Chapter 2

Structure of the atom

I. Electron: Demonstration: J.J. Thomson's experiment, Properties of cathode rays

II. Nucleus: Demonstration: Rutherford experiment, Constitution of the atomic nucleus

III. Element identification: Representation, Atomic mass, Relative atomic mass

I. Electron: Highlighting

The characteristics of the electron were obtained from the work of CROOKES, J. PERRIN, MILLIKAN and J.J. THOMSON.

I-1. J.J. Thomson's experiment (1912)

Thanks to the laws of electromagnetism, J.J. Thomson was able to determine the ratio between the charge and mass of the electron. Measurement of the e/m ratio is based on the deflection of an electrified particle by an electric and magnetic field.

- **Device description**

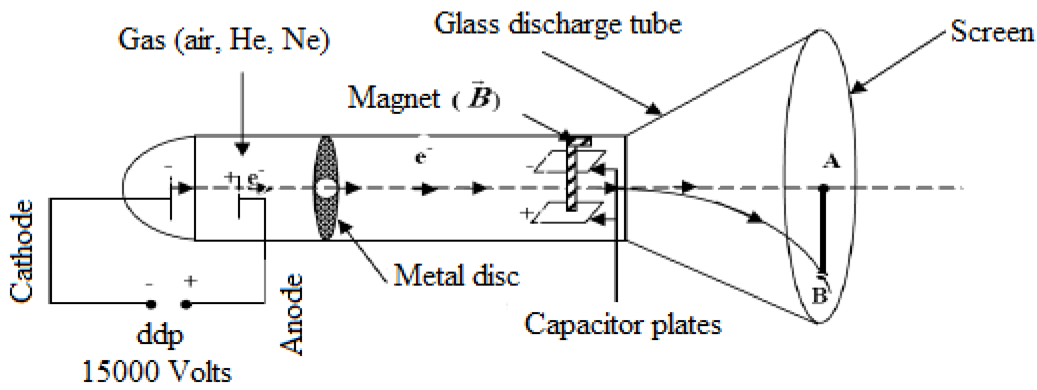

Figure 1: e/m ratio measuring instrument

- ✓ **Left:** where the gas is introduced at very high pressure. The ions formed are accelerated by a potential difference (pd) and pass through the hollow cathode C.

  From the moment the ions arrive at the hollow cathode, they are no longer subject to any force, and the velocity acquired in the electric field remains constant.

- ✓ **Ampoule:** Accelerated charged particles pass through an ampoule in a vacuum to avoid any obstacle to their propagation.

  Accelerated particles pass through a vacuum ampoule, which flares (widens) towards the receiver so as not to disturb the particle trajectories. The bottom of the ampoule has a large surface area. It is coated with a thin layer of a luminescent solid (barium platinocyanide; zinc superlide; ....), which has the property of emitting visible light radiation at any point where an ion strikes it.

- ✓ **The electromagnetic analyzer:** placed outside the bulb, close to the cathode. It consists of an electromagnet and a capacitor whose armatures have exactly the same shape, so that the electric and magnetic fields are rigorously superimposed.

This operation produces linear ion trajectories.

I-2. Study of channel ray deviations

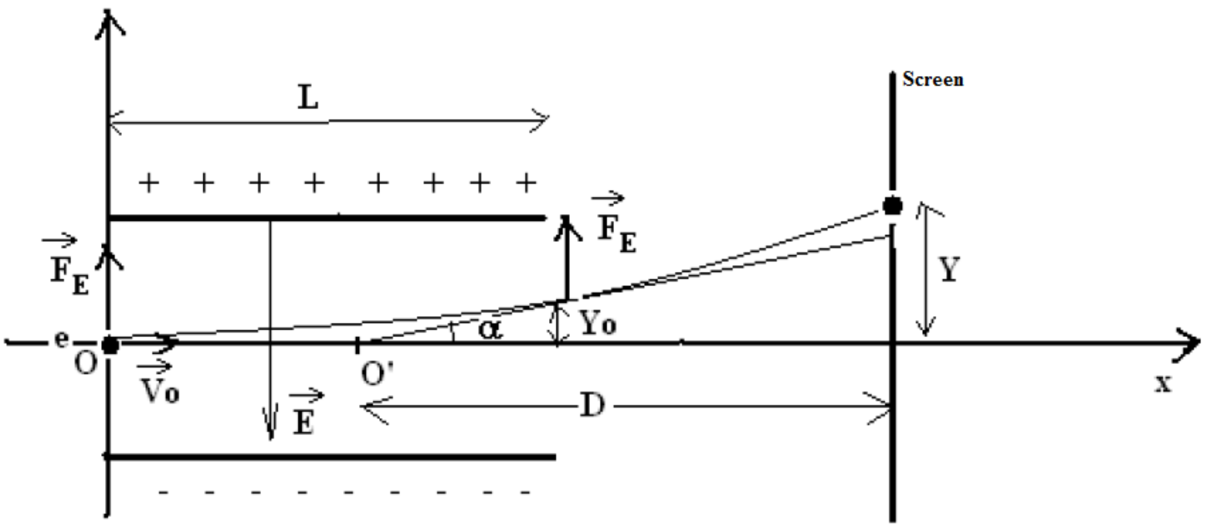

Figure 2: Cathode ray deflection

<u>Electric field action:</u>

Let's consider a particle m with charge q = -e and velocity V_0.

- If the capacitor is not charged, the particle moves along OX.

- If the capacitor is charged, the electron is subjected to a force towards the positive plate along OY of intensity:

$$F_e = e.E = m_e.\gamma \qquad (1)$$

Following OX: uniform rectilinear motion $\gamma_n = 0$

$$x = V_0 * t \qquad (2)$$

Next OY: uniformly accelerated motion:

$$\gamma = \frac{e * E}{m} \qquad (3)$$

Along OY , motion is uniformly accelerated, so we can write :

$$m.\frac{d^2y}{dt^2} = e.E \qquad (4)$$

By integrating this equation assuming: at t = 0, y=0 we find :

$$y_0 = \frac{1}{2}.\gamma.t^2 = \frac{1}{2}.\frac{e}{m}.E.t^2 \qquad (5)$$

Next OX : $x = V_0 * t \Rightarrow t = \frac{x}{V_0}.$

$$(5) \Leftrightarrow \quad y_0 = \frac{1}{2}.\frac{e}{m}.\frac{x^2}{V_0^2} \qquad (6)$$

At capacitor output: x = L

$$y_0 = \frac{1}{2}.\frac{e}{m}.\frac{E.L^2}{V_0^2} \qquad (7)$$

Electron deflection in a uniform magnetic field:

The electron has a velocity $\vec{V_0}$ perpendicular to the magnetic field $\vec{B}$, and is subject to a magnetic force $\vec{F_m}$ opposite to the electrical force $\vec{F_e}$ of intensity:

$$F_m = e.V_0.B\sin\alpha = e.V_0.B \qquad (8)$$

$\overrightarrow{V_0}$ is perpendicular to $\vec{B}$: sinα=1.

The direction of this force is given by the rule of the three fingers of the right hand: the thumb, index and middle fingers indicate the direction of the magnetic field, the speed and the magnetic force respectively.

The electron's trajectory inside the magnetic field is circular with a radius (r) equal to:

$$r = \frac{m_e . V_0}{e . B} \quad (9)$$

Deducted from: the magnetic force is equal to the centrifugal force, hence:

$$|\overrightarrow{F_c}| = m_e . \frac{V_0^2}{r} = e . V_0 . B \Rightarrow r = \frac{m_e . V_0}{e . B}$$

<u>Simultaneous action of both fields:</u>

By simultaneously applying and acting appropriately on the intensities of E and B, electron deflection can be avoided; which means:

$$|\overrightarrow{F_e}| = |\overrightarrow{F_m}| \Rightarrow e . E = e . V_0 . B$$

$$V_0 = \frac{E}{B} \quad (10)$$

By replacing the expression of V_0 in the expression of y_0:

$$y_0 = \frac{1}{2} . \frac{e}{m_e} . \frac{E . L^2}{E^2} . B^2 = \frac{1}{2} . \frac{e}{m_e} . \frac{B^2 L^2}{E}$$

$$\frac{e}{m_e} = \frac{2 . E . y_s}{B^2 . L^2} \quad (11)$$

From the measurement of y_0, the experimental parameters E and B and knowing L, it is possible to calculate $\frac{e}{m_e}$:

$$\frac{e}{m_e} = 1{,}759 . 10^{11} C/Kg$$

I-2. Properties of cathode rays

In 1895, the British scientist W. Crookes carried out an important experiment on atoms, using a glass tube (now known as the Crookes tube) in which air was rarefied. He placed 2 electrodes in the tube, between which he applied a voltage of around 10,000 volts.

He then observed that, at low pressure, radiation produced luminescence on the tube walls. He called these rays "cathode rays". He shows that these rays are electrically charged, as they are deflected by the magnetic field of a magnet (they are deflected by an electric field towards the positive pole, indicating that the particles making up these rays are negatively charged).

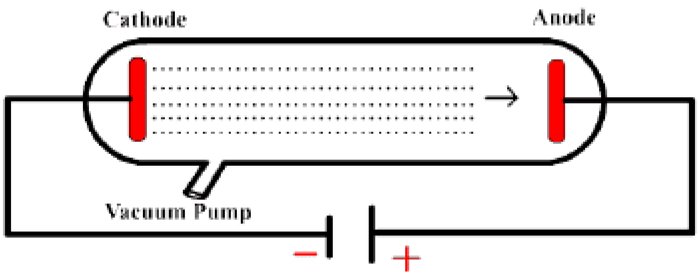

Figure 3: Crookes experiment

II. Core: Highlighting

It is made up of **protons** with a positive electric charge, and **neutrons** with zero electric charge. The particles that make up the nucleus are also called **nucleons**.

II-1. Rutherford experiment

Rutherford's experiment involved bombarding a very thin sheet of gold with helium nuclei (He^{2+}). By studying the trajectories of the particles, he found that most of them passed through the gold foil without being deflected, and that a small number were either strongly deflected as they passed through it, or were sent backwards: these were the particles that passed close to the positive charges. This shows that the matter in the gold foil is concentrated in particles (very small in volume) those are far apart in size and positively charged, and which have come to be known as the **atom's nuclei.**

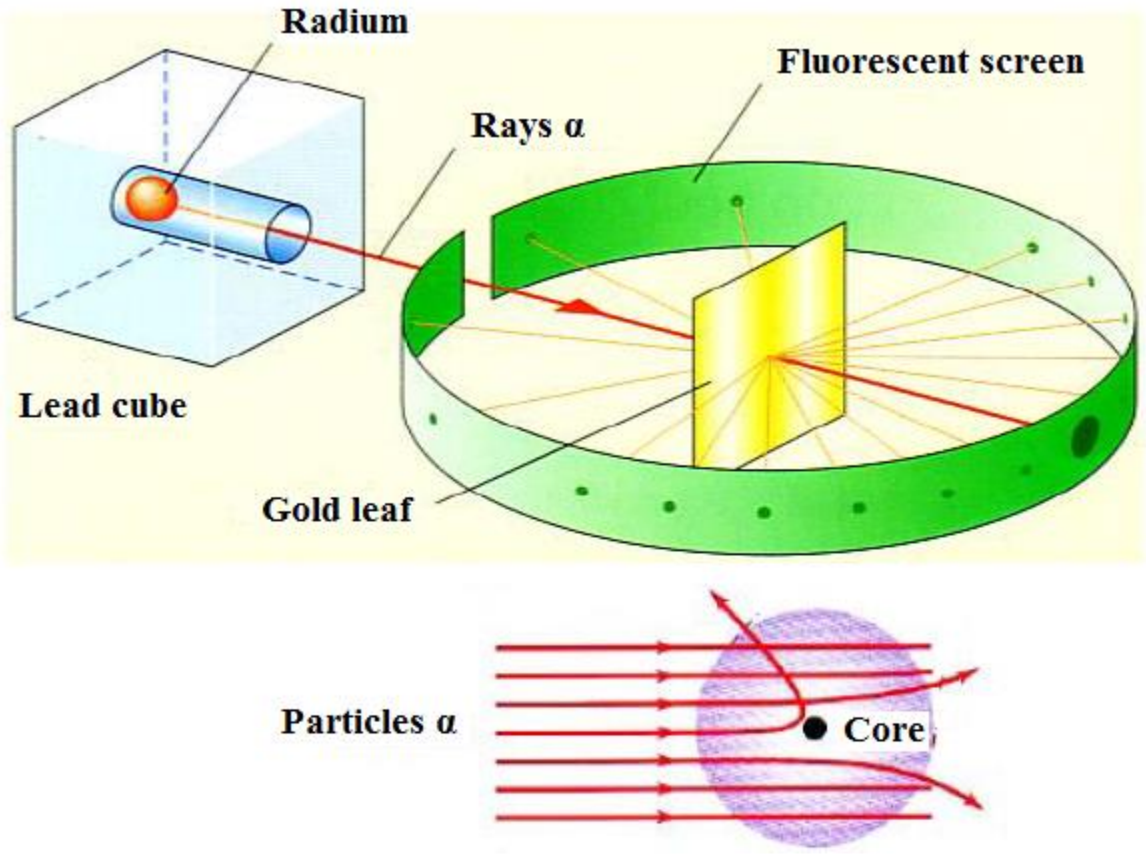

Figure 4: The schematic of Rutherford's experiment

II-2. Constitution of the atomic nucleus

According to Rutherford, all atoms are composed of a positively charged central nucleus. The nucleus contains two types of ingredient particles:

- Positively charged protons (+)
- Neutrons which are neutral.

Around this nucleus gravitate negatively-charged electrons, divided into different layers according to their energy level. The electrons are negatively charged, to compensate for the positive charge of the protons and make the atom electrically neutral. An atom thus has the same number of protons and electrons.

An element is characterized by the number of protons in its nucleus: this is the atomic number **Z**, and the number of nucleons (protons + neutrons) defines the mass number **A**.

The nucleus is made up of nucleons: Protons and neutrons.

$$\text{Proton: } m_p = 1{,}673.10^{-27}\ Kg \text{ ; charge: } q = 1{,}602.10^{-19}\ C$$

$$\text{Neutron: } m_n = 1{,}675.10^{-27}\ Kg \text{ ; charge: } q = 0\ C$$

$$\text{Pelectron: } m_e = 9{,}109.10^{-31}\ Kg \text{ ; charge: } q = -\ 1{,}602.10^{-19}\ C$$

$$\text{Therefore: } m_n \approx m_p = 1836\ m_e$$

$$\text{Core radius} \approx 10^{-14}\ \text{m}$$

$$\text{Radius of the atom} \approx 10^{-10}\ \text{m}$$

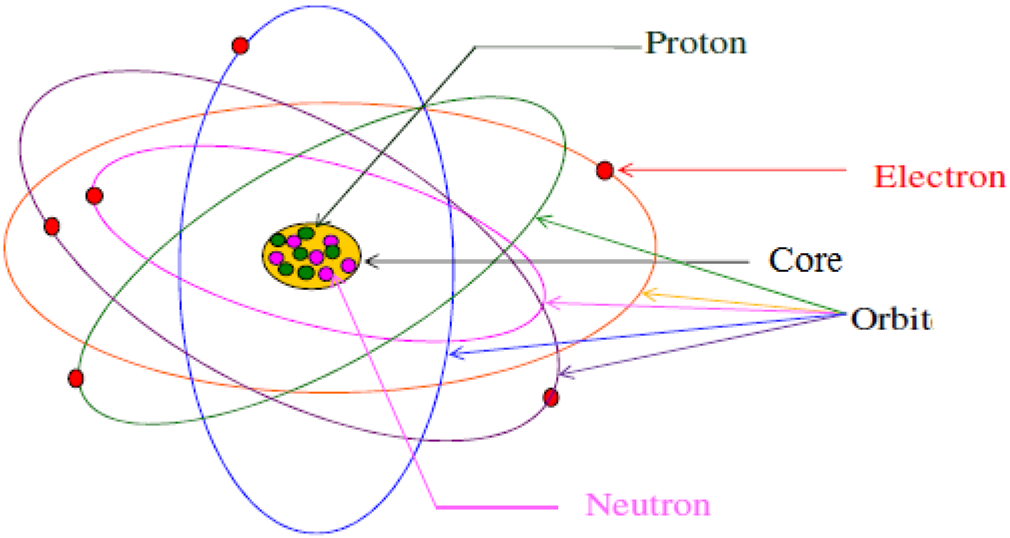

Figure 5: Structure of the atom

III. Element identification

III-1. Representation

The kernel of an element *X* can be represented symbolically by: $^{A}_{Z}\mathbf{X}$

Where: **X** represents the symbol of an atomic species or element,

Z is the number of protons, also called the **atomic number**.

A is the number of nucleons, i.e. the number of protons Z + the number of neutrons **N** in the nucleus. Also known as the **mass number**:

This symbolic representation $^{A}_{Z}\mathbf{X}$ is also called: **Nucleide** or **Nuclide**.

Example: The iron atom $^{56}_{26}Fe$ contains:

Z = 26 (26 protons in the nucleus, so 26 electrons).

A = 56 (56 nucleons, so N = 56 - 26 = 30 neutrons in the nucleus).

Atomic mass unit (amu)

In the international system, the unit of mass is the Kg. This is totally unsuited to the elementary scale of the atom. Hence the need for another unit, the atomic mass unit (a.m.u.) with:

$$1\ amu = 1{,}6606.10^{-27}\ Kg$$

$$m_e = 9{,}109.10^{-31}\ Kg = 5{,}5.10^{-4}\ amu$$

$$m_P = 1{,}673.10^{-27}\ Kg = 1{,}0074\ amu$$

$$m_n = 1{,}675.10^{-27}\ Kg = 1{,}0087\ amu$$

- ## Monoatomic and polyatomic ions

Monoatomic ions are formed from the atom by the **loss** or **gain of** one or more electrons. During the transition from atom to ion, the nucleus remains unchanged (Z is unchanged), but the appearance of the material changes. For example, copper is a red metal, but the copper ion has a blue color.

- **Anions**: the atom has gained one or more electrons; ions are negatively charged.
- **Cations**: the atom has lost one or more electrons, so ions are positively charged.

  Example:

- ✓ The copper ion $^{63}_{29}Cu^{2+}$ contains: Z = 29 (29 protons and 29 - 2 = 27 electrons, as it has lost 2 electrons) and A = 63 (63 nucleons, so N = 63 - 29 = 34 neutrons).
- ✓ The chlorine ion $^{35}_{17}Cl^{-}$ contains: Z = 17 (17 protons and 17 + 1 = 18 electrons because it has gained 1 electron) and A = 35 (35 nucleons, so N = 35 - 17 = 18 neutrons).

Ions group together to form ionic compounds which are electrically neutral: solid NaCl dissolved in water gives an ionic solution of (Na^{+} and Cl^{-}).

Polyatomic ions are made up of several atoms, all of which have gained or lost one or more electrons (example: the sulfate anion SO_4^{2-} and the ammonium cation NH_4^{+}).

III-2. Atomic mass and relative atomic mass

Isotopes are atoms or nuclides of the same chemical element (they have the same number of protons) **but** a different number of neutrons (hence different mass numbers and atomic mass).

$$^{A}_{Z}X \quad ^{A'}_{Z}X \quad ^{A''}_{Z}X$$
$$^{1}_{1}H \quad ^{2}_{1}H \quad ^{3}_{1}H$$

Note:

The chemical properties of two isotopes of the same element are strictly the same, as they are determined by the electron sequence, which is the same for both isotopes.

Example: natural magnesium comprises 03 isotopes: $^{24}_{12}Mg; ^{25}_{12}Mg; ^{26}_{12}Mg$. Z = 12 but A is different.

In nature, all elements are mixtures of isotopes. Calculating the atomic mass of a chemical element therefore depends on the abundance of each isotope.

Abundance is the percentage presence of the isotope in the chemical element. The average molar mass is calculated by the following equation:

$$M = \frac{\sum M_i . x_i}{100}$$