Chapter Two: Atomic Structure

An atom consists of a central nucleus and an outer electron cloud containing a number of negatively charged particles called electrons that revolves around the nucleus. This number of electrons varies from one element to another. As for the central nucleus, it consists of positively charged particles known as protons and neutral particles called neutrons. This chapter discusses some of the experiments that led to understanding the structure of atoms.

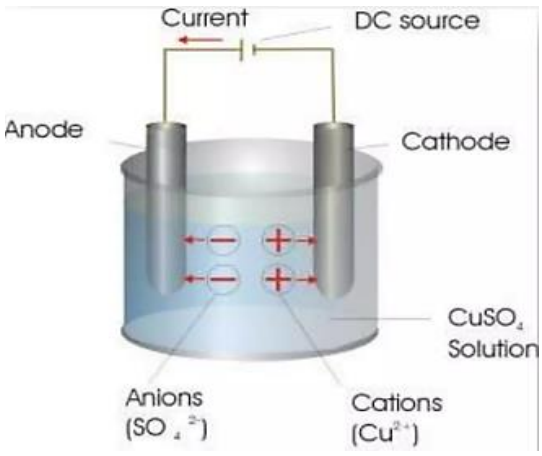
1- Discovery of Atomic Structure

1-1-Electron

Faraday's Electrolysis Experiment 1833

Scientist Faraday performed the electrolysis of copper sulfate ($CuSO_4$) compound. He placed this solution in a glass beaker and then submerged two electric electrodes, a positive electrode (+) and a negative electrode (-), into it. He observed the following:

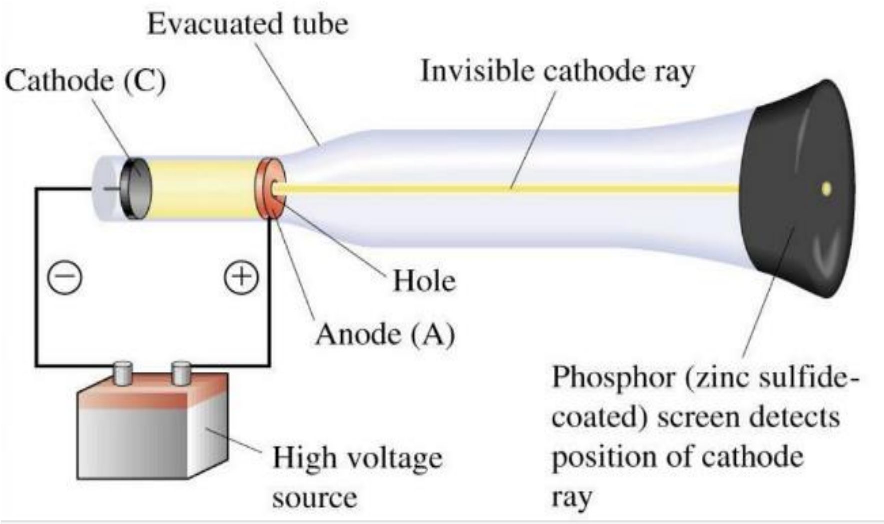
- Copper atoms deposited at the negative electrode (-).
- Oxygen gas was released at the positive electrode (+).
- The blue color of the solution vanished, turning into a slightly reddish liquid.



Faraday discovered that atoms contain positive and negative particles that are arranged according to their charges in an electric current. This contradicted Dalton's theory that the atom is an indivisible sphere, as he demonstrated that atoms carry charges.

William Crookes' Experiment - 1879

William Crookes conducted his experiments using a glass tube evacuated of almost all air (under very low pressure of about 10^{-6} atm), known as the cathode ray tube. Inside the tube, he placed two metal pieces called electrodes, which were connected to a high-voltage electrical source. When the voltage difference reaches 15,000 volts, the screen becomes luminous.



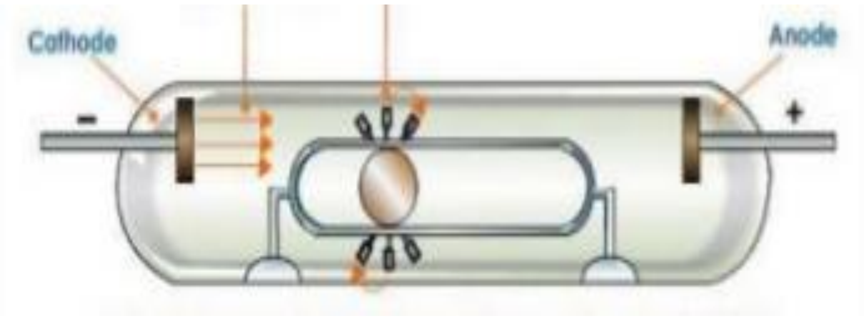
Conclusions:

- At low voltage differences, the gas remains a non-conductor of electricity due to the neutral nature of its atoms. However, it becomes a conductor under low pressure when exposed to a high voltage difference.

- Under high voltage and low pressure inside the tube, one of the electrodes emits small particles that collide with gas molecules, leading to a glow on the tube's wall known as Cathode Rays.

- When a metallic object is placed in the path of the cathode rays, it forms a silhouette on the screen. This implies that the rays move in straight lines and travel from the cathode to the anode, as the shadow forms at the anode.

- When a fan or a paddle wheel is placed between the electrodes in the path of the cathode rays, the latter starts to rotate. From this observation, we can conclude that these rays consist of particles with kinetic energy and thus possess mass.

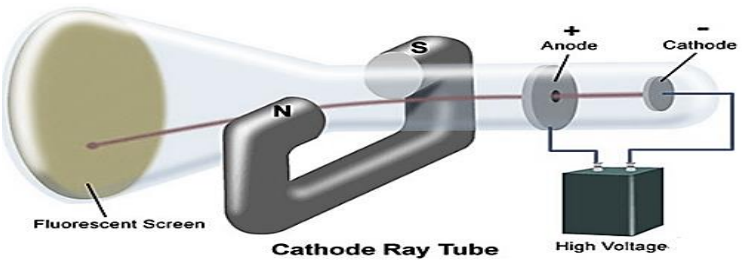


- when replacing the gas with another gas (resulting in a change in the color of the light beam), the cathode rays maintain their behavior. This indicating their interaction within all substances.

J.J.Thomson's experiment 1895

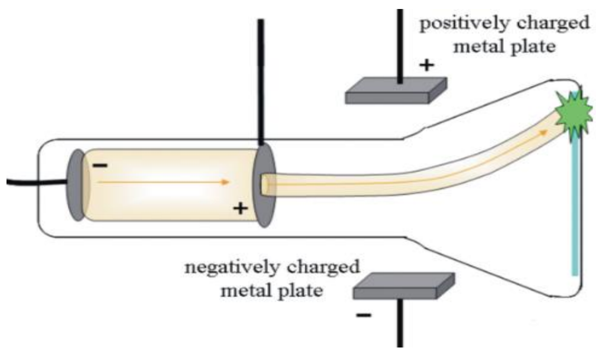
Thomson utilized the same Crookes apparatus and conducted several experiments with it, including:

a) Thomson used a magnetic induction field (B) to deflect a bundle of electrons downward due to the magnetic force (Fm). The magnetic force (Fm) is given by $\vec{F}_m = \beta q v$, where q is the electric charge, v is the velocity of the charge, and β is the strength of the magnetic field.

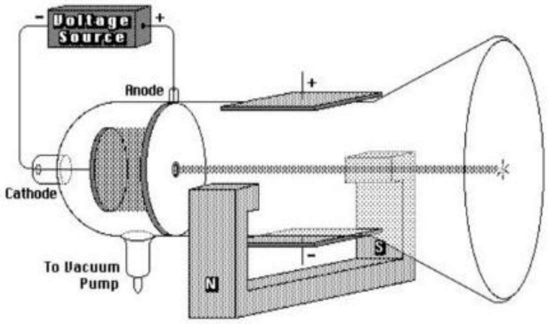


b) Thomson made a slight modification by introducing a positively charged capacitor plate (anode) into this apparatus. Through this experiment, Thomson noticed that the cathode rays were deflected towards the positively charged anode of the capacitor due to the electric force $\vec{F}_e$ ($F_e = qE$), indicating that they carried a negative charge. Here, q is the electric charge and E is the electric fieldفيلد strength.

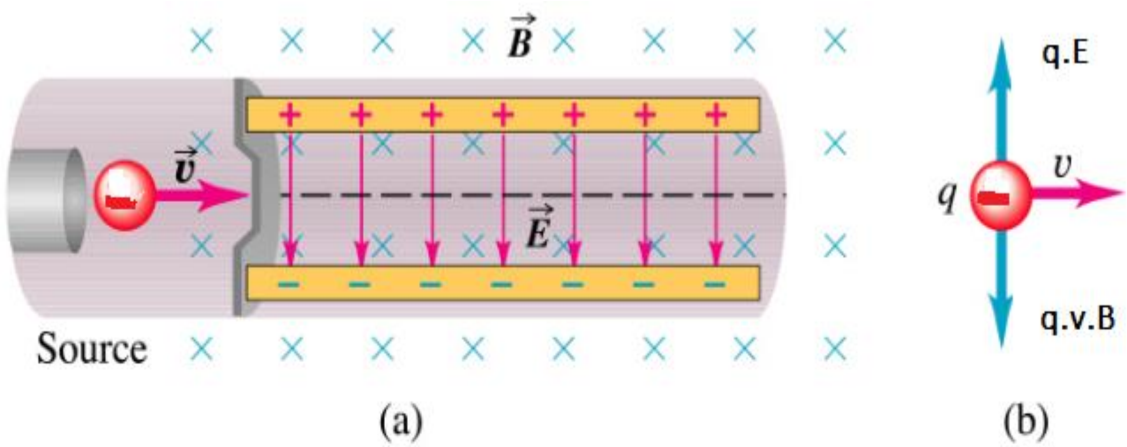
c) When the electron bundle is subjected to both an electric field E and a magnetic field β



simultaneously, the electrons experience an upward electric force and a downward magnetic force. By adjusting the value of the magnetic field strength, the two forces can be balanced, resulting in a net force of zero. This equilibrium condition causes the electron bundle to return to its straight path, as indicated by the glowing spot at the center of the screen.



This figure illustrates the aforementioned:



Using the Lorentz force law, where the magnetic force equals the electric force, we have: $qv\beta$ = qE

Since the charge q is the electron's charge, we can substitute it with e. This relationship allows us to calculate the electron's velocity:

$$v = E/\beta$$

By substituting the electric field E with the voltage difference V over the distance d between the plates, we obtain:

$$e.\vartheta.\beta = \frac{e.V}{d}$$

And given our knowledge of the kinetic energy provided to the electrons through the voltage difference, using the equation:

$$eV = ½\, m\, \vartheta^2$$

By substituting this into the previous equation, we get:

$$e.\vartheta.\beta = \frac{m.\vartheta^2}{2d}$$

In summary, through simplification, we obtain:

$$e.\beta = \frac{m.\vartheta}{2d}$$

By rearranging the equation, we have:

$$\frac{e}{m} = \frac{\vartheta}{2.\beta.d}$$

Where e is the charge of the electron, m is its mass, ϑ is the velocity of electrons, B is the value of the magnetic field, and d is the distance between the plates generating the electric field.

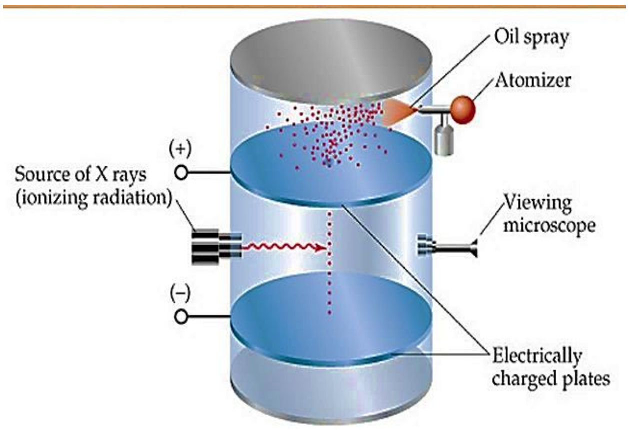
Thomson was able to calculate the value of the ratio between the charge of the electron and its mass, which is equal to:

$$\frac{e}{m} = 1.758.10^8 C/g$$

It was discovered that this ratio does not change with the change of the gas used or the cathode material, and therefore, it is the main component of atoms of any substance. Since the ratio is very large, it was concluded that these particles are very small.

Millikan experiment 1911

In the year 1911, scientist Robert Millikan succeeded in estimating the charge of the electron using the following apparatus:



- In this apparatus, oil was sprayed onto two parallel plates that were charged.
- The upper plate contained a small hole through which the oil could pass.
- A beam of X-rays was passed through the air in the chamber, ionizing the air and causing ions to attach to the oil droplets. As a result, the oil droplets acquired positive or negative charges depending on their collision with positive or negative ions.
- Millikan used a telescope to observe the droplets. When an electric field was applied between the plates, the motion of the droplets changed due to the forces acting on them.

The forces acting on the charged droplet:

Gravity Force (P):

$$P = m.g = \frac{4}{3}.\pi.r^3.\rho.g$$

Where: ρ: Volumic Mass of the oil.

g: Acceleration due to gravity.

Stokes Force (R): Its direction is always opposite to the droplet's translational motion.

$$R = 6.\pi.r.\eta.\vartheta$$

Where: ϑ: Droplet velocity

η: Air viscosity coefficient

r: Droplet radius

Archimedes Thrust (A): Its direction is always upward and often negligible.

$$A = \frac{4}{3}.\pi.r^3.\rho`g$$

Where: ρ: Volumic Mass of the air.

g: Acceleration due to gravity.

Electric Force (F_e): Its direction is related to the direction of the electric field and the charge of the droplet.

$$F_e = q.E$$

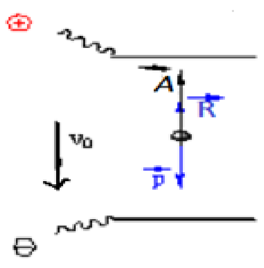
Where: q: Charge of the droplet

E: Electric field

Three cases can be distinguished:

- **No Electric Field:** In the absence of an electric field, the droplet falls downward due to gravity.

$$\sum \vec{F}_{ext} = m.\vec{\gamma}$$



In the absence of an electric field

$$\Rightarrow \vec{P} + \vec{R} + \vec{A} = m.\vec{\gamma}$$

The droplet reaches its maximum speed very quickly, and from there, the droplet's speed remains constant.

$$\Rightarrow P - A - R = 0$$

$$\frac{4}{3}.\pi.r^3.\rho.g - \frac{4}{3}.\pi.r^3.\grave{\rho}.g - 6.\grave{\pi}.r.\eta.\vartheta_0 = 0$$

$$\Rightarrow \frac{4}{3}.\pi.r^3.g(\rho - \grave{\rho}) - 6.\pi.r.\eta.\vartheta_0 = 0$$

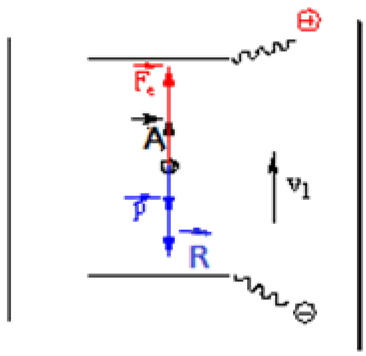
$$\Rightarrow \frac{4}{3}.\pi.r^2.g(\rho - \grave{\rho}) - 6.\pi.\eta.\vartheta_0 = 0$$

$$\Rightarrow r^2 = \frac{6.\pi.\eta.\vartheta_0}{\frac{4}{3}.\pi.g(\rho - \grave{\rho})} = \frac{9.\eta.\vartheta_0}{2.g(\rho - \grave{\rho})}$$

$$\Rightarrow r = 3.\sqrt{\frac{\eta.\vartheta_0}{2.g(\rho - \grave{\rho})}} \dots\dots\dots\dots\dots\dots\dots..(1)$$

- In the presence of the electric field, the droplet ascends toward the positively charged plate (the droplet has a negative charge) with a new speed ϑ_1. In addition to the previous forces, the droplet is influenced by an electrical force, F_e.

"The droplet moves at a constant speed, indicating that acceleration is negligible."



In the presence of the electric field

$$\sum \vec{F}_{ext} = m.\vec{\gamma}$$

$$\Rightarrow \vec{P} + \vec{F_e} + \vec{R} + \vec{A} = m.\vec{\gamma}$$

$$\Rightarrow -P + F_e - R + A = 0$$

$$\Rightarrow P - A + R = F_e$$

$$\Rightarrow \frac{4}{3}.\pi.r^3.g(\rho - \grave{\rho}) + 6.\pi.r.\eta.\vartheta_1 = q.E$$

$$\Rightarrow q = \frac{\frac{4}{3}.\pi.r^3.g(\rho - \grave{\rho}) + 6.\pi.r.\eta.\vartheta_1}{E} \quad \ldots\ldots\ldots\ldots..(2)$$

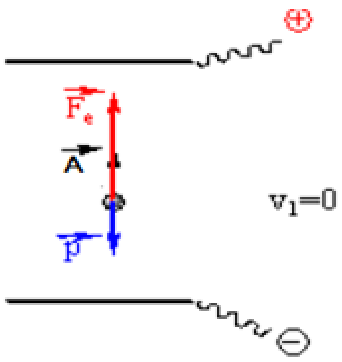
When we substitute (1) into (2), we find:

$$q = \frac{\frac{4}{3}.\pi.r.\frac{9.\eta.\vartheta_0}{2.g(\rho - \grave{\rho})}.g(\rho - \grave{\rho}) + 6.\pi.r.\eta.\vartheta_1}{E}$$

$$\Rightarrow q = \frac{\frac{2}{3}.\pi.r.9.\eta.\vartheta_0 + 6.\pi.r.\eta.\vartheta_1}{E}$$

$$\Rightarrow q = \frac{6.\pi.r.\eta}{E}(\vartheta_0 + \vartheta_1)$$

- In the last case, the electric field strength is adjusted so that the droplet becomes stationary, meaning its velocity is zero. Therefore, the Stokes' drag force is negligible, and the droplet is subjected to three forces: gravity, Archimedes Thrust, and the electric force.



The droplet is at rest

By varying the electric field strength E, Millikan obtained several values for the charge and concluded that they are multiples of the number 1.6 × 10^{-19} C, which is considered the smallest unit of charge and is named the elementary charge e. This value remains constant regardless of the nature of the gas used, its pressure, or the method of ionization.

Through this understanding:

$$\begin{cases} \frac{e}{m_e} = 1.758.10^8 C/g \\ e = 1.6.10^{-19} C \end{cases}$$

$$\Rightarrow m_e = \frac{e}{e/m_e} = 9.1.10^{-28} g$$