PROBLEMS WITH RUTHERFORD MODEL

1. INTRODUCTION

At the end of nineteenth century, the explanation of absorption and emission spectra of elements was a challenging task for the scientists worldwide. By that time, electron was discovered and its charge and mass were also determined. Further, it was also established that electrons reside in the atom and to account for the electrical neutrality of the atom, the quantity of positive and negative charge in an atom must be same.

In an attempt to explain the experimentally obtained absorption and emission spectra, several theories of atomic structure were proposed by different scientists, which are termed as atomic models. These include the Thomson's atomic model, Rutherford's nuclear model, and the Bohr's model. In this chapter, we will discuss the various problems encountered by the Rutherford model and how these were overcome by the Bohr's model.

2. THOMSON'S ATOMIC MODEL

English physicist J.J. Thomson (1904) was the first to propose the arrangement of the positive charges and negatively charged electrons in an atom. According to Thomson, the entire positive charge of the atom is uniformly distributed within a sphere of radius of the order of 10^{-10} m. The negatively charged electrons are scattered throughout this sphere of positive charge (Fig. 2.1). The condition of electrical neutrality is thus preserved. The electrons are not at rest but are free to move within the cloud of positive charge. This was called Thomson's plum pudding model because the negatively charged electrons (the "plums") are embedded in a sphere of uniform positive charge (the "pudding"). Many different names are given to this model, for example, plum pudding model, raisin pudding model or watermelon model.

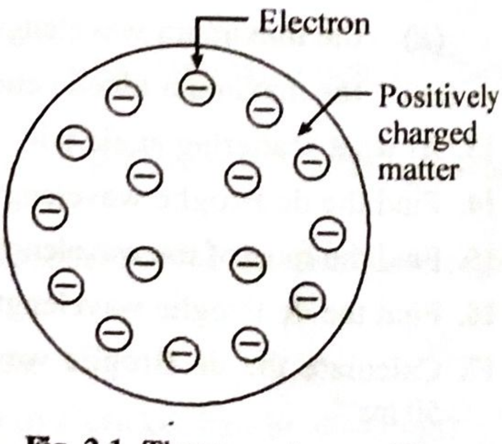

Fig. 2.1. Thomson plum pudding model.

Success

The Thomson's atomic model met with very little success. This model attempted to explain the periodicity of chemical properties of elements as well as the electromagnetic spectra of atoms.

Drawbacks

Thomson's atomic model could not explain the

1. large angle scattering in Rutherford α-scattering experiment.
2. concept of nucleus of an atom.
3. origin of spectral lines in case of hydrogen atom.

3. RUTHERFORD NUCLEAR MODEL

Rutherford and his students, Geiger and Marsden, investigated the penetration of alpha particles through matter (Fig. 3.1). A narrow beam of high-energy α-particles was incident on a thin gold foil (thickness ~ 100 nm). The thin gold foil had a circular fluorescent zinc sulphide screen around it. Whenever α-particles struck the screen, a tiny flash of light was produced at that point. The alpha particles scattered in different directions were detected by an α-particle detector.

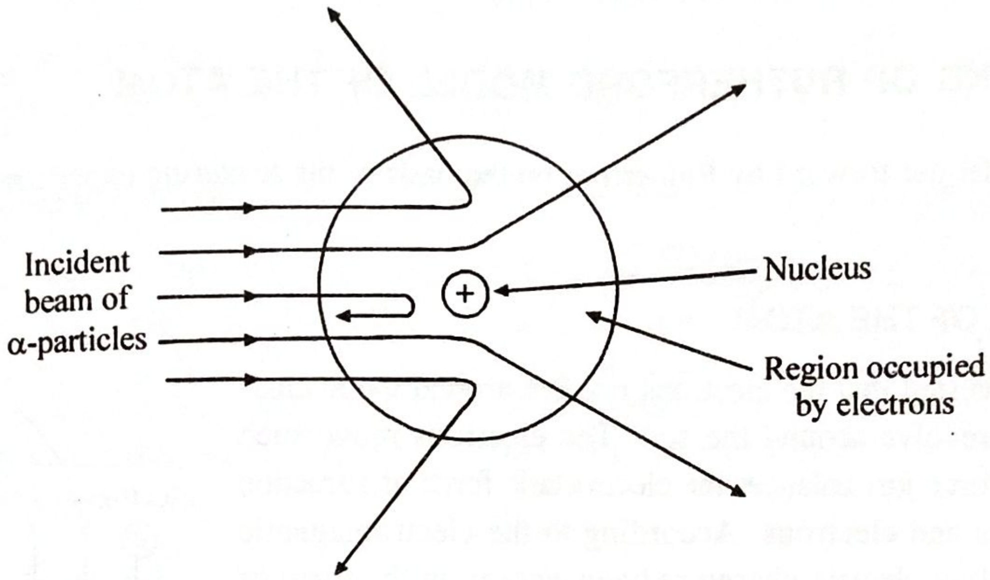

Fig. 3.1. Scattering of α-particles by thin gold foil.

Observations

The results of scattering experiment were quite unexpected. According to Thomson model of atom, the mass of each gold atom in the foil should have been spread evenly over the entire atom, and α-particles had enough energy to pass directly through such a uniform distribution of mass. It was expected that the particles would slow down and change directions only by small angles as they passed through the foil.

It was observed that

1. Most of the α-particles passed straight through the gold foil without any deflection.
2. Some of the α-particles suffered small deflections and were deflected at angles less than 90°.
3. Few α-particles were deflected through angles more than 90°.
4. A very few α-particles (~ 1 in 20,000) were deflected by nearly 180°.

Explanation

On the basis of the observations, Rutherford concluded that :

1. The large-angle deflection of some α-particles is due to the strong electrostatic repulsive force exerted by a very small and massive positive point charge that exists at the centre of each gold atom. This very small portion of the atom was called nucleus by Rutherford.
2. Since most of the α-particles passed straight through the gold foil, this indicated that most of the space in atoms is empty.
3. Calculations by Rutherford showed that the volume occupied by the nucleus is negligibly small as compared to the total volume of the atom. The radius of the atom is about 10^{-10} m, while that of nucleus is 10^{-14} m.

Proposed Rutherford's Nuclear Model

On the basis of above observations and conclusions, Rutherford proposed the nuclear model of atom, according to which :

1. The whole positive charge and entire mass of an atom is concentrated at its centre in a sphere of radius 10^{-14} m, called the nucleus.
2. The electrons move in circular orbits about the nucleus and the necessary centripetal force is provided by the electrostatic force of attraction between the nucleus and electrons.
3. Atom is electrically neutral as the total positive charge on the nucleus is equal to the total negative charge of the electrons in the atom.

3.1. DRAWBACKS OF RUTHERFORD MODEL OF THE ATOM

The atomic model put forward by Rutherford on the basis of his scattering experiment had the following limitations.

3.1.1. STABILITY OF THE ATOM

Rutherford suggested that the electrons revolve around the nucleus just as the planets revolve around the sun. The electrons move such that the centrifugal force just balances the electrostatic force of attraction between the nucleus and electrons. According to the electromagnetic theory, an accelerating electric charge radiates energy in the form of electromagnetic radiation. The electrons revolving in circular orbits experience a centripetal acceleration and hence should gradually lose energy in the form of electromagnetic radiation. As a result, the electron should approach the nucleus by a spiral path, giving out radiation of a constantly increasing frequency and ultimately falling into the nucleus. Hence, the atom would be highly unstable and would collapse (Fig. 3.2), but in actual practice the atom is stable. This highlights the inadequacy of Rutherford model in explaining the stability of an atom.

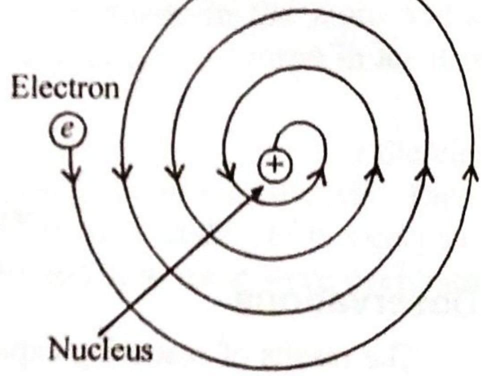

Fig. 3.2. Instability of an atom

This contradiction was resolved by Bohr in 1913. He combined Rutherford's atomic model, Planck's concept of energy quantization and Einstein's concept of photons and put forward few postulates which described the hydrogen atom. He argued that electrons are allowed to move in certain discrete orbits called stationary orbits. An electron cannot radiate any energy while moving in a particular orbit. The emission of radiation takes place only when an electron jumps from one orbit to another orbit of lower energy (Fig. 3.3). Thus in general, the atom remains stable.

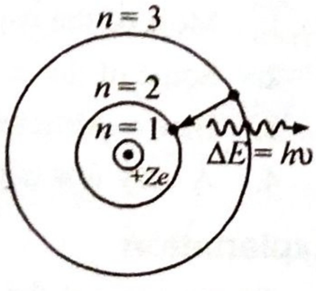

Fig. 3.3. Orbital transition of electron.

3.1.2. DISCRETE ATOMIC SPECTRA

According to Rutherford model, the electron spirals gradually towards the nucleus, which results in a constant increase in its angular frequency. Classical approach gives the following expression for the wavelength emitted by an accelerating charge.

$$\lambda \propto \frac{1}{r^{3/2}}$$

As r decreases, the emission wavelength increases continuously. Therefore, the electron should emit electromagnetic radiation of a continuous range of frequencies, resulting in a continuous atomic spectrum.

But it is contrary to the experimental observation, which shows that the atoms exhibit discrete line spectra.

3.1.3. ORBITS

Rutherford proposed that electrons revolve around the nucleus in fixed orbits. However, he did not specify the orbits and the number of electrons in each orbit.

Hence, the analysis based on classical physics failed to provide a satisfactory picture of the atomic structure. These problems were resolved by Niels Bohr in 1913.

4. BOHR'S ATOMIC MODEL

In 1913, Bohr (student of Rutherford) put forward a bold new hypothesis to explain the atomic structure. Bohr used the Rutherford model of the atom as his starting point. He assumed that an electron moves about the nucleus without radiating energy only in certain discrete orbits, called permitted orbits. The transition of the electron from one orbit to another is accompanied by the emission or absorption of a photon of energy $\Delta E = h\upsilon$ (ΔE is the difference in the energy between the two levels). Bohr's model is based on the following postulates :

Postulates

1. The electrons revolve in circular paths around the nucleus Fig. 4.1. The centripetal force required for rotational motion is provided by the electrostatic attractive force between the electrons and nucleus.

$$\frac{mv^2}{r} = \frac{Ze^2}{4\pi\varepsilon_0 r^2}$$

where v is the velocity of the electron, r is the radius of orbit and Z is the atomic number of the atom.

2. Electrons are permitted to circulate only in those orbits for which the angular momentum L of the electron is an integral multiple of $\hbar = h/2\pi$, where h is Planck constant. Therefore, for any permitted orbit,

$$L = mvr = n\hbar$$

where $n = 1, 2, 3, \ldots\ldots$ is the principal quantum number.

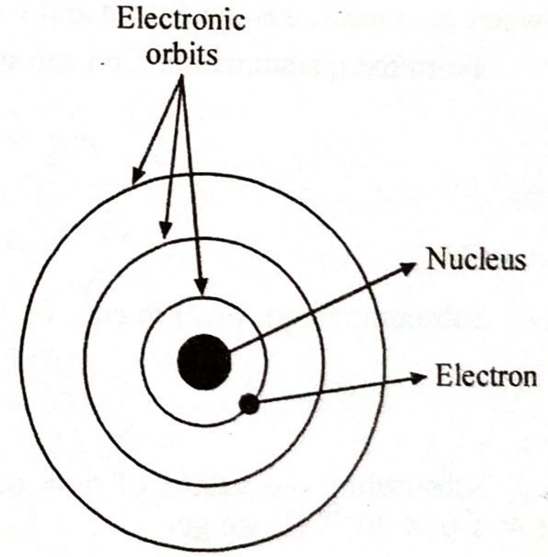

Fig. 4.1. Bohr's Atomic Model.

3. When an electron jumps from higher energy orbit (say E_2) to lower energy orbit (say E_1) then energy difference $E_2 - E_1$ is emitted in the form of a photon. But if electron goes from E_1 to E_2, it absorbs the same amount of energy (Fig. 4.2).

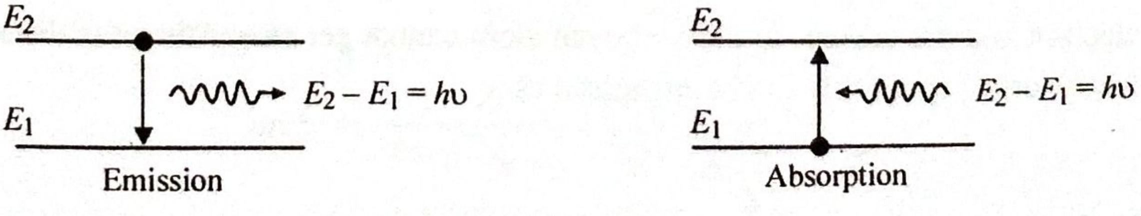

Fig. 4.2. Emission and absorption of radiation.

4.1. BOHR'S QUANTIZATION RULE AND ATOMIC STABILITY

According to Bohr's theory, only those orbits are permitted for which the angular momentum of electron is an integral multiple of $\hbar$. This is called the quantization rule, *i.e.* the electron can exist only in discrete energy levels. These energy levels are called stationary orbits. The electron orbiting in any of the stationary orbits does not radiate energy. It radiates or absorbs energy only when it jumps from one orbit to another. This accounts for the atomic stability.

Using this model, Bohr could predict the radii of atomic orbits, speed and energy of electrons in these orbits.

Note : Stationary state was a term used by Bohr to mean a state of an atom that was stable, non-radiating and had energy constant with time. It does not mean fixed in position or without motion, since electrons in stationary orbits move with high speed.