12. ATOMS

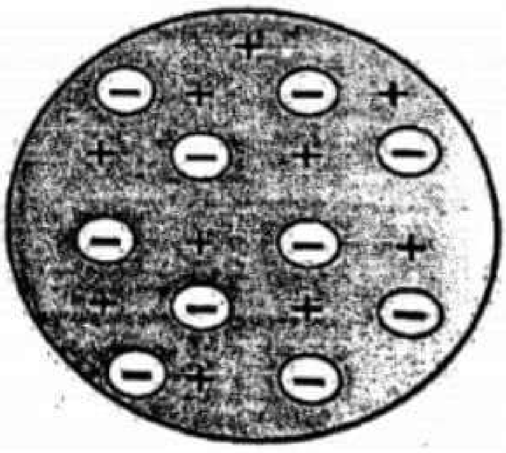
In this unit, we shall discuss the models of atoms in some detail. The first contribution in this regard come from Dalton, who proposed that matter is made of atoms, which are indivisible. J.J. Thomson proposed a structure for the atom, which is modified by Rutherford and later by Niels Bohr.

Thomson Model of Atom-

According to the Thomson model, every atom consist of a positively charged sphere of radius of the order of 10^{-10}m in which entire mass and positive charge of the atom are uniformly distributed. Inside this sphare, the electrons are embeded like seeds in a watermelon. or like plums in a pudding. The number of electron is such that their negative charge is equal to the positive charge of the atom. Thus the atom is electrically neutral.

Limitations of Thomson Atom model-

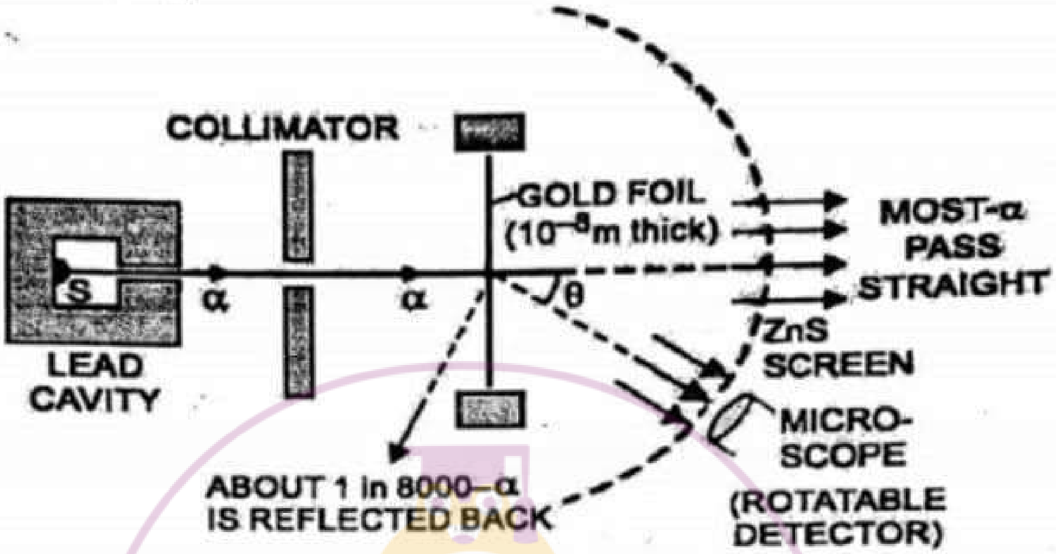
(i) It could not explain the origin of spectral series of hydrogen and other atoms, observed experimentally.



(ii) It could not explain the large angle scattering of α-particles from thin metal foils, as observed by Rutherford.

Rutherford's α-ray Scattering Experiment :

The experimental setup used by Rutherford and his Collaborators, Geiger and Marsden is shown in fig -



S is a piece of radioactive source ($_{83}Bi^{214}$) Contained in a lead cavity. The α- particles emitted by the source are collimated into a narrow beam with the help of a Lead slit (Collimator).

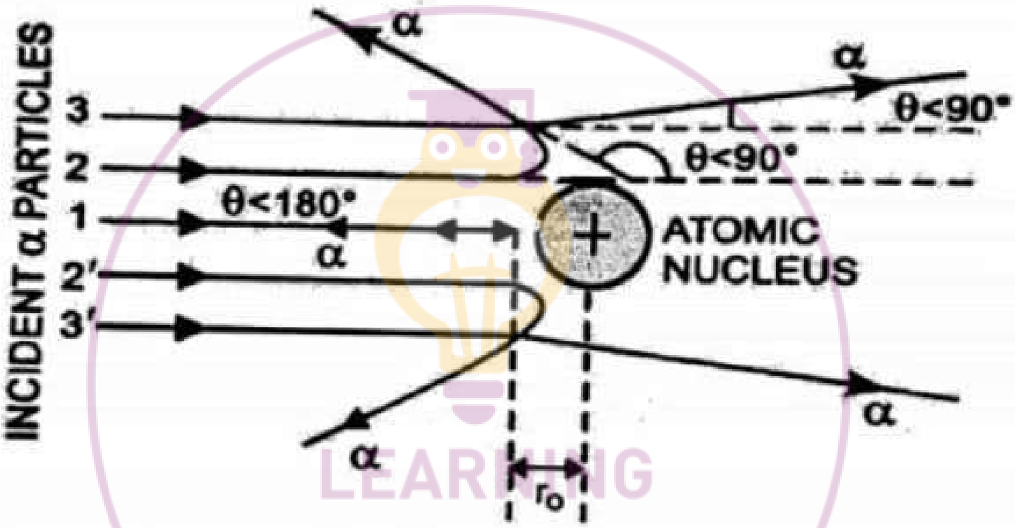
The Collimated beam is allowed to fall on a thin gold foil of thickness of the order of 2.1×10^{-7}m. The α-particles scattered in different directions are observed through a rotatable detector Consisting of a zinc sulphide screen and a microscope.

The α-particles produce bright flashes on the ZnS screen. These are observed in the microscope and counted at different angles from the direction of incidence of the beam. The angle θ of deviation of an α-particle from its original direction is called its scattering angle θ.

Therefore, the trajectory of α-particle can be computed using Newton's law of motion and Coulomb force of repulsion between α-particle and gold nucleus i.e.

$$\boxed{F = \frac{1}{4\pi\epsilon_0}\frac{(2e)(2e)}{r^2}}$$

where r is the distance of α-particle from the centre of the nucleus. The magnitude and direction of the force on an α-particle changes continuously as it approaches the nucleus first and then moves away from it.



As shown in fig an α-particle (1) tending to collide with the nucleus, slow down due to repulsive force of the nucleus, finally stops and is then repelled back. This α-particle, therefore retrace its path, scattering through 180°.

The α-particles 2 and 2' tending to hit the nucleus at its periphery, experience strong repulsive force and get scattered through large angles (θ > 90°).

The α-particles 3 and 3', which pass at a distance from the nucleus experience small repulsive forces and get scattered through small angles.

The α-particles which pass at large distances from the nucleus go almost undeviated.

We can show that the number of α-particles scattered per unit area $N(\theta)$ at scattering angle θ varies inversely as $\sin^4(\frac{\theta}{2})$.

$$\boxed{N(\theta) \propto \frac{1}{\sin^4(\frac{\theta}{2})}}$$

Distance of Closest Approach-

When α-particle is directed towards the nucleus, the kinetic energy of α-particle goes on decreasing and in turn electrical potential energy goes on increasing due to Coulomb's repulsive force between nucleus and α-particle.

At a certain distance r_0 from the nucleus, K.E. of α-particle reduces to zero. The particle stops and it cannot go closer to the nucleus. It is repelled by the nucleus and therefore, it retrace its path, turning through 180°. This distance r_0 is known as the distance of closest approach.

Electrical potential at distance r_0 due to nucleus

$$\boxed{V = \frac{1}{4\pi\epsilon_0} \times \frac{Ze}{r_0}}$$

Potential Energy of α-particle at distance r_0 from the nucleus = Potential $\times$ Charge

$$\boxed{P.E. = \frac{Ze}{4\pi\epsilon_0 r_0} \times 2e}$$

Kinetic Energy of α-particle of mass m moving with velocity v is $\Rightarrow$ $\boxed{K.E. = \frac{1}{2}mv^2}$

As at the distance of closest approach -

$$K.E. = P.E.$$

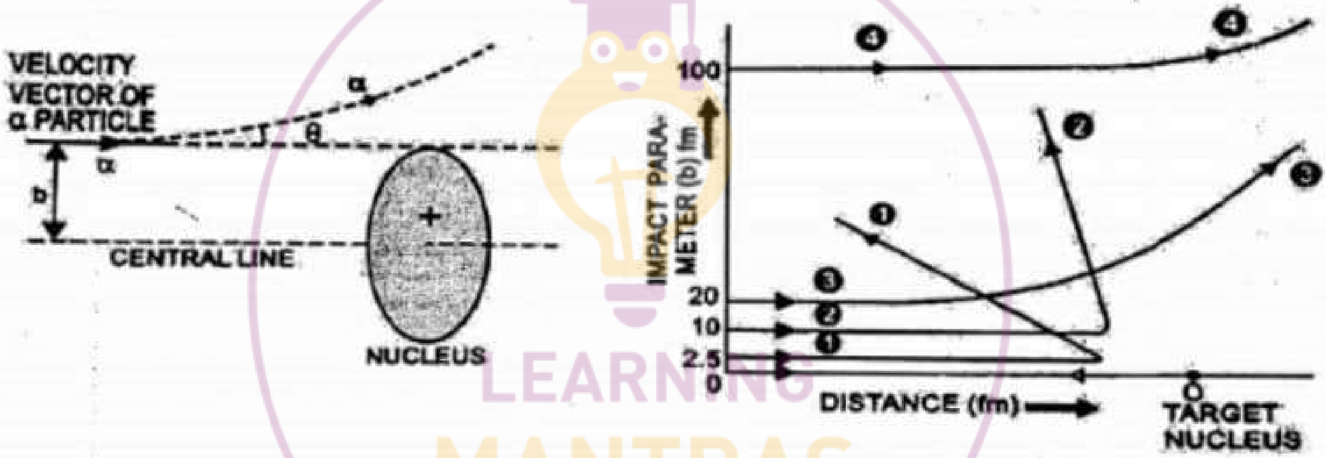
$$\frac{1}{2}mv^2 = \frac{ze \times 2e}{4\pi\epsilon_0 r_0}$$

or

$$\boxed{r_0 = \frac{ze \times 2e}{4\pi\epsilon_0 \left(\frac{1}{2}mv^2\right)}}$$

Impact Parameter (b) -

It is defined as the perpendicular distance of the initial velocity of α-particle from the central line of the nucleus, when the particle is far away from the nucleus.



When the impact parameter is large, an α-particle will deviate through a much smaller angle. However, when impact parameter is small, force experienced is large and the α-particle will scatter through a large angle.

Rutherford calculated analytically the relation between the impact parameter b and scattering angle θ, which is given by-

$$\boxed{b = \frac{1}{4\pi\epsilon_0} \frac{ze^2 \cot \theta/2}{K.E.}} \qquad \left[K.E. = \frac{1}{2}mv^2\right]$$

Rutherford's Atom Model -

(1.) Every atom consist of a tiny central core, called the atomic nucleus in which the entire positive charge and almost entire mass of the atom are concentrated.

(2.) The size of the nucleus is of the order of 10^{-15} m which is very small as compared to the size of the atom which is of the order of 10^{-10} m.

(3.) The atomic nucleus is a number of electrons. As atom is electrically neutral, the total negative charge of electrons surrounding the nucleus is equal to total positive charge on the nucleus.

(4.) These electrons revolve around the nucleus in various circular orbits. The centripetal force required by electron for revolution is provided by the electrostatic force of attraction between the electrons and the nucleus.

Energy of the electron in orbit -

Let F_c = Centripetal force required to keep a revolving electron in orbit

F_e = electrostatic force of attraction between the revolving electron and the nucleus

then for a dynamically stable orbit in a hydrogen atom $(z=1)$ -

$$F_c = F_e$$

$$\frac{mv^2}{r} = \frac{e \cdot e}{4\pi\epsilon_0 r^2} \Rightarrow mv^2 = \frac{e^2}{4\pi\epsilon_0 r}$$

K.E. of the electron in the orbit $= \frac{1}{2}mv^2$

Hence $\boxed{K.E. = \dfrac{e^2}{8\pi\epsilon_0 r}}$

Potential energy of electron in orbit -

$$\boxed{U = \frac{e(-e)}{4\pi\epsilon_0 r} = \frac{-e^2}{4\pi\epsilon_0 r}}$$

$\therefore$ Total energy of electron in hydrogen atom -

$$E = K.E. + U$$

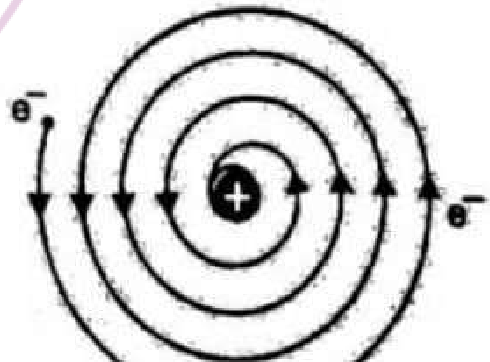
$$E = \frac{e^2}{8\pi\epsilon_0 r} - \frac{e^2}{4\pi\epsilon_0 r}$$

or $\boxed{E = -\dfrac{e^2}{8\pi\epsilon_0 r}}$

Hence the total energy of electron in orbit of hydrogen atom is negative. Hence, the electron is bound to the nucleus i.e. the electron is not free to leave the orbit around the nucleus.

Limitation of Rutherford Atom Model -

(i) According to the classical EM theory, the revolving electrons must radiate energy in the form of EM waves. As revolving electron loses energy continuously, it must spiral inwards and finally fall into the nucleus, but as matter is stable, we cannot expect the atoms to collapse.



(ii) As the revolving electrons spiral inwards, their angular velocities and hence their frequencies of revolution would change continuously. Therefore, frequency of EM waves emitted must change continuously.

Therefore, atoms should emit continuous spectrum but we observe only a line spectrum.

Bohr Model of Hydrogen Atom-

There are three basic postulates of this model-

(1) Every atom consist of a central core called nucleus, in which entire positive charge and almost entire mass of the atom are concentrated. A suitable number of electrons revolve around the nucleus in circular orbits. The centripetal force required for revolution is provided by the electrostatic force of attraction between the electron and the nucleus.

Centripetal force = Electrostatic force of attraction

$$\frac{mv^2}{r} = \frac{1}{4\pi\epsilon_0}\frac{(Ze)(e)}{r^2}$$

$$\therefore \boxed{\frac{mv^2}{r} = \frac{KZe^2}{r^2}} \qquad \left[\begin{array}{l} K = 1/4\pi\epsilon_0 \\ Z = 1 \end{array}\right.$$

(2) According to Bohr, electron can revolve only in certain discrete non radiating orbits, called stationary orbits, for which total angular momentum of the revolving electron is an integral multiple of $h/2\pi$, where h is plank's constant.

Thus the angular momentum of a orbiting electron is quantised.

$$\boxed{mvr = \frac{nh}{2\pi}} \qquad n = 1, 2, 3, \ldots$$

Here n is called principle quantum number.

* The electron, while revolving in such orbits, shall not lose energy i.e. its energy would stay constant.