$

Gamma emission (γ)

Gamma emission is an emission that has gamma particles involved at the product side of the nuclear equation to produce other nuclides. **Also**, if a **γ photon** is emitted, the process is described as γ-decay. In this case, there is no change in both mass number and atomic number of the parent nuclide.

Gamma decay of Uranium-235.

$$^{235}_{92}U \longrightarrow ^{0}_{0}\gamma + ^{235}_{92}U$$

Activity 8.17: Verifying Balanced and Unbalanced Nuclear Equations

Examine each nuclear reaction and determine whether it is balanced or unbalanced.

$^{244}_{96}Cm \rightarrow {}^{240}_{97}Bk + {}^{4}_{2}He$

$^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{3}_{2}He$

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

$^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e$

Activity 8.18:Determining Missing Values in Nuclear Reactions

For each of the following examples, find the missing values.

$^{238}_{92}U \rightarrow {}^{A1}_{Z1}Th + {}^{4}_{2}He$

$^{14}_{6}C \rightarrow {}^{A2}_{Z2}N + {}^{0}_{-1}e$

$^{60}_{27}Co \rightarrow {}^{A3}_{Z3}Ni + {}^{0}_{-1}e$

Activity 8.19: The Neutrino Hypothesis: Exploring Its existence through research

Research the ‘neutrino’ and explain the reason(s) why it was postulated to exist.

Annex 8.1: Solutions to some activities (Atomic Physics)

Activity 8.3: Limitations of the J.J. Thompson's model

Thompson's model of the atom faced limitations because it could not account for the results and observations of Rutherford's alpha particle experiment. Alpha particles (positive charges) were directed into a metal foil and detected on a screen afterwards.

The observations made by Rutherford that were limitations to Thompson's model are:

i. Most of the alpha particles went through the thin metal foil without any change in path

ii. A few alpha particles were deflected through small angles

iii. Very few alpha particles were deflected backwards

Thompson's model had limited success because if the electrons, which were negatively charged, were uniformly positioned throughout the mass of positive charge, there would be no strong resultant force to deflect the heavy alpha particles backwards, as observed by Rutherford.

Activity 8.5

Note that your research may give slightly different values!

Wave	Frequency range (Hz)	Wavelength range
Radio wave	Less than 3.0×10^{11}	Greater than 1 millimetre
Microwave	3×10^{11} to 10^{13}	25 micrometres – 1 millimetre
Infrared	10^{13} to 4×10^{14}	750 nanometres to 25 micrometres
Visible light	4×10^{14} to 7.5×10^{14}	400 to 750 nanometres
Ultraviolet	10^{15} to 10^{17}	1 to 400 nanometres
X-rays	10^{17} to 10^{20}	1 picometre to 1 nanometre
Gamma rays	10^{20} to 10^{24}	Less than 1 picometer

Activity 8.7

1. $E = hf = 6.63 \times 10^{-34}\ \text{J s} \times 3.2 \times 10^{10}\ \text{Hz} = 2.1 \times 10^{-23}\ \text{J}$

2. $\lambda = \frac{hc}{E}$

$$\lambda = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}\ \text{m s}^{-1}}{6.5 \times 10^{-19}\ \text{J}}$$

$\lambda = 3.1 \times 10^{-7}\ \text{m} = 300\ \text{nm}$

3. $E = \frac{hc}{\lambda}$

$$E = \frac{6.63 \times 10^{-34}\ \text{J s} \times 3.0 \times 10^{8}\ \text{m s}^{-1}}{550 \times 10^{-9}\ \text{m}}$$

$E = 3.6 \times 10^{-19}\ \text{J}$

4. E = hf,

Making ‘f’ the subject

$f = \frac{E}{h}$

$E = 10.21\text{eV} = 10.21 \times 1.6 \times 10^{-19}$

Substituting into the formula

$$f = \frac{E}{h} = \frac{10.21 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}} = 2.48 \times 10^{15}\text{Hz}$$

Activity 8.8

1. The ionisation energy is the energy needed to allow an electron to leave its ground a state and be freed from the electrostatic pull of the atom.

2. $E_1 = -\frac{13.6}{1^2} = -13.58 \text{ eV} = -13.6 \text{ eV}$

$E_2 = -\frac{13.6}{2^2} \text{ eV} = -3.39 \text{ eV}$

$\Delta E = hf$, $\Delta E = E_2 - E_1$ then $hf = E_2 - E_1$

Making 'f' the subject

$f = \frac{\boldsymbol{E_2 - E_1}}{\boldsymbol{h}}$

$\boldsymbol{E_2 - E_1} = -3.39 - (-13.6) = 10.21 \text{ eV}$

$\boldsymbol{E_2 - E_1} = 10.21 \times 1.6 \times 10^{-19} \text{J}$

Substituting into the formula

$f = \frac{\boldsymbol{E_2 - E_1}}{\boldsymbol{h}} = \frac{10.21 \times 1.6 \times 10^{-19}}{6.5 \times 10^{-34}} = 2.48 \times 10^{15} \text{ Hz}$

3. Given $E_n = -\frac{2.16 \times 10^{-18}}{n^2} \text{J}$, when n = 1

$E_1 = \frac{2.16 \times 10^{-18}}{1^2} = -2.16 \times 10^{-18} \text{J}$

When n = 2, the state has energy

$E_2 = \frac{-2.16 \times 10^{-18}}{2^2} = -0.54 \times 10^{-18} \text{J}$

When n = 3, the state has energy

$E_3 = \frac{-2.16 \times 10^{-18}}{3^2} = -0.24 \times 10^{-18} \text{J}$

$E_3 - E_2 = hf$ but $f = \frac{c}{\lambda}$

$E_3 - E_2 = \frac{hc}{\lambda} \rightarrow \lambda = \frac{hc}{E_3 - E_2}$

$\lambda = \frac{6.6 \times 10^{-34} \times 3.0 \times 10^{8}}{-0.24 \times 10^{-18} - (-0.54 \times 10^{-18})} = 6.6 \times 10^{-7} \text{m}$

Annex 8.2: Solutions to some activities (Nuclear Physics)

Activity 8.9

- **Calcium (Ca)**
  - Mass Number: 40 (most common isotope: Ca-40)
  - Atomic Number: 20
  - Proton Number: 20
  - Neutron Number: 20 (40 - 20 = 20)
- **Chlorine (Cl)**
  - Mass Number: 35 (most common isotope: Cl-35)
  - Atomic Number: 17
  - Proton Number: 17
  - Neutron Number: 18 (35 - 17 = 18)
- **Oxygen (O)**
  - Mass Number: 16 (most common isotope: O-16)
  - Atomic Number: 8
  - Proton Number: 8
  - Neutron Number: 8 (16 - 8 = 8)
- **Helium (He)**
  - Mass Number: 4 (most common isotope: He-4)
  - Atomic Number: 2
  - Proton Number: 2
  - Neutron Number: 2 (4 - 2 = 2)

Activity 8.12

	α	β	γ
Nature	Helium nucleus	Fast Moving electron	Electromagnetic wave
Charge	Positive	Negative	Neutron
Mass	Heaviest	Heavy	No effect
Penetration	Least	Great	Greater
Electric and Magnetic Effect	Little	High	No effect
Ionization	High	Moderate	Least
Fluorescence	Large	Small	Nil
Velocity	Slow	Fast	Very slow
Stopping Material	Thin paper	Aluminum Foil	Thick lead

Annex 8.3: Further Information on Nuclear Physics

Important applications of nuclear radioactivity across different fields

1. **Medical Applications**

   Radiotherapy: Used in cancer treatment to target and kill cancerous cells.

   Diagnostic Imaging: Techniques like PET (Positron Emission Tomography) and SPECT (Single Photon Emission Computed Tomography) use radioactive tracers to visualize bodily functions.

   Sterilisation: Radioactive sources are used to steriliSe medical equipment and pharmaceuticals by killing bacteria and other pathogens.

2. **Industrial Applications**

   Radiographic Testing: Used for non-destructive testing of materials and welds to identify structural integrity.

   Gauging Devices: Radioactive isotopes are used in devices for measuring the thickness of materials in manufacturing processes.

Tracer Studies: Radioisotopes are used as tracers in industrial processes to follow the movement of materials and diagnose leaks in systems like oil pipelines.

3. **Energy Production**

   Nuclear Power: Nuclear reactors use controlled chain reactions of radioactive isotopes, primarily uranium-235 and plutonium-239, to generate electricity.

   Nuclear Propulsion: Radioactivity is also used in submarines and spacecraft for power and propulsion systems.

4. **Agriculture**

   Food Irradiation: Radioactivity is used to preserve food by killing bacteria and parasites, extending shelf life.

   Mutation Breeding: Inducing mutations in plants to develop new varieties with desirable traits and disease resistance.

   Fertiliser Efficiency: Radioisotopes are used in tracer studies to optimize fertilizer usage by tracking the uptake of nutrients by plants.

5. **Scientific Research**

   Radiometric Dating: Techniques like carbon dating use the decay of radioactive isotopes to determine the age of archaeological finds.

   Environmental Tracing: Radioactive isotopes can help track pollution sources and study environmental changes.

   Tracer Studies in Biology and Chemistry: Radioisotopes are used as tracers to study biological processes, chemical reactions, and drug metabolism.

   Fundamental Research: Radioactive materials are used in experiments to study the properties of atoms, nuclear reactions, and subatomic particles.

   Geological Dating: Other isotopes like Uranium-238 and Potassium-40 are used to date rocks and geological formations to determine the age of the Earth

6. **Space Exploration**

   Radioisotope Thermoelectric Generators (RTGs): These are used in spacecraft to provide power for long-duration missions, utilizing the heat generated from radioactive decay.

7. Smoke Detectors

Some smoke detectors use americium-241, a weak radioactive source, to detect smoke particles.

In all these applications, the controlled use of radioactivity allows for significant advancements in technology, science, and medicine while emphasising safety to minimise radiation exposure.

Annex 8.4: Solutions to some activities (Nuclear decay equations)

Activity 8.16

From the law of conservation of mass numbers

$14 + 4 = y + 1 \rightarrow y = 18 - 1 = 17$

From the law of conservation of atomic numbers $x + 2 = 8 + 1 \rightarrow x = 9 - 2 = 7$

Activity 8.17

Balanced or unbalanced

$^{244}_{96}Cm \rightarrow\ ^{240}_{97}Bk + ^{4}_{2}He$ UNBALANCED

$^{210}_{84}Po \rightarrow\ ^{206}_{82}Pb + ^{3}_{2}He$ UNBALANCED

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

$^{60}_{27}Co \rightarrow\ ^{60}_{28}Ni + ^{0}_{-1}e$ BALANCED

Activity 8.18

$^{238}_{92}U \rightarrow\ ^{238}_{90}Th + ^{4}_{2}He$

$^{14}_{6}C \rightarrow\ ^{14}_{7}N + ^{0}_{-1}e$

$^{60}_{27}Co \rightarrow\ ^{60}_{28}Ni + ^{0}_{-1}e$

REVIEW QUESTIONS

Review Questions 8.1 (Atomic Physics)

1. What are the main limitations of Dalton's Atomic Model?
2. Describe the key features of Thompson's Atomic Model.
3. What is the major limitation of Rutherford's Atomic Model?
4. How does Bohr's Atomic Model explain electron energy levels?
5. What formula relates the energy of a photon during a transition?
6. What is the significance of Planck's Constant in calculating photon energy?

Review Questions 8.2 (Nuclear Physics)

1. Describe the structure of alpha, beta, and gamma radiation.
2. Radiation is detected from inside a thick concrete bunker. What type of radiation is it likely to be?
3. Describe the structural difference between carbon-12 and carbon-14.
4. Research and summarise the use of carbon-14 in the aging of fossils.

Review Questions 8.3 (Nuclear decay equations)

1. Some nuclides were obtained in some nuclear bombardment processes. Determine the values of *x*, *y* and *z* in the following nuclear reaction equation below:

   i. $^{222}_{86}Rn \rightarrow ^{x}_{84}Po + ^{4}_{2}He$ + energy

   ii. $^{y}_{82}Pb \rightarrow ^{214}_{83}Bi + ^{0}_{-1}e$ + energy

   iii. $^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{z}_{6}C + ^{1}_{0}n$ + energy

   iv. $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{148}_{57}La + ^{85}_{35}Br + x\ ^{1}_{0}n$ + energy

ANSWERS TO REVIEW QUESTIONS

Answers to Review Questions 8.1

1. Dalton's Model limitations:
   - Doesn't explain isotopes or ions.
   - Assumes atoms are indivisible.
2. Thompson's Model key features:
   - Electrons embedded in a sphere of positive charge.\
3. Rutherford's Model limitation:
   - Doesn't explain electron behaviour (not spiraling in towards the nucleus) or energy levels.
4. Bohr's Model explanation:
   - Electrons occupy specific energy levels (shells).
   - Energy levels are quantized.
5. Photon energy formula:
   - $E = hf$ (Energy = Planck's Constant x Frequency)
6. Planck's Constant (h) relates the energy of a photon to its frequency.

Answers to Review Questions 8.2

1. Alpha particles are made up of two protons and two neutrons. Beta particles are high speed electrons. Gamma is a high frequency electromagnetic wave.
2. Gamma radiation.
3. Carbon 12 contains 6 protons and 6 neutrons. Carbon 14 contains 6 protons and 8 neutrons.
4. Living organisms take in and excrete carbon throughout their lives. Some of this carbon is carbon-14 which is radioactive; the level of carbon-14 inside a living organism is stable. When the organism dies, the amount of carbon-14 begins to decrease as the nuclei emit their radiation to become stable. By measuring the activity of a fossilised organism and comparing this to that of a live sample we can estimate the time since death.

Answers to Review Questions 8.3

1.

i. $^{222}_{86}Rn \rightarrow {}^{x}_{84}Po + {}^{4}_{2}He$ + energy

Mass number is conserved

222 = x + 4

∴ x = 222 – 4 = 218

ii. $^{y}_{82}Pb \rightarrow {}^{214}_{83}Bi + {}^{0}_{-1}e$ + energy

y = 214 + 0 = 214

iii. $^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{z}_{6}C + {}^{1}_{0}n$ + energy

9 + 4 = z + 1

∴ z = 13 – 1 = 12

iv. $^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{148}_{57}La + {}^{85}_{35}Br + x\,{}^{1}_{0}n$ + energy

For Mass number conservation,

235 +1 = 148 + 85 + x => 236 = 233 + x => x = 236-233 = 3

Also, for Atomic number conservation,

92 + 0 = 57 + 35 + x(0) => 92 =92 + 0 =92 (conserved).

EXTENDED READING

- Khan Academy - Atomic Structure [Khan Academy Atomic Structure](https://www.khanacademy.org/science/chemistry/atomic-structure)
- Chemistry LibreTexts [Chemistry LibreTexts - Atomic Models](https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_General_Chemistry_(OpenStax)/02%3A_Atoms_and_Elements/2.02%3A_Models_of_the_Atom), Detailed explanations of various atomic models.
- BBC Bitesize - Atomic Structure [BBC Bitesize - Atomic Structure](https://www.bbc.co.uk/bitesize/topics/zn8syrd/articles/z3xq4wx) User-friendly overview of atomic models for students.
- A fun, informative breakdown of atomic models. NASA - Atomic Structure [NASA Atomic Structure](https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-an-atom-58.html)

These links should provide you with a good overview and images of different atomic models.

- https://www.sciencephoto.com/media/608516/view/balmer-series-animation
- https://study.com/academy/lesson/balancing-nuclear-equations-predicting-the-product-of-a-nuclear-reaction.html

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2. "Physics for Scientists and Engineers" by Paul A. Tipler, et al.
3. "Atomic Physics" by C.J. Foot
4. Khan Academy - Atomic Nucleus
5. Crash Course - Radioactivity
6. HyperPhysics - Atomic Nucleus
7. "The Atomic Nucleus" by J. R. Rumble (Journal of Chemical Education)
8. "Radioactivity" by R. E. Krebs (American Journal of Physics)
9. NASA - Atomic Nucleus
10. Los Alamos National Laboratory - Radioactivity
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12. "Nuclear Physics" by Irving Kaplan
13. "Introduction to Nuclear Reactions" by C. A. Bertulani
14. "Nuclear Reactor Physics" by Weston M. Stacey
15. Khan Academy - Nuclear Reactions
16. Nuclear Reactions - HyperPhysics
17. Balancing Nuclear Reactions - Chemistry LibreTexts
18. "Nuclear Reactions and Nuclear Stability" by R. E. Krebs (American Journal of Physics)
19. "Balancing Nuclear Reactions" by J. R. Rumble (Journal of Chemical Education)
20. Balancing Nuclear Reactions - Physics Classroom
21. Nuclear Reactions - MIT OpenCourseWare

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