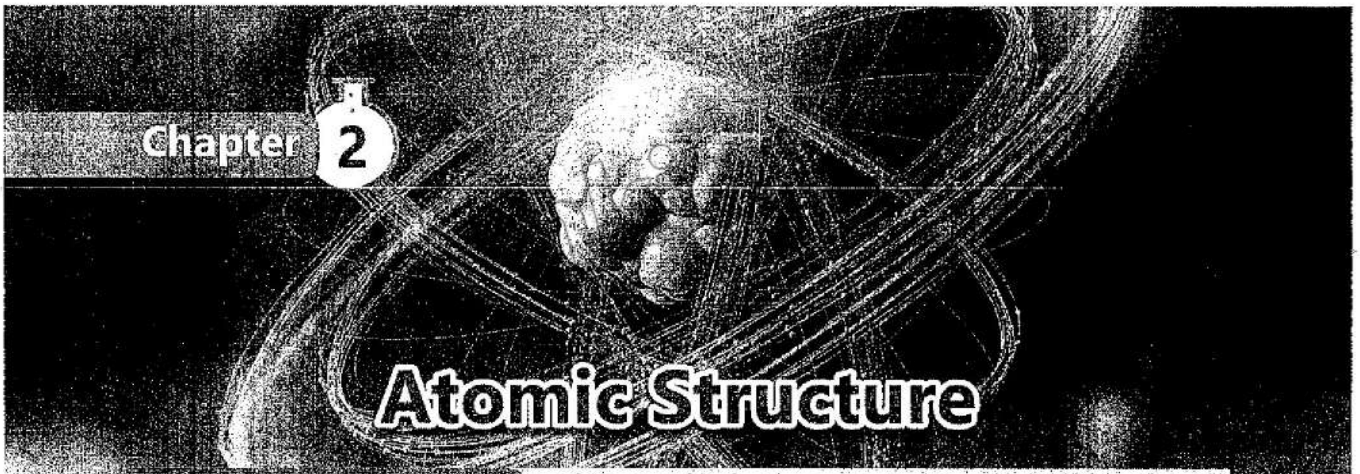


Chapter 2

Atomic Structure

Student Learning Outcomes

After studying this chapter, students will be able to:

- Explain the structure of the atom as a central nucleus containing neutrons and protons surrounded by electrons in shells
- State that, orbits (shells) are energy levels of electrons and a larger shell implies higher energy and greater average distance from nucleus
- State that electrons are quantum particles with probabilistic paths whose exact paths and locations cannot be mapped (with reference to the uncertainty principle}
- Explain that a nucleus is made up of protons and neutrons held together by strong nuclear force
- Explain that an atomic model is an aid to understand the structure of an atom.
- State the relative charge and relative masses of a subatomic particles (an electron, proton and neutron)
- Interpret the relationship between a subatomic particle, their mass and charge.
- Illustrate the path that positively and negatively charged particles would take under the influence of a Uniform Electric Field.
- Define proton number / atomic number as the number of protons in the nucleus of an atom.
- Explain that the proton number is unique to each element and used to arrange elements in periodic table
- State that radioactivity can change the proton number and alter an atom's identity
- Define nucleon number / atomic mass as sum of number of protons and neutrons in the nucleus of an atom.
- Define isotopes as different atoms of the same element that have same number of protons but different neutrons
- State that isotopes can affect molecular mass but not chemical properties of an atom
- Determine the number of protons and neutrons of different isotopes
- Define relative atomic mass as the average mass of isotopes of an element compared to 1/12th of mass of an atom of Carbon-12
- State that isotopes can exhibit radioactivity

- Discuss the importance of isotopes using carbon dating and medical imaging as examples. Describe the formation of positive (cation) and negative (anion) ions from atoms.
- Interpret and use the symbols for atoms and ions
- Calculate relative atomic mass of an element from relative masses and abundance of isotopes,
- Calculate the relative mass of an isotope given relative atomic mass and abundance of all stable isotopes.

Introduction

Elements are very different from one another. A large number of elements exist as solids and very few are present as liquids while the rest exist as gases. All these elements are however made up of atoms.

Have you ever thought why these elements are so different from one another? Iron looks very different from gold which, in turn, is very different from aluminium or zinc (Fig: 2.1). Iron is a heavy metal while aluminium and zinc are light metals. Metals are mostly lustrous while non-metals like sulphur and carbon appear dull. The difference in the properties of elements is due to the difference in the properties of their constituent atoms.

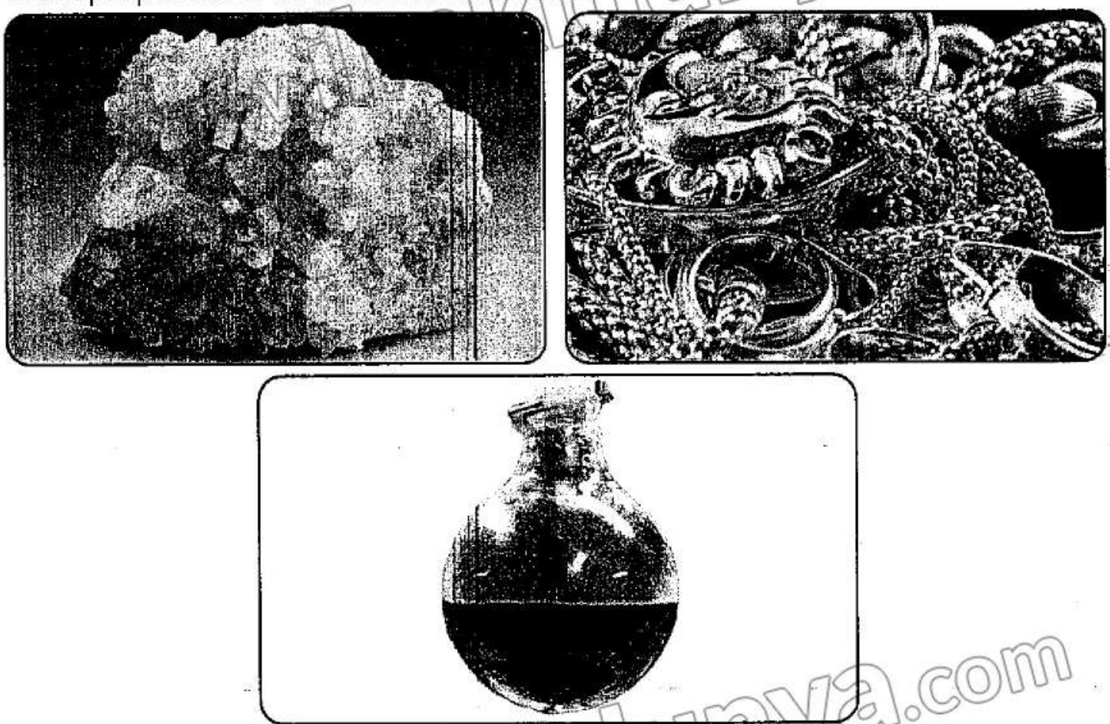


Fig (2.1) Different Elements look different

Write down the names of the elements shown in the above pictures.

2.1 Structure of Atom

In 1803, an English chemist, John Dalton, in his famous theory 'Dalton's atomic theory', proposed atoms to be indivisible. In other words, according to him, it was not possible to divide atoms to smaller particles. In the last decade of nineteenth century, a group of scientists were trying to pass electricity through gases at reduced pressure. During the course of these experiments known as 'Discharge Tube Experiments', they discovered that atoms are no longer the smallest particles of matter; rather there exist particles that are even smaller than atoms. In other words, atoms are composed of negatively charged particles called electrons and positively charged particles called protons. It was also discovered that a proton is 1836 times heavier than an electron. In a discharge tube, the presence of the negatively charged particles was ascertained because of their deflection towards the positive plate in an electric field. Similarly, the presence of positively charged particles was confirmed due to their deflection towards the negative plate.

Interesting Information!

Although the nucleus is less than one hundred-Thousandth (1/100,000) of the size of the atom, it contains more than 99.9% of the mass of the atom.

Discovery of Electrons

A discharge tube is a hard glass tube provided with two metallic electrodes and a vacuum pump to evacuate the gas present in it Fig (2.2). When a very high voltage is applied to an evacuated glass tube the glass surface behind the positive electrode started to glow, due to the rays emitted from the cathode. These rays were named as cathode rays. In 1897, British physicist Joseph John Thomson studied the properties of cathode rays by passing them through the oppositely charged electric plates. It was observed that cathode rays bent towards the positively charged plate showing that they carry negative charge. Thomson also installed two magnets on either side of the discharge tube and noticed that cathode rays were also diverted by the magnetic field. Thomson used the findings of his experiments to calculate the mass to charge ratio of cathode rays which finally proved that cathode rays are in fact, negatively changed material particles. These

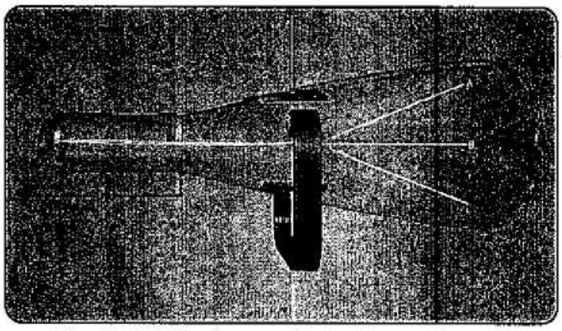


Fig (2.2) Discharge Tube Experiment Cathode Rays

particles were later named as electrons. It was also shown that electrons are the subatomic particles of all elements.

Discovery of Proton

The presence of positively charged particles in an atom had been first observed by E.Goldstein in 1886. It was based on the concept that atoms are electrically neutral having same number of positive and negative charges. He performed a series of experiments with a gas-discharge tube having a perforated cathode. A new type of rays were produced from the anode which moved towards the cathode. He called these new rays as canal rays or anode rays.

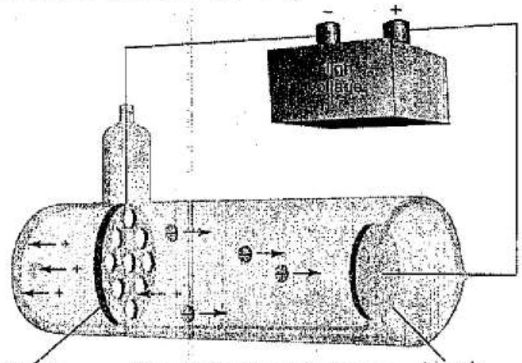


Fig (2.3) Anode Rays

The properties of these rays seemed to vary depending on the gas used in the discharge tube. In fact what he discovered was gas ions and this also included hydrogen ion (H^+). Goldstein at that time knew nothing about its significance.

In 1917, Rutherford performed experiments which proved that the hydrogen nucleus is present in other nuclei. Rutherford thought that a hydrogen nucleus or a proton must be the fundamental building block of all nuclei and also possibly a new fundamental particle as well.

Origin of Cathode and Anode Rays

Cathode rays are so named because they are emitted by the cathode in a discharge tube. A very high electrical potential of thousands of volts was applied in the discharge tube which ionized the residual gas atoms present in the tube. The positive ions thus produced travelled towards the cathode as anode or canal rays. When they collided with the cathode they knocked electrons out of its surface. This stream of electrons was called cathode rays.

Discovery of Neutron

Later on, in 1933, another particle neutron was also discovered, which is known to carry no charge. The mass of a neutron is almost the same as that of a proton. These three particles i.e. electron, proton and neutron were given the name fundamental particles and are shown to be present in all atoms irrespective of the fact that these atoms behave very different from one another. It was, however, also shown that the number of these particles is different in different atoms.

After the discovery of these particles, a very important question arose as to how these particles are arranged in a tiny place called atom. In other words, what is the structure of an atom?

Lord Rutherford, in 1911, provided answer to this question. He carried out a remarkable experiment in which he hit a stream of special type of particles to a very thin gold foil. From this experiment he concluded that an atom has two portions. A tiny central portion which he called as nucleus and a relatively large area surrounding this, which he called extra nuclear portion.

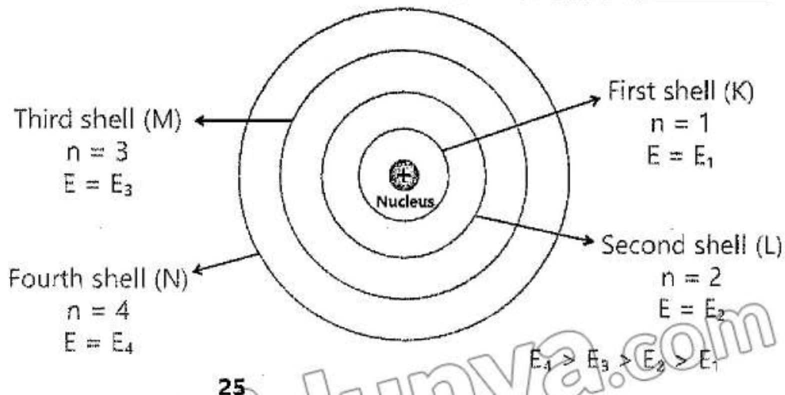
It was also discovered that almost all the mass of an atom is concentrated in the nucleus, because both the heavy particles i.e. protons and neutrons are found to be present here. In the nucleus these two particles are held together by a strong nuclear force. Electrons are, however, revolving around the nucleus in fixed circular paths called orbits or shells. Since electron present in each shell has a fixed energy, these shells are also named as energy levels. The shell which is nearest to the nucleus is called first shell or K shell and the electron present in it has a fixed value of energy. Similarly, the second shell will also be at a definite distance from the nucleus which will, of course, be greater than the first shell and electron present in it will also possess greater value of energy. Similarly, electron may also be present in the third or higher shells.

Each shell is further sub-divided into sub-shells or orbitals. The number of sub-shells present in a shell is equal the value of n for that shell. For the first shell, (n = 1), it will, therefore, have only one sub-shell which is called **s** sub-shell. For (n = 2), there will be two sub-shells **s** and **p**. The second shell will, therefore, have two sets of sub-shells. The third shell (n = 3) has three sub-shells **s**, **p** and **d**. The fourth shell consists of four sub-shells **s**, **p**, **d** and **f**.

Interesting Information!

The size of an atom is so small that it is not possible to see with naked eyes. However, a transition electron microscope can be used to see atoms.

According to modern approach, electrons are like charged clouds whose location around the nucleus cannot be predicted with one hundred percent certainty. All



we can say is that there is a certain probability of finding the electron at a certain probable distance from the nucleus.

Table (2.1) Charges and Masses of Sub-Atomic Particles

Particle	Charge	Mass
Electron	-1.6022×10^{-19} C	9.109×10^{-31} Kg
Proton	$+1.6022 \times 10^{-19}$C	1.673×10^{-27} Kg
Neutron	0.0	1.675×10^{-27} Kg

Interesting Information!

The largest atom cesium is approximately nine times bigger than the smallest atom helium.

In order to find out the number of electrons which can be accommodated in these extra nuclear shells, the scientists have devised formula called ($2n^2$) formula where n can have values 1,2, 3 ... and so on and they represent the number of shells. Shells have also been named as **K, L, M, N** ... and so on. When the value of n is one, it means first or K shell and the maximum number of electrons which can be present in this shell is ($2 \times 1^2 = 2$). K shell can, however, have less than two electrons or it may not have any electron.

Similarly when ($n = 2$), it means second or L shell and the maximum number of electrons it can accommodate is ($2 \times 2^2 = 8$). For ($n = 3$) or M shell, it can accommodate 18 electrons at the most. This process will go on until the electrons present in an atom are finished.

The maximum number of electrons which can be accommodate in sub-shells **s**, **p**, **d** and **f** are 2, 6 10 and 14 respectively. In the first shell there are 2 electrons which shell go to (**s**) sub-shell. In the second shell, 8 electrons will be further sub-divided, s-subshell will have 2 electrons and 6 electrons will be accommodated in p sub-shell.

2.2 Atomic Number and Mass Number

Electrons, protons and neutrons are called the fundamental particles of all types of matter. In other words, the atoms of all the elements present in this world contain same electrons, protons and neutrons. However, an atom of one element differs from an atom of another element because it contains different number of the fundamental particles.

The number of protons present in the atoms of an element is always fixed and it is called the atomic number of that element. Since an atom, as a whole, is electrically neutral, the number of electrons present in an atom will be the same as the number of protons. Atomic number of an element is represented by **Z**. Atomic number of an element is unique to that element and the element is identified by this number. In a periodic table of elements, the elements are arranged according to ascending order of their atomic numbers.

The total number of protons and neutrons present in an atom almost accounts for the total mass of that atom and hence it is called its nucleon number or mass number. It is represented by **A**. The mass of electron being very small is not included in the mass number.

Just like atomic number, the atom of an element may also be identified from its mass number. For example, the number of protons present in an oxygen atom is 8, so its atomic number is 8 while the total number of protons and neutrons present in it is 16, so its mass number is 16. Information about the atomic number and the mass number is often included with the symbol of any element. The atomic number is written as a left subscript while the mass number as a left superscript. So, oxygen atom would be symbolized as ${}^{16}_{8}O$. Similarly, carbon atom symbolized as ${}^{12}_{6}C$ will have 6 protons and 6 neutrons.

The number of neutrons **N** present in an atom can be calculated if its atomic number **Z** and mass number (A) are known.

$$N = A - Z$$

Thus, the number of neutrons in chlorine atom, symbolized as ${}^{35}_{17}Cl$, can be calculated as 35 – 17 = 18

Interesting Information!

Copernicium (Cn) is a synthetic element and it was discovered in 1996. This metal turns into a gas at room temperature.

Sample Example 1:

Calculate the number of neutrons, protons and electrons in barium ${}^{137}_{56}Ba$

Solution: Each barium atom will have 56 protons and 56 electrons. The number of neutrons in boron will be calculated as follows:

$$N = A - Z$$

$$N = 137 - 56 = 81$$

So each ${}^{137}_{56}Ba$ atom will have 81 neutrons, 56 protons and 56 electrons.

Solved Example 2:

Calculate the number of neutrons, protons and electron in an atom of uranium $^{238}_{92}U$

Solution: Each uranium atom will have 92 protons and 92 electrons. The number of neutrons will be calculated as follows:

$$N = A - Z$$

$$N = 238 - 92 = 146$$

So each $^{238}_{92}U$ atom will have 146 neutrons, 92 protons and 92 electrons.

Exercise

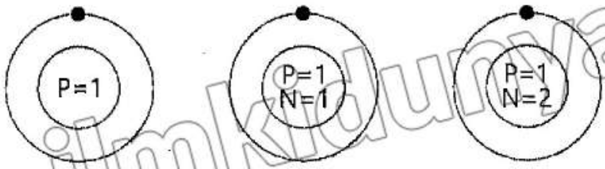
Calculate the number of neutrons, protons and electrons in the following atoms.

$^{195}_{78}Pt$, $^{55}_{25}Mn$, $^{127}_{53}I$

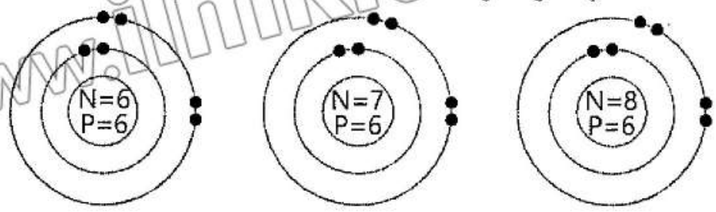
2.3 Isotopes and their Masses

All the atoms of an element must necessarily have the same atomic number, but their mass number may vary depending upon the number of neutrons present in the nucleus. Atoms of the same element having different number of neutrons in their nuclei are called isotopes. For example, element carbon has three isotopes as its atoms have six, seven and eight neutrons in their nuclei. These isotopes are represented as $^{12}_{6}C$, $^{13}_{6}C$, $^{14}_{6}C$. Similarly, hydrogen exists in three isotopes Hydrogen, Deuterium and Tritium represented by $^{1}_{1}H$, $^{2}_{1}H$, $^{3}_{1}H$. $^{1}_{1}H$ is the only atom which does not have a neutron. Since the chemical properties of the elements are determined by the number of electrons, all three isotopes will show almost the same chemical behaviour, although their physical properties may be different.
$^{2}_{1}H$ has twice the mass of $^{1}_{1}H$ while the mass of $^{3}_{1}H$ is thrice as the mass of $^{1}_{1}H$. Similarly, the masses of three different isotopes of carbon are different.

Isotopes of Hydrogen Atom, $^{1}_{1}H$, $^{2}_{1}H$, $^{3}_{1}H$



Isotopes of Carbon Atom, $^{12}_{6}C$, $^{13}_{6}C$, $^{14}_{6}C$



Exercise: Why isotopes of an element show same chemical properties while their physical properties are different?

Radioactive Isotopes

The isotopes of the same element do not have the same physical properties. Several isotopes of the same chemical elements exist whose nuclei are unstable. They emit excess energy in the form of radiation. This radiation is called radioactivity and the isotope which emits energy is called radioactive isotope. Every element has one or more radioactive isotope. Tritium $^{3}_{1}H$ is a radioactive isotope and the other two are stable and do not emit any radiation.

When a radioactive element emits radiation, it is transformed into another chemical element. This process is called radioactive decay. This new element may be stable or may be radioactive so that it also emits radiation.

$^{238}_{92}U$ (Uranium) $\longrightarrow$ $^{234}_{90}Th$ (Thorium) + energy

$^{234}_{90}$ Thorium is unstable and further disintegrates to give $^{231}_{91}$Pa (Protactinium)

$^{234}_{90}Th$ (Thorium) $\longrightarrow$ $^{23}_{91}Pa$ (Protactinium)

$^{210}_{83}Bi$ (Bismuth) $\longrightarrow$ $^{206}_{81}Tl$ (Thallium) + energy

Interesting Information!

Every year, our body replaces about 98% of its atoms.

Applications of Radioactive Isotopes

Radioactive isotopes are useful in medical imaging. Doctors use them to diagnose the disease by injecting the patient with a small amount of radioactive fluid. Technetium – 99m is used for diagnostic imaging across human organs like brain, lungs, etc. Doctors use a special camera to watch how the radioactive fluid moves.

Exercise

1. Why does a radioactive isotope emit radiation?
2. Give an example of a radioactive isotope which disintegrates to give a stable atom.

Interesting Information!

Gallium has many interesting properties. Its melting point is below body temperature so it is liquid at room temperature. It has water like viscosity. It does not evaporate.

Radiocarbon dating is a method for finding out the age of an historical object containing organic material with the help of radioactive isotope of carbon $^{14}_{6}C$. The method involves measuring the proportion of ^{14}C in a sample from a dead plant or animal like a piece of wood or a bone which provides information that can be used to calculate when an animal or plant died. The older the sample is, the less ^{14}C is to be detected.

Radioactive isotopes are used to test the strength of metals and concrete mixture. They are used to generate cheap nuclear power and to find oil fields. In medicine they are used to diagnose and treat many medical conditions and diseases, including cancer and thyroid disorders.

Ionization of Atoms by a Radioactive Source

Radiation emitted from a radioactive source causes ionization of atoms. For example, heat or light energy coming from the Sun or a radioactive element can remove electron or electrons from the atom. However, this ionizing radiation should have enough energy to remove the tightly bound electron from the orbit of an atom.

$$Na \xrightarrow{\text{Energy}} \underset{\text{Cation}}{Na^{+}} + e^{-}$$

However, the electron will be lost only when there is present another atom which can accept it.

$$Cl + e^{-} \longrightarrow \underset{\text{Anion}}{Cl^{-}} + \text{Energy}$$

Interesting Information!

All artificial isotopes are unstable and therefore radioactive.

Relative Atomic Mass

Ever since the existence of atom was recognized, the chemists were trying to find out a method which would allow them to compare the masses of different atoms. It was necessary because without knowing the relative masses of atoms, we would not know in which ratio of masses we mix the reactants to carry out a chemical reaction. In 1961, the chemists adopted a new scale for the measurement of the relative masses of atoms. The unit mass on this scale is $1/12^{th}$ of the mass of lighter isotope of carbon taken as 12. The mass of one atom of carbon on this scale is exactly 12 and the masses of the other atoms are measured relative to this unit. The relative atomic mass of an element is thus defined as the mass of an atom of that element relative to the mass of light isotope of carbon taken as 12. The relative atomic masses of elements are expressed in atomic mass unit (amu). It is defined as one-twelfth the mass of an atom of carbon-12.

$$1amu = 1.67377 \times 10^{-27} kg$$

For example, the mass of one atom of hydrogen-1 is 1.007 amu, the mass one atom of sulphur-32 is 31.972 amu.

Exercise

How would you compare the masses of the atoms of C, Mg and Cl?

Calculation of Relative Atomic Mass from Isotopic Abundance

An element usually consists of a few different isotopes with different mass numbers. These mass numbers are called relative isotopic masses. Each isotope will also have its own naturally occurring abundance which is called isotopic abundances.

Relative atomic mass of an element can be calculated from the relative isotopic masses and isotopic abundance.

The element Krypton (Kr) has five isotopes. Their relative isotopic masses and isotopic abundances are shown in the following table (2.2).

Table (2.2) Isotopic Abundances of Krypton

Relative Isotopic Mass	Isotopic Abundance
80	2.0%
82	12.0%
83	12.0%

84	57.0%
85	17.0%

Sample Example 1:

Relative atomic mass of krypton

$$= \frac{80 \times 2.0 + 82 \times 12.0 + 83 \times 12.0 + 84 \times 57.0 + 85 \times 57.0}{100}$$

$$= 83.7$$

Sample Example 2:

Calculate the relative atomic mass of light isotope of chlorine

Relative atomic mass of chlorine $= \frac{Cl \times 75.77 + 37 \times 24.23}{100}$

$$35.45 = \frac{Cl \times 75.77 + 37 \times 24.23}{100}$$

$$3545 = Cl \times 75.77 + 37 \times 24.23$$

$$3545 - 896.51 = Cl \times 75.77$$

$$2648.49 / 75.77 = Cl$$

$$34.95 = Cl$$

Relative atomic mass of light isotope of chlorine is 34.95.

Exercise

Calculate the relative atomic mass of Lead (Pb). Isotopic abundances of isotopes are 2.0, 24.0, 22.0, 52.0 respectively.

^{204}Pb ^{206}Pb ^{207}Pb ^{208}Pb

Key Points

1. An English chemist, John Dalton, proposed that atoms are indivisible.
2. Discharge tube experiments showed that atoms are no longer smallest particles of matter. Rather they are made up of still smaller particles called electron, proton and neutron.
3. Electrons, protons and neutrons are shown to be present in all the elements irrespective of the fact that the elements behave very differently. Different elements, however, contain different number of these particles.
4. Lord Rutherford discovered that all atoms have a central part which he named as nucleus. The protons and neutrons are present in this nucleus while the electrons are revolving around the nucleus.
5. An atom being electrically neutral contains the same number of electrons and protons.
6. Electrons revolve around the nucleus in different shells.
7. The number of protons present in the nucleus of an element is called the atomic number of that element.
8. The total number of protons and neutrons present in the nucleus of an element in called its mass number.
9. Isotopes are the atoms of the same element which have the same number of protons but different number of neutrons.
10. Isotopes of an element have same chemical properties but they differ in their physical properties.
11. Isotopes of an element may be stable or radioactive. Radioactive isotopes have many useful applications in medicine.
12. Radioactive isotopes have unstable nuclei and they throw out radiation.
13. Relative atomic mass of an element can be calculated from the relative isotopic masses of this element and their isotopic abundances.

Exercise

1. Tick (✓) the correct answer.

(i) How many electrons can be accommodated at the most in the third shell of the elements?

(a) 8 (b) 18 (c) 10 (d) 32

(ii) What information was obtained from discharge tube experiments?

(a) Structure of atom was discovered.
(b) Neutrons and protons were discovered.
(c) Electrons and protons were discovered.
(d) Presence of nucleus in an atom was discovered.

(iii) Why have isotopes not been shown in the periodic table?

(a) Periodic table cannot accommodate a large number of isotopes of different elements.

(b) Some of the isotopes are unstable and they give rise to different elements

(c) All the isotopes have same atomic number; so there is no need to give them separate places.

(d) Isotopes do not show periodic behavior.

(iv) Which particle is present in different number in the isotopes?

(a) Electron (b) Neutron

(c) Proton (d) Both neutron and electron

(v) Predict the boiling point of heavy water (D_2O).

(a) 101.4°C (b) 98.2°C

(c) 100°C (d) 105.4°C

(vi) What will be the relative atomic mass of hydrogen given the abundances of its two isotopes, 99.9844% and 0.0156%.

(a) 1.0078 (b) 1.0784 (c) 1.0800 (d) 1.0700

(vii) How is radiocarbon dating useful for archeologists?

(a) It helps determine the age of organic matter.

(b) It helps determine the composition of matter.

(c) It helps determine the usefulness of matter.

(d) It helps determine whether the matter is radioactive or not.

(viii) What does keep the particles present in the nucleus intact?

(a) Particles are held together by strong nuclear force.

(b) Particles are held together by weak nuclear force.

(c) Particles are held together by electrostatic force.

(d) Particles are held together by dipolar force.

(ix) How do electrons keep themselves away from the oppositely charged nucleus?

(a) By keeping themselves stationary

(b) By revolving around the nucleus

(c) Due to their wave-like nature

(d) A magnetic field around the nucleus keeps them away

(x) Rubidium consists of two isotopes ^{85}Rb and ^{87}Rb. The percent abundance of the light isotope is 72.2%. What is the percent abundance of the heavier isotope? Its atomic mass is 85.47

(a) 15% (b) 28% (c) 37% (d) 72%

2. Questions for Short Answers

i. Why is it said that almost all the mass of an atom is concentrated in its nucleus?

ii. Why are elements different from one another?

iii. How many neutrons are present in $^{210}_{83}Bi$?

iv. Why is tritium ($^{3}_{1}H$) a radioactive element?

v. How can an atom absorb and envolve energy?

3. Constructed Response Questions

i. Why does the energy of electron increase as we move from first shell to second shell?

ii. Why is it needed to lower the pressure of the gas inside the discharge tube?

iii. What is the classical concept of an electron? How has this concept changed with time?

iv. Why the nuclei of the radioactive elements are unstable?

v. During discharge tube experiments, how did the scientists conclude that the same type of electrons and protons are present in all the elements?

4. Descriptive Questions

i. Explain the structure of a hydrogen atom.

ii. How does the theory of atomic structure explain the ionization of atoms by a radioactive isotope?

iii. What is radioactivity? Explain any three applications of radioactive isotopes.

iv. Find out the relative atomic mass of mercury from the following data.

Isotope		Relative Abundance	Isotope		Relative Abundance
^{196}Hg	=	0.0146%	^{199}Hg	=	16.34%
^{198}Hg	=	10.02%	^{200}Hg	=	23.13%
^{201}Hg	=	13.22%	^{202}Hg	=	29.80%
^{204}Hg	=	6.85%			

5. Investigative Questions

i. How can scientists synthesize elements in the laboaratory?

ii. A system just like our solar system exists in an atom. Comment on this statement.