Class IX Chemistry Chapter 4: Structure of the Atom

Discovery of Electron:

In 1897, Sir William Crookes carried out a series of experiments to study the behavior of metals heated in a vacuum using cathode ray tubes .

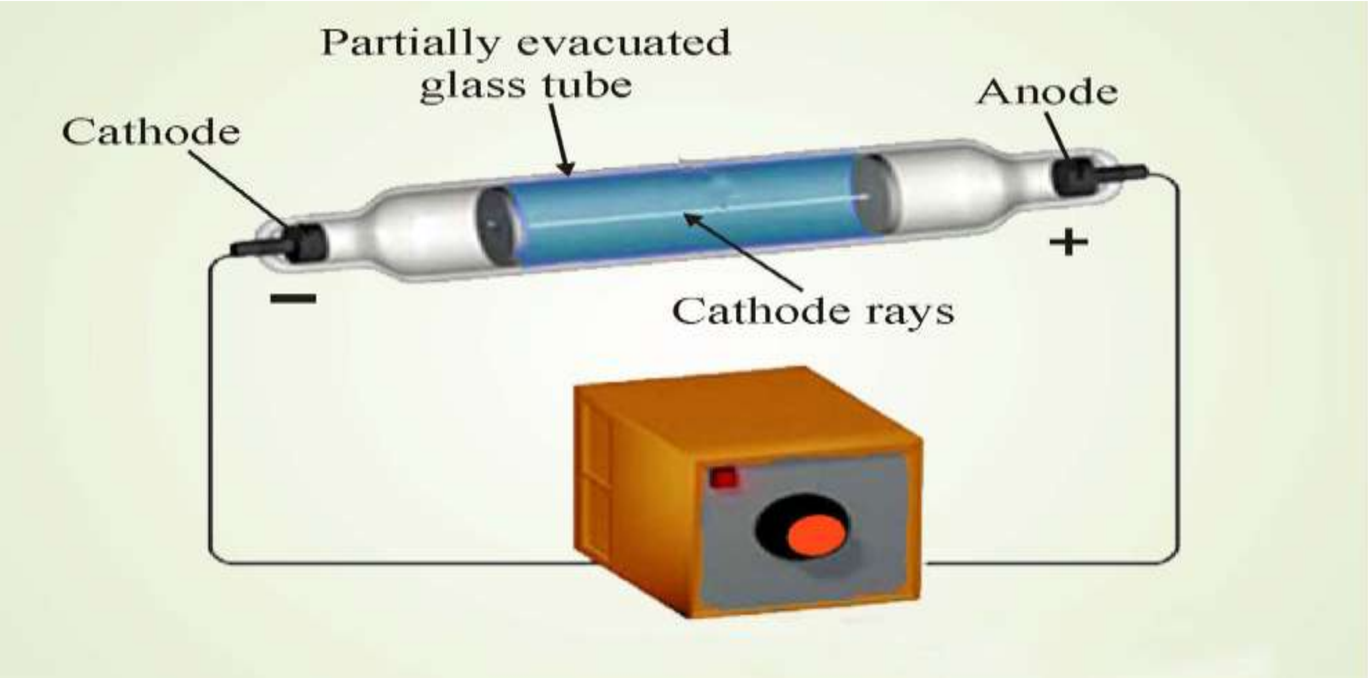


Fig.1: A cathode ray tube; cathode rays are obtained on applying high voltage across the electrodes in an evacuated glass tube

A cathode ray tube consists of two metal electrodes in a partially evacuated glass tube. An evacuated tube is a glass tube from which most of the air has been removed. The negatively charged electrode is called cathode whereas the positively charged electrode is called anode.

These electrodes are connected to a high voltage source. Such a cathode ray tube has been shown in Fig. 01.

Observation

It was observed that when very high voltage was passed across the electrodes in evacuated tube at 0.0001 atm. pressure , the cathode produced a stream of particles with greenish glow at anode. These particles were shown to travel from cathode to anode and were called **cathode rays**. In the absence of external magnetic or electric field these rays travel in straight line.

Cathode rays are called **cathode rays** because they are emitted by the negative electrode, or cathode, in a vacuum tube.

In 1897, an English physicist Sir J.J. Thomson showed that the rays were made up of a stream of negatively charged particles.

This conclusion was drawn from the experimental observations when the experiment was done in the presence of an external electric field.

Following are the important properties of cathode rays:

- Cathode rays travel in straight line
- The particles constituting cathode rays carry mass and possess kinetic energy
- The particles constituting cathode rays have negligible mass but travel very fast
- Cathode ray particles carry negative charge and are attracted towards positively charged plate when an external electric field is applied (Fig.02)
- The nature of cathode rays generated was independent of the nature of the gas filled in the cathode ray tube as well as the nature of metal used for making cathode and anode. In all the cases the charge to mass ratio (e/m) was found to be the same.

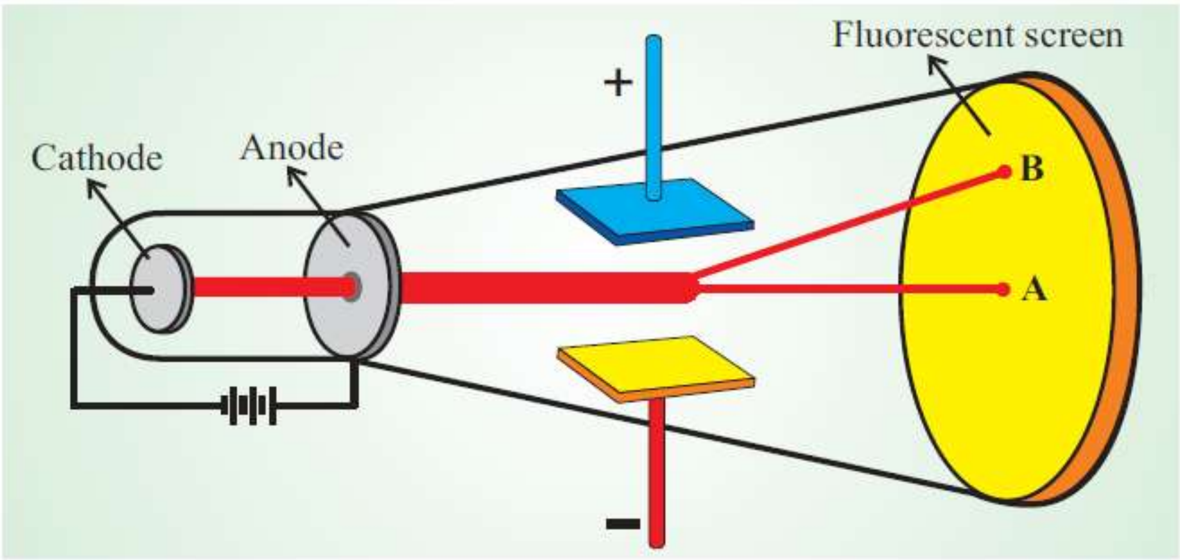


Fig. 02: The cathode rays are negatively charged; these travel in straight line from cathode to the anode (A), however in the presence of an external electrical field these bend towards the positive plate (B)

These particles constituting the cathode rays were later called electrons. Since it was observed that the nature of cathode rays was the same irrespective of the metal used for the cathode or the gas filled in the cathode ray tube. This led Thomson to conclude that all atoms must contain electrons. This meant that the atom is not indivisible as was believed by Dalton and others. In other words, we can say that the Dalton's theory of atomic structure failed partially.

This conclusion raised a question, "If the atom was divisible, then what were its constituents?" Today a number of smaller particles are found to constitute atoms. These particles constituting the atom are called **subatomic particles**.

in 1897 when J. J. Thomson measured the mass of cathode rays, showing they were made of particles, but were around 1800 times lighter than the lightest atom, hydrogen. Therefore they were not atoms, but a new particle, the first *subatomic* particle to be discovered, which he originally called "*corpuscle*" but was later named *electron*

Discovery of Proton:

Much before the discovery of electron, Eugen **Goldstein** (in 1886) performed an experiment using a perforated cathode (a cathode having holes in it) in the discharge tube filled with air at a very low pressure. When a high voltage was applied across the electrodes in the discharge tube, a faint red glow was observed behind the perforated cathode.

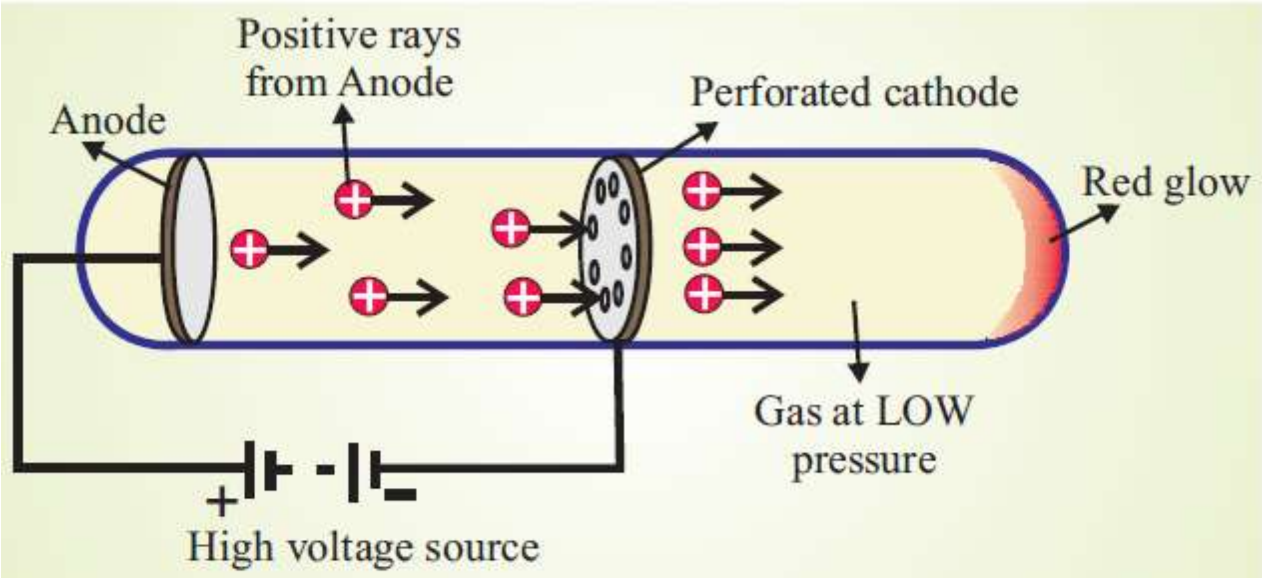


Fig. 03: Goldstein's cathode ray tube with perforated cathode

This glow was due to another kind of rays flowing in a direction opposite to that of the cathode rays. These rays were called as **anode rays** or positive rays. These were positively charged and were also called **canal rays** because they passed through the holes or the canals present in the perforated cathode.

The following observations were made about anode rays (canal rays):

- Like cathode rays, the anode rays also travel in straight lines.
- The particles constituting anode rays carry mass and have kinetic energy.
- The particles constituting canal rays are much heavier than electrons and carry positive charges
- The positive charge on the particles was whole number multiples of the amount of charge present on the electron.
- The nature and the type of the particles constituting the anode rays were dependent on the gas present in the discharge tube.

The origin of anode rays can be explained in terms of interaction of the cathode rays with the gas present in the vacuum tube.

It can be explained as given below:

The electrons emitted from the cathode collide with the neutral atoms of the gas present in the tube and remove one or more electrons present in them. This leaves behind positive charged particles which travel towards the cathode. When the cathode ray tube contained hydrogen gas, the particles of the canal rays obtained were the lightest and their charge to mass ratio (e/m ratio) was the highest.

Rutherford showed that these particles were identical to the hydrogen ion (hydrogen atom from which one electron has been removed). These particles were named as **protons** and were shown to be present in all matter. Thus, we see that the experiments by Thomson and Goldstein had shown that an atom contains two types of particle which are oppositely charged and an atom is electrically neutral.

- In addition to the discovery of electrons and protons as the constituents of atom, the phenomenon of **radioactivity** that is the spontaneous emission of rays from atoms of certain elements also proved that the atom was divisible.

Roentgen's X-Rays (1895)

Roentgen experimented with a CRT using an electric current at very high voltage. He noticed that some rays emanated from the apparatus, and that these rays penetrated and passed through different substances.
X-rays have short-waves, a high frequency and very high energy that lets them go through soft tissue. The medical applications very soon became apparent and X-rays are used extensively in medical diagnostics.

Henri Becquerel (1896)

The story is that Becquerel left an unexposed photographic film in a metal cartridge in his desk, on top of the film was a chunk of uranium ore (a mineral called pitchblende). He found that the film had been exposed even though it had not come into contact with any light. He decided that uranium spontaneously emitted powerful invisible rays without the application of energy, which unlike light were able to pass through opaque objects. A substance that gives off these invisible rays is **radioactive**. The main impact of the discovery of radioactivity was that it *proved that atoms contained parts and that it was definitely divisible.*

Pierre and Marie Curie

They took up the work of Becquerel. They succeeded in isolating two new radioactive elements :
Radium and Polonium (after her native Poland). These are even more radioactive than uranium. (FYI: Marie Curie was the first woman to hold a professorship at the Sorbonne, the first person to win the Nobel Prize twice, her daughter also won the Nobel Prize.)

EARLIER MODELS OF ATOM

- On the basis of experimental observations, different models have been proposed for the structure of an atom

Thomson Model

Knowing that all matter is made of atoms and all the atoms are electrically neutral. Having discovered electron as a constituent of atom, Thomson concluded that there must be an equal amount of positive charge present in an atom.

On this basis **Thomson** proposed a model for the structure of atom.

According to his model, atoms can be considered as a large sphere of uniform positive charge with a number of small negatively charged electrons scattered throughout it, Fig. 04. This model was called as **plum pudding** model.

The electrons represent the plums in the pudding made of negative charge. This model is similar to a water-melon in which the pulp represents the positive charge and the seeds denote the electrons. However, we must note that a water melon has a large number of seeds whereas an atom may not have as many electrons.

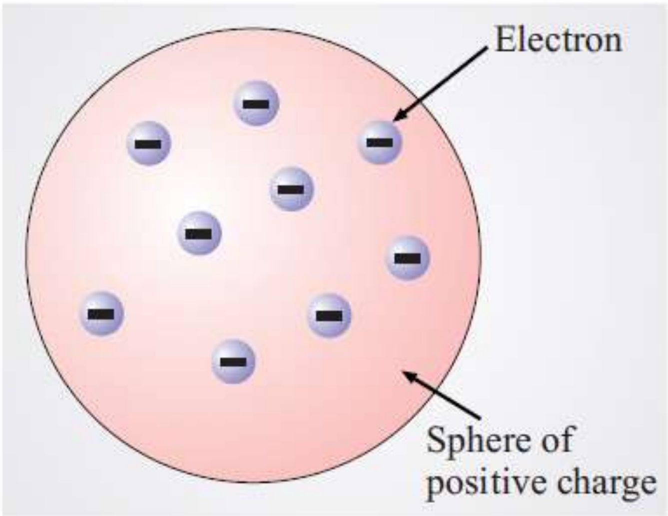


Fig. 04 : Thomson's plum-pudding model

Rutherford's model

Ernest Rutherford and his co-workers were working in the area of radioactivity. They were studying the effect of alpha (α) particles on matter. The alpha particles are helium nuclei, which can be obtained by the removal of two electrons from the helium atom.

In 1910, Hans Geiger (Rutherford's technician) and Ernest Marsden (Rutherford's student) performed the famous α-ray scattering experiment. This led to the failure of Thomson's model of atom. Let us learn about this experiment

α-Ray scattering experiment

In this experiment a stream of α particle from a radioactive source was directed on a thin (about 0.00004 cm thick) piece of gold foil.

On the basis of Thomson's model it was expected that the alpha particles would just pass straight through the gold foil and could be detected by a photographic plate placed behind the foil. However, the actual results of the experiment, Fig. 5, were quite surprising.

It was observed in **α-Ray scattering experiment** that:

(i) Most of the α-particles passed straight through the gold foil.

(ii) Some of the α-particles were deflected by small angles.

(iii) A few particles were deflected by large angles.

(iv) About 1 in every 12000 particles experienced a rebound.

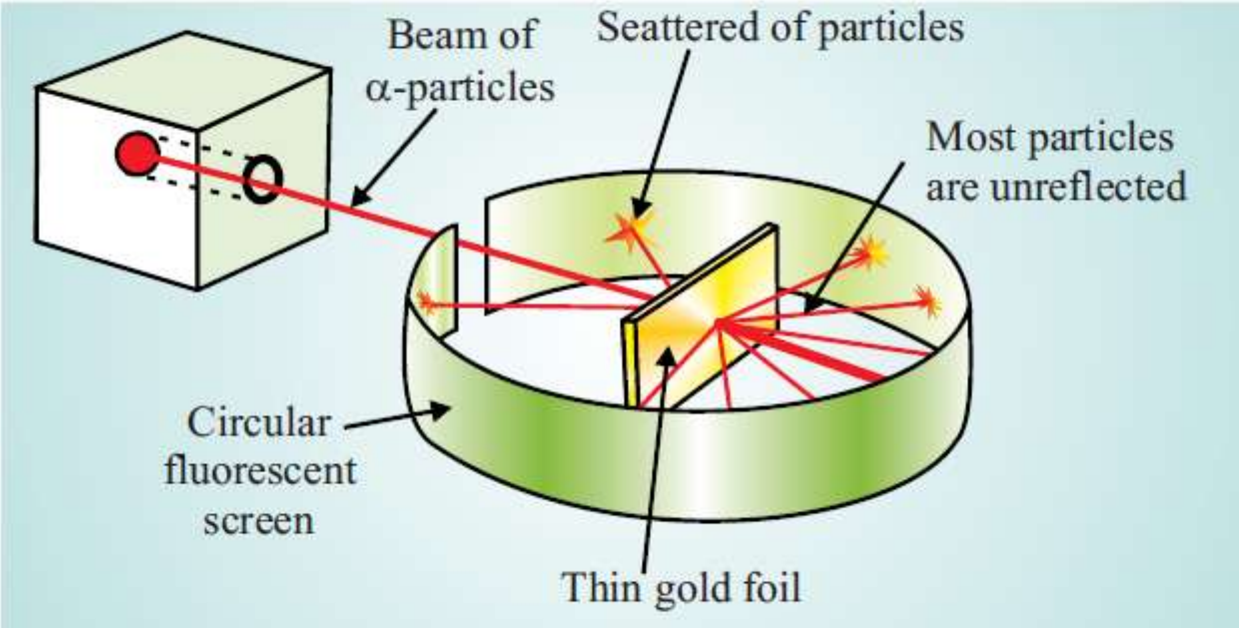


Fig. 05 : The experimental set-up and observations in the α- ray scattering experiment performed by Geiger and Marsden

Rutherford's model of atom

The results of α-ray scattering experiment were explained by Rutherford in 1911 and another model of the atom was proposed. According to Rutherford's model, Fig. 06(a).

An atom contains a dense and positively charged region located at its centre; it was called as **nucleus**,

All the positive charge of an atom and most of its mass was contained in the nucleus,

The rest of an atom must be empty space which contains the much smaller and negatively charged electrons

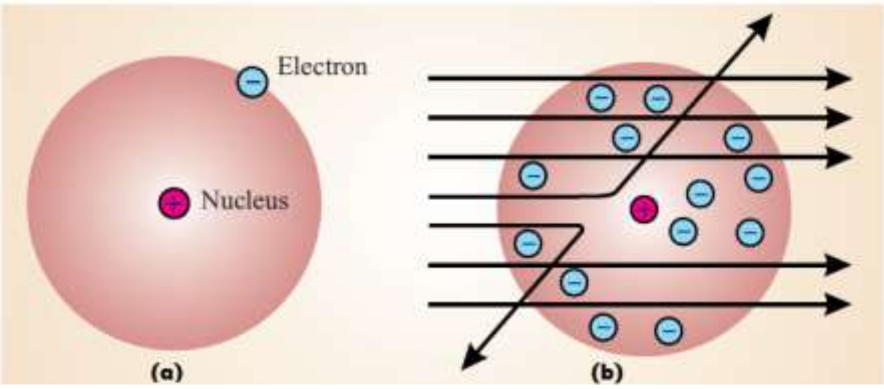


Fig 06: (a) Rutherford's model of atom (b) Explanation of the results of scattering experiment by Rutherford's model.

On the basis of the proposed model, the experimental observations in the scattering experiment could be explained. This is illustrated in Fig. 5.6(b).

The α particles passing through the atom in the region of the electrons would pass straight without any deflection. Only those particles that come in close vicinity of the positively charged nucleus get deviated from their path. Very few α-particles, those that collide with the nucleus, would face a rebound.

- On the basis of his model, Rutherford was able to predict the size of the nucleus. He estimated that the radius of the nucleus was at least 1/10000 times smaller than that of the radius of the atom. We can imagine the size of the nucleus with the following analogy. If the size of the atom is that of a cricket stadium then the nucleus would have the size of a fly at the centre of the stadium.

DRAWBACKS OF RUTHERFORD'S MODEL

- Rutherford's model is unable to explain the stability of the atom.

According to Rutherford's model the negatively charged electrons revolve in circular orbits around the positively charged nucleus.

However, according to Maxwell's electromagnetic theory (about which you may learn in higher classes), if a charged particle accelerates around another charged particle then it would continuously lose energy in the form of radiation. The loss of energy would slow down the speed of the electron. Therefore, the electron is expected to move in a spiral fashion around the nucleus and eventually fall into it as shown in Fig. 07.

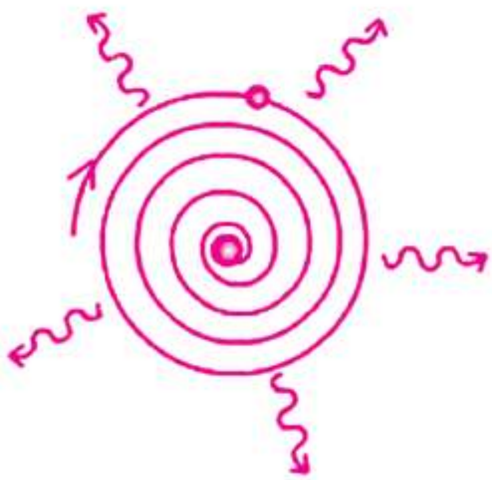


Fig. 07: The electron in the Rutherford's model is expected to spiral into the nucleus

In other words According to Rutherford's model, the atom will not be stable. However, we know that the atom is stable and such a collapse does not occur. Thus, Rutherford's model is unable to explain the stability of the atom.

- The Rutherford's model also does not say anything about the way the electrons are distributed around the nucleus
- The Rutherford's model also fail to explain the relationship between the atomic mass and atomic number (the number of protons).This problem was solved later by Chadwick by discovering neutron, the third particle constituting the atom

BOHR'S MODEL OF ATOM

The problem of the stability of the atom and the distribution of electrons in the atom was solved by **Neils Bohr** by proposing new model of the atom.

In 1913, Niels Bohr,a student of Rutherford proposed a model to account for the shortcomings of Rutherford's model.

Bohr's model can be understood in terms of two postulates proposed by him. The postulates are:

Postulate 1: The electrons move in definite circular paths of fixed energy around a central nucleus ; just like our solar system in which different planets revolve around the Sun in definite orbit.

Similar to the planets, only certain circular paths around the nucleus are allowed for the electrons to move. These paths are called **orbits**, or **energy levels**. The electron moving in the orbit does not radiate.

In other words, it does not lose energy; therefore, these orbits are called **stationary orbits or stationary states**. The bold concept of stationary state could answer the problem of stability of atom faced by Rutherford's model.

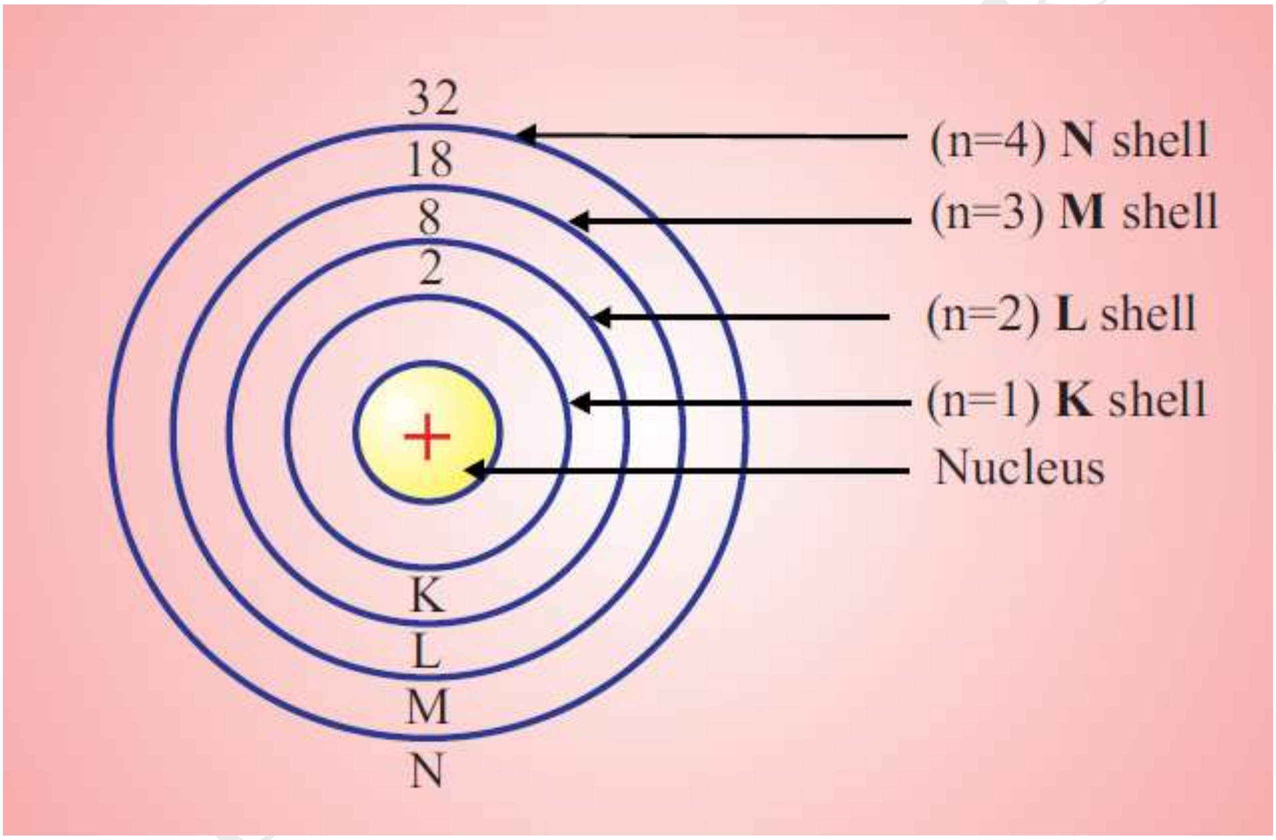


Fig. 08: *Illustration showing different orbits or the energy levels of fixed energy in an atom according to Bohr's model*

Shell and Sub Shell

It was later realized that the concept of circular orbit as proposed by Bohr was not adequate and it was modified to energy shells with definite energy. While a circular orbit is two dimensional, a shell is a three dimensional region.

The shells of definite energy are represented by letters (K, L, M, N etc.) or by positive integers (1, 2, 3, …. etc.) Fig. 08.

The energies of the shells increase with the number n; n = 1, level is of the lowest energy. Further, the maximum number of electrons that can be accommodated in each shell is given by $2n^2$, where n is the number of the level. Thus, the first shell (n=1) can have a maximum of two electrons whereas the second shell can have 8 electrons and so on. Each shell is further divided into various sublevels called **subshells.**

Postulate 2: The electron can change its shells or energy level by absorbing or releasing energy. An electron at a lower state of energy E_i can go to a final higher state of energy *Ef* by absorbing a single photon of energy given by:

$E = h_v = E_f - E_i$

Similarly, when electron changes its shell from a higher initial level of energy E_i to a lower final level of energy *Ef*, a single photon of energy *h*v is released (Fig. 09).

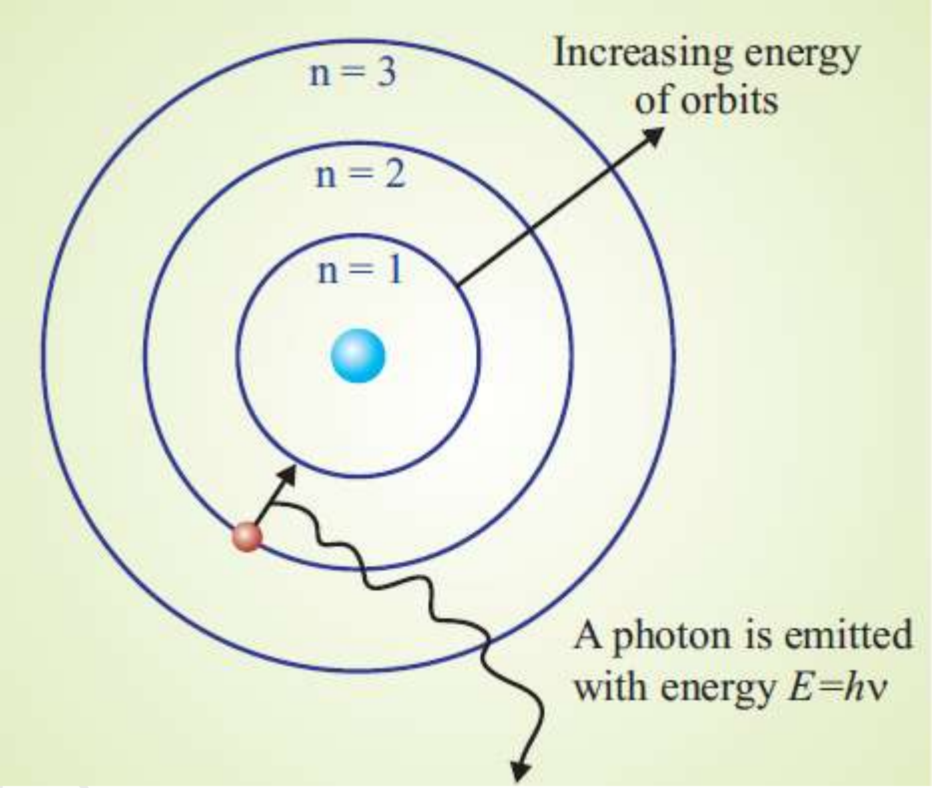


Fig. 09: *The electrons in an atom can change their energy level by absorbing suitable amounts of energy or by emitting energy.*

- The Bohr's model of atom removes two of the limitations of Rutherford's model. These are related to the stability of atom and the distribution of electrons around the nucleus.

DISCOVERY OF NEUTRON

In 1932 Chadwick discovered the presence of particles having no charge in the atom called neutrons.

You would recall that the third limitation of Rutherford's model was its inability to explain the relationship between the atomic mass, and the atomic number (the number of protons) of an atom. Let us learn how this problem was solved with the discovery of neutron.

According to the Rutherford's model, the mass of helium atom (containing 2 protons) should be double that of a hydrogen atom (with only one proton). [Ignoring the mass of electron as it is very light]. However, the actual ratio of the masses of helium atom to hydrogen atom is 4:1. It was suggested that there must be one more type of subatomic particle present in the nucleus which may be neutral but have mass. Such a particle was discovered by James Chadwick in 1932 and called Neutrons.

Neutrons are electrically neutral and present in the nucleus of all atoms, except hydrogen. A neutron is represented as 'n' and is found to have a mass slightly higher than that of a proton. Thus, if the helium atom contained 2 protons and 2 neutrons in the nucleus, the mass ratio of helium to hydrogen (4:1) could be explained.

- Millikan worked on an oil-drop experiment in which he measured the charge on a single electron

Characteristics of the fundamental subatomic particles				
Particle	Symbol	Mass (in kg)	Actual Charge	Relative charge
Electron	e	9.109389×10^{-31}	1.602177×10^{-19}	–1
Proton	*p*	1.672623×10^{-27}	1.602177×10^{-19}	1
Neutron	n	1.674928×10^{-27}	0	0

ATOMIC NUMBER AND MASS NUMBER

You have learnt that the nucleus of atom contains positively charged particles called protons and neutral particles called neutrons. **The number of protons in an atom is called the atomic number and is denoted by the symbol 'Z'**.

All atoms of an element have the same atomic number. The electrons occupy the space outside the nucleus. In order to account for the electrically neutral nature of the atom, the number of protons in the nucleus is exactly equal to the number of electrons. Thus,

Atomic number = number of protons = number of electrons

According to Dalton's theory, the atoms of different elements are different from each other. We can now say that this difference is due to difference in the numbers of protons present in the nucleus of the element. In other words, different elements differ in terms of their **atomic number**.

For example, the atoms of hydrogen and helium are different because hydrogen has one proton in its nucleus whereas the nucleus of helium atom contains two protons. Their atomic numbers are
1 and 2, respectively.

You have learnt in the Rutherford's model that the mass of the atom is concentrated in its nucleus. This is due to the presence of two heavy particles namely protons and neutrons in the nucleus. These particles are called **nucleons**. *The number of nucleons in the nucleus of an atom is called its **mass number***. It is denoted by 'A' and is equal to the total number of protons and neutrons present in the nucleus of an element. Thus,

Mass number (A) = number of protons(Z) + number of neutrons(n)

Atomic number and mass number are represented on the symbol of an element. An element, X with an atomic number, Z and the mass number, A is denoted as follows: $^{A}X_{Z}$ or $^{A}_{Z}X$.

For example, $^{12}_{6}C$ means that the carbon has an atomic number of 6 and the mass number of 12. This can be used to compute the number of different fundamental particles in the atom.

- Let us calculate the number of different fundamental particles in the atom for carbon.

As the atomic number is 6 this means:

Number of protons = number of electrons = 6

As Mass number = number of protons + number of neutrons

⇒ 12 = 6 + number of neutrons

⇒ Number of neutrons = 12 – 6 = 6

Thus, an atom of $^{12}_{6}C$ has 6 protons, 6 electrons and 6 neutrons.

ELECTRONIC CONFIGURATION: DISTRIBUTION OF ELECTRONS IN DIFFERENT ORBITS

The electrons move in definite paths called orbits or shells around a central nucleus. These orbits or shells have different energies and can accommodate different number of electrons in them.

- The question arises that how are the electrons distributed amongst these shells?

The answer to this question was provided by Bohr and Bury. According to their scheme, the electron distribution is governed by the following rules:

I. These orbits or shells in an atom are represented by the letters K, L, M, N,… or the positive integral numbers, n = 1,2,3,4,….

II. The orbits are arranged in the order of increasing energy. The energy of M shell is more than that of the L shell which in turn is more than that of the K shell.

III. The maximum number of electrons present in a shell is given by the formula $2n^2$, where 'n' is the number of the orbit or the shell. Thus, the maximum number of electrons that can be accommodated in different shells are as follows:

Maximum number of electrons in K shell (or n = 1 level) = 2n2 = 2 × $(1)^2$ = 2

Maximum number of electrons in L shell (or n = 2 level) = 2n2 = 2 × $(2)^2$ = 8

Maximum number of electrons in M shell (or n = 3 level) = 2n2 = 2 × $(3)^2$ = 18 and so on…

IV. The shells are occupied in the increasing order of their energies.

V. Electrons are not accommodated in a given shell, unless the inner shells are completely filled.

The arrangement of electrons in the various shells or orbits of an atom of the element is known as electronic configuration

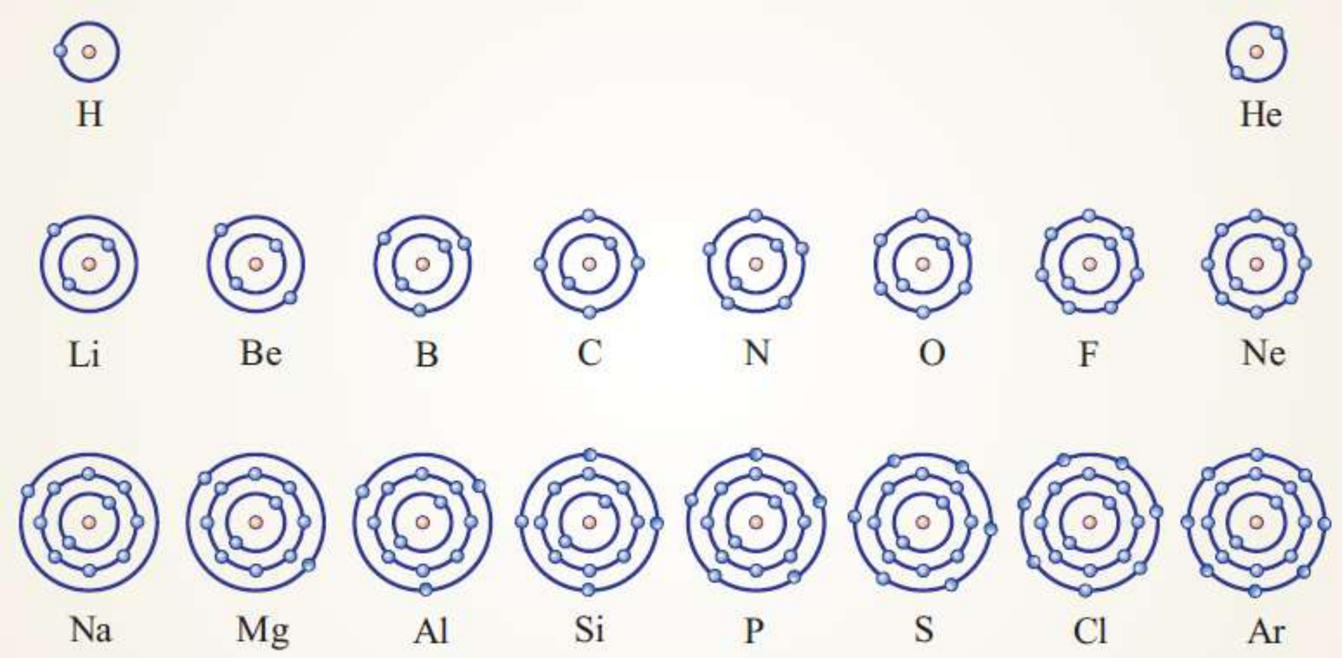


***Fig. 10** The structures, according to Bohr's model of atoms, of elements with atomic number 1 to 18.*

Concept of Valence or Valency

Ddifferent elements have different number of electrons in the outermost or the valence shell. These electrons in the outermost shell are known as valence electrons. **The number of valence electrons determines the combining capacity of an atom in an element.**

Valence is the number of chemical bonds that an atom can form with univalent atoms. Since hydrogen is a univalent atom, the valence of an element can be taken by the number of atoms of hydrogen with which one atom of the element can combine. For example, in H_2O, NH_3, and CH_4 the valencies of oxygen, nitrogen and carbon are 2, 3 and 4 respectively.

The elements having a completely filled outermost shell in their atoms show little or no chemical activity. In other words, their combining capacity or valency is zero. The elements with completely filled valence shells are said to have stable electronic configuration. The main group elements can have a maximum of eight electrons in their valence shell. This is called **octet rule.**

The combining capacity or the tendency of an atom to react with other atoms to form molecules depends on the ease with which it can achieve octet in its outermost shell. The valencies of the elements can be calculated from the electronic configuration by applying the octet rule. It can be seen as follows:

- If the number of valence electrons is four or less then the valency is equal to the number of the valence electrons.
- In cases when the number of valence electrons is more than four then generally the valency is equal to 8 minus the number of valence electrons.

Thus,

Valency = Number of valence electrons (for 4 or lesser valence electrons)

Valency = 8 - Number of valence electrons (for more than 4 valence electrons)

Isotopes and Isobars

Joseph John Thompson and Francis Aston both discovered isotopes in 1913. There were others that was involved in the discovery. Dr. Margaret Todd was the first to use the term Isotopes.

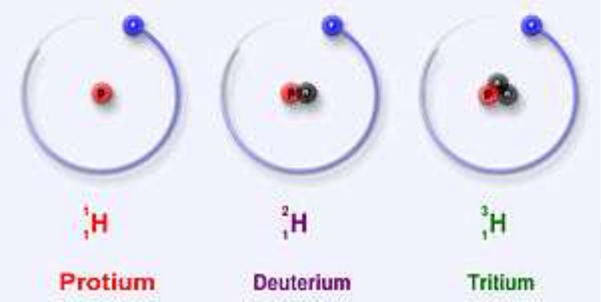
Isotopes:-Isotopes are atoms of the same element having the same atomic numbers but different mass numbers.

Eg :- Hydrogen has three isotopes. They are Protium , Deuterium (D) and Tritium (T) $^{1}_{1}H$ $^{2}_{1}H$ $^{3}_{1}H$ resp.

Carbon has three isotopes. They are :- $^{12}_{6}C$, $^{14}_{6}C$ *and* $^{16}_{6}C$

Chlorine has two isotopes They are :- $^{35}_{17}Cl$ and $^{37}_{17}Cl$

Uranium has two isotopes They are :$^{235}_{92}U$ and $^{239}_{92}U$



Isobars: - Isobars are atoms of different elements having different atomic numbers but same mass numbers. These pairs of elements have the same number of nucleons.

Eg :- Calcium (Ca) – atomic number - 20 and Argon (Ar) – atomic number 18 have different atomic numbers but have the same mass numbers – 40.

Iron (Fe) and Nickel (Ni) have different atomic numbers but have the same atomic mass numbers – 58.

Example: $^{40}_{20}Ca$ and $^{40}_{18}Ar$; $^{40}_{20}Ca$ and $^{58}_{26}Fe$ and $^{58}_{27}Ne$

Isotones: Two nuclides are **isotones** if they have the very same neutron number *N*, but different proton number *Z*. For example, boron-12 and carbon-13 nuclei both contain 7 neutrons, and so are isotones.

Similarly, ^{36}S, ^{37}Cl, ^{38}Ar, ^{39}K, and ^{40}Ca nuclei are all isotones of 20 because they all contain 20 neutrons.

Also $^{30}_{14}Si$, $^{31}_{15}Si$, $^{31}_{16}Si$ (All have 16 neutrons).

Despite its similarity to the Greek for "same stretching", the term was formed by the German physicist K. Guggenheim by replacing the "p" in "isotope" with "n" for "neutron.