II. Principal constituents of matter

1. Introduction

Three particles form the basis of all matter: the proton, the neutron and the electron. These particles are defined according to two criteria: their electric charge and their masses. Protons have a positive charge, electrons have a negative charge, and neutrons do not carry an electrical charge. Protons and neutrons have relatively equal mass and are 1850 times heavier than electrons.

2. Faraday's laws: the relationship between matter and electricity

If a sufficient potential difference is applied between two electrodes immersed in an electrolyte solution (HCl), an electric current flows and a series of chemical reactions occur simultaneously at the electrode-electrolyte contact surface.

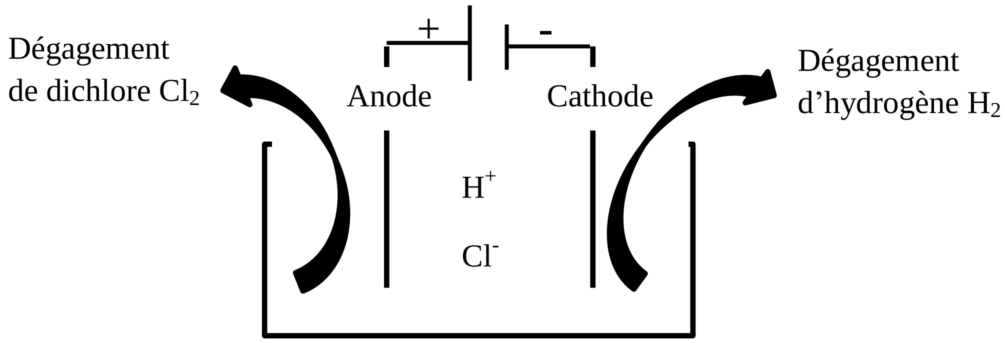

Figure 9: Simplified scheme of hydrochloric acid electrolysis

At the electrodes, gases are released in molecular form: chlorine is released at the anode (+) and hydrogen at the cathode (-). This decomposition of hydrochloric acid is expressed by the equation:

$$2HCl \longrightarrow H_2 + Cl_2$$

In solution, we know that HCl is dissociated into two ions, H+ and Cl-. The fact that hydrogen appears at the negative electrode forces us to admit that the hydrogen ion is positively charged (Coulomb's law) and the chloride ion is negatively charged..

In the context of electrochemistry, Faraday's laws are primarily associated with the process of electrolysis, where chemical reactions are driven by the application of an electric current. There are two main laws:

- **Faraday's First Law of Electrolysis:**

This law states that the amount of chemical substance (e.g., ions) that is deposited or liberated at an electrode during electrolysis is directly proportional to the quantity of electricity (in coulombs) passed through the electrolyte. Mathematically, it can be expressed as::

$$m = \left(\frac{Q}{F}\right)\left(\frac{M}{z}\right)$$

m: the mass of the substance released at the electrode (g) and M its molar mass (g/mol)

Q: the total electric charge passed through the substance

F: Faraday's constant is 96485 C mol^{-1},

Z: the valence of the substance

M/z corresponds to the equivalent of the total substance released.

- **Faraday's Second Law of Electrolysis:**

- This law states that the amounts of different substances deposited or liberated at the electrodes during electrolysis are directly proportional to their respective chemical equivalent weights.
- Mathematically, it can be expressed as:

$$\frac{m_1}{m_2} = \frac{E_1}{E_2}$$

Where:

- m1and m2 are the masses of different substances deposited or liberated.
- E1 and E2 are the chemical equivalent weights of the substances.

3. Highlighting the components of matter

During the period 1875-1910, various experiments demonstrated that atoms are not the ultimate constituents of matter, and that they themselves are made up of several types of particles.

3.1 J.J. Thomson and the discovery of the electron (e/m for Electrons)

In the late 19th, physicist J.J. Thomson began experimenting with cathode ray tubes. **Cathode ray tubes are sealed glass a tube from which most of the air has been evacuated**. A high voltage is applied across two electrodes at one end of the tube, which causes a beam of particles to flow from the cathode (the negatively-charged electrode) to the anode (the positively-charged electrode). The tubes are called cathode ray tubes because the particle beam or "cathode ray" originates at the cathode. The ray can be detected by painting a material known as phosphors onto the far end of the tube beyond the anode. The phosphors spark, or emit light, when impacted by the cathode ray.

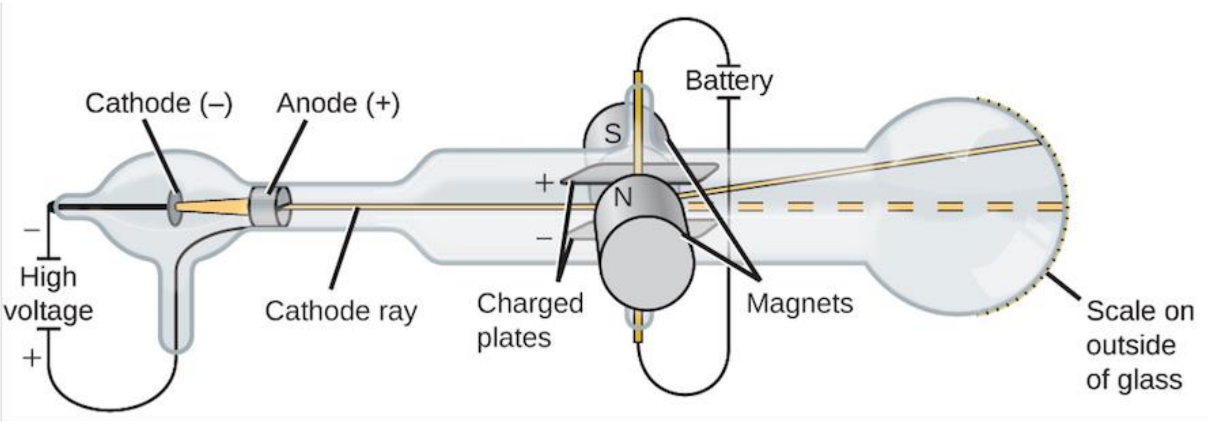

Figure 10: A diagram of J.J. Thomson's cathode ray tube

The charge to mass ratio (e/m) of an electron was experimentally determined by J.J. Thomson. The experimental set-up consists of a cathode ray tube which has three parts:

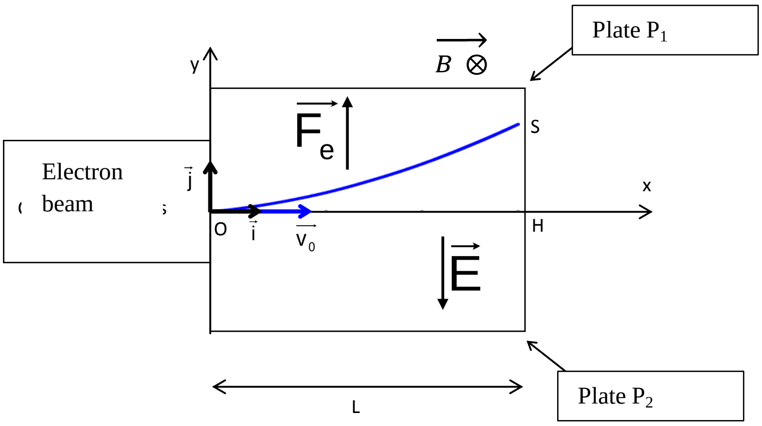

Figure 11 : Electron trajectory in a frame of reference under a magnetic and electric field

a) Deflection under an electric field

Thomson designed a device in which an electron beam is deflected as it passes between two plates in an electric field. By measuring the deflection of the electron beam, he was able to determine the ratio e/m_e (Figure II.4).

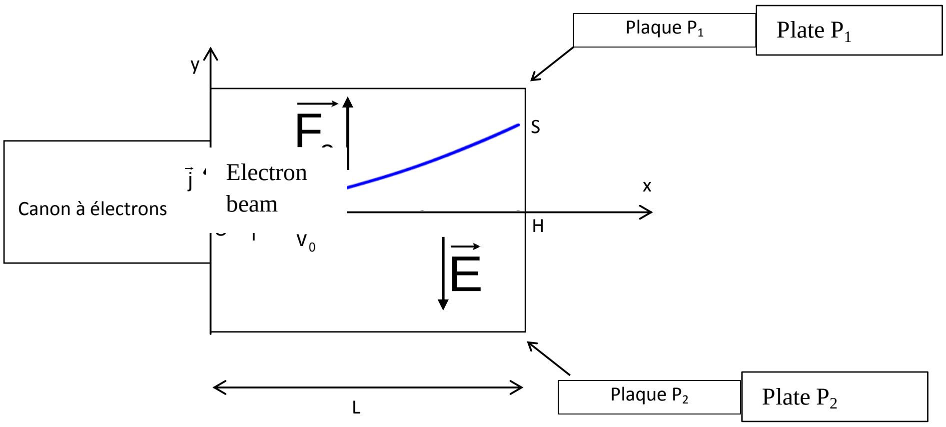

Figure II.4 : Electron trajectory in a reference frame under an electric field

$$\frac{e}{m_e} = \frac{2 * y * v_0^2}{E * L^2}$$

Example:

At the exit of the region between plates P1 and P2 (Figure II.4), the electron has undergone a vertical deflection SY. Determine the value of the ratio (e/m_e).

Given y=YS = 2.0x10^{-2} m. Plate length: L = 9.0x10^{-2} m Initial velocity of the electron: v0 = 2.4x10^{7} m.s^{-1} Value of the electric field: E = 1.6x10^{4} V.m-1

$$\frac{e}{m_e} = \frac{2 * y * v_0^2}{E * L^2}$$

Numerical application gives

$$\frac{e}{m_e} = \frac{2 * 2 \times 10^{-2} \times (2{,}4 \times 10^7)^2}{1{,}6 \times 10^4 \times (9 \times 10^{-2})^2} = 1{,}8 \times 10^{11} C.kg$$

__b) Deflection under a magnetic field__

An electron moving in a magnetic induction field B ⃗, is subjected to a magnetic force

$\overrightarrow{F_m} = e * (\vec{v} \wedge \vec{B})$.

Norm :

$$f_m = |qvB \sin \alpha|$$

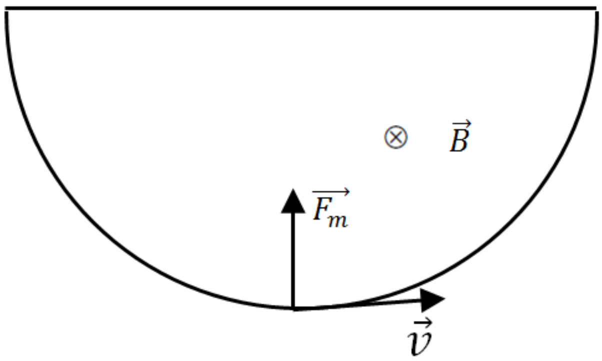

Figure II.5 : Electron trajectory in a frame of reference under a magnetic field

$F_m = q * v * B$ (car sin 90 = 1)

$\sum F = m * \vec{a}$ => $m * a = e * v * B$

In a circular trajectory $a = \frac{v^2}{r} \Longrightarrow \frac{e}{m} = \frac{v}{B*r}$

r: trajectory radius (m)

B: value of magnetic field (Tesla)

If we combine the two fields (magnetic and electric) so that they are equal and opposite, i.e. their forces are equal. At this moment, the beam is straight.

$\overrightarrow{F_e}=\overrightarrow{F_m}$ then $e * v * B = e * E \Longrightarrow v = \frac{E}{B}$

replace v with its value in y

The e/m ratio will be equal to: $\frac{e}{m} = \frac{2*y*E}{B^2x^2}$

Example:

Calculate the e/m ratio for the hydrogen atom (H)

Solution

$1.6x10^{-19}/1.6x10^{-27}= 1 \text{ x } 10^{08}$ C.kg

The e/m ratio in the case of an electron is a thousand times higher than that of an H+ ion, indicating that either these particles (é) were very low mass (which was the case), or that they were very highly charged.

II.3.1.3. Millikan experiment

In this experiment, the quantum nature of charge is experimentally determined. Robert Millikan was awarded the Nobel Prize in Physics in 1923 for this brilliant experiment. A simplistic illustration of his apparatus is shown below (Figure II.6).

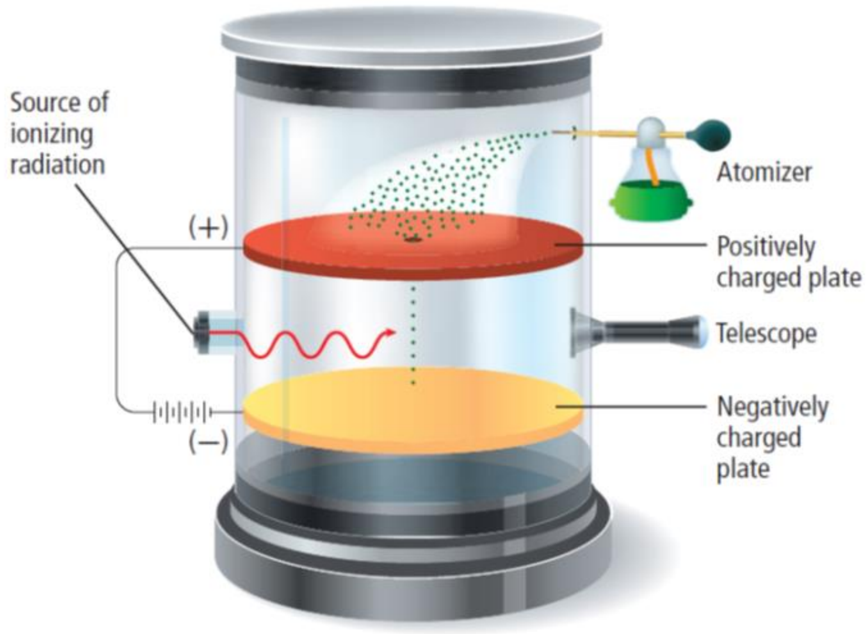

Figure II.6 : Millikan oil drop experiment

A spherical oil droplet, falling through a viscous medium like air, will quickly reach a constant speed. When it reaches this state of equilibrium, the viscous force is balanced by other forces acting on the droplet during its fall, such as gravity, the buoyant force of the air, electric forces, etc. In this experiment, an electric force is introduced through an ionization source to alter the motion of the droplet. By measuring the speed of the oil droplet under different conditions, the amount of charge can be determined. If the charge of the droplet is an integer multiple of the fundamental unit (charge of the electron), it will be possible to confirm the quantity of the charge.

a) In the absence of (Rx),

A droplet is subjected to two main forces: gravity (p) and the Stokes force (f) during its movement,.

$p = mg = 4/3\ \pi\ r^3 \rho\ g$ (ρ is the volumetric mass of the oil, m is the mass of the droplet) r is the radius of the droplet and g is the acceleration of gravity..

$f = 6\pi\ ŋ\ r\ v$ (ŋ is the viscosity of the air and v is the speed of fall (m/s))

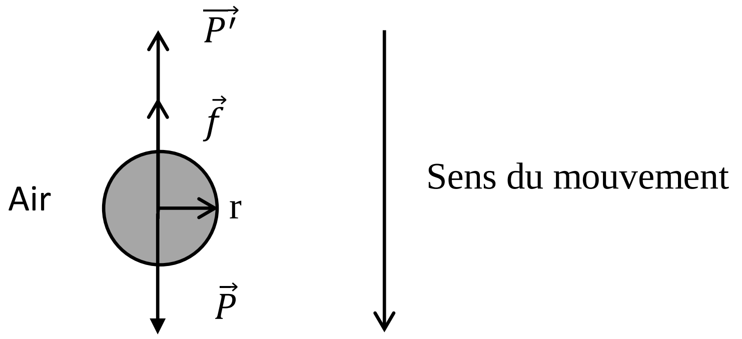

Figure II.7: Movement of the oil drop under the effect of gravity and the force of Stocks .

Let's consider the balance of forces, taking the maximum displacement rate (v).

$p + f = ma = 0$ (a : acceleration)

v=cst

a = dv/dt = 0

after projection

$p - f = 0.$

$p = f$

$4/3\ \pi\ r^3\ \rho\ g = 6\ \pi\ \eta\ r\ v$

$r^2 = 9\ \eta\ v\ /\ 2\ \rho\ g$

b) In the presence of Rx

By applying a vertical (uniform) electric field, the droplets will be directed towards the positive pole. By adjusting the field intensity, it is then possible to practically immobilize them. The forces acting on an oil droplet in equilibrium are as follows:

- Force due to gravity ($\vec{p}$)
- Force due to the electric field $\overrightarrow{f_e}$
- Stokes' frictional force (f) (when the droplet is immobilized, f=0)

$\vec{p} = mg = V*\rho*\vec{g} = 4/3\pi*r^3*\rho*\vec{g}$

$\overrightarrow{f_e} = q\vec{E}$

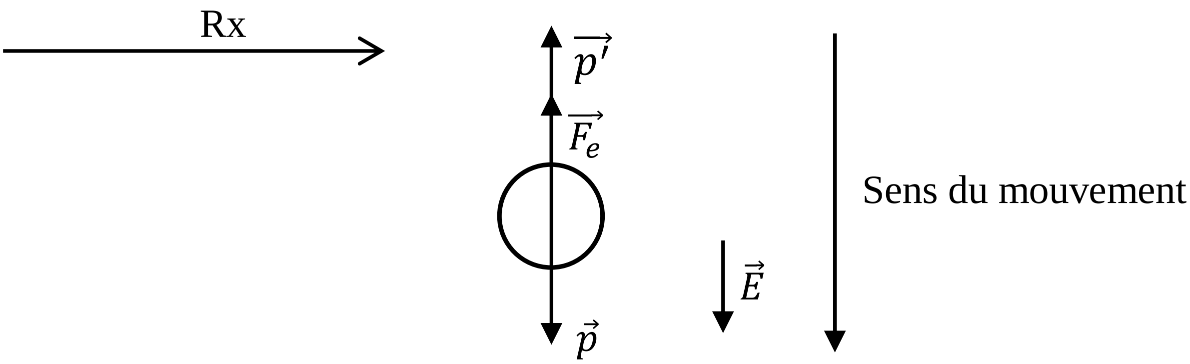

Figure 2.8 : Déplacement de la goutte d'huile en présence des RX

After projection, the force balance is written :

$p - F_e = 0 \Rightarrow p = F_e \Rightarrow$

$4/3\pi*r^3*\rho*g = -qE$ (q is negative)

$q = -\ 4/3\pi*r^3*g\ (\rho)\ /\ E$

The charge taken up by the particles q is found to be a multiple of 1.602×10^{-19} coulomb, considered to be the elementary charge. Depending on the volume of the drop, q can be equal to 2e, 3e, 4e.

Example:

Determine the radius r of the droplet, given that it moves a distance of 2.11 mm over a period of time Δt =10 s.

Data: Density of oil: $\rho = 890\ kg.m^{-3}$

Value of gravity field: $g = 9.8\ N.kg^{-1}$

Air viscosity: $\eta = 1.8.10^{-5}\ kg.m^{-1}.s^{-1}$

Solution:

$$v_1 = \frac{2}{9}.\frac{\rho.g.r^2}{\eta} = \frac{d}{\Delta t}$$

$$r^2 = \frac{d.\eta}{\rho.g.\Delta t}.\frac{9}{2}$$

$$r = \sqrt{\frac{d.\eta}{\rho.g.\Delta t}.\frac{9}{2}}$$

$$r = \sqrt{\frac{2,11\times 10^{-3}\times 1,8\times 10^{-5}}{890\times 9,8\times 10,0}\times\frac{9}{2}} = 1,4\times 10^{-6}\ m = \mathbf{1,4\ \mu m}$$

II.3.2. Discovering the nucleus and its constituents

The discovery of the electron, a negatively charged particle, led to two questions: where does the mass of the atom reside? What is the counterpart of the electrons' negative charge, since the atom is neutral?

II.3.2.1. Rutherford experiment (demonstration of the nucleus)

The existence of the atomic nucleus was discovered in 1911 by Ernest Rutherford. The experiment involved firing a beam of alpha particles (emitted by a radioactive source, such as partinium) onto a sheet of gold, and observing what happened to them (figure II.9).

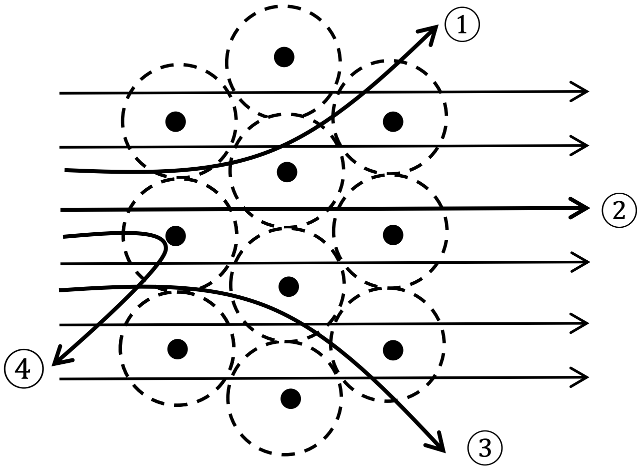

Figure II.9 : Rutherford experiment (1911)

He found that most of the particles passed through the sheet without encountering any matter: the matter was therefore essentially void. However, some of these particles are strongly deflected (Figure II.9).

Rutherford deduced that in matter (in this case, in the gold foil), mass is concentrated in particles that are very dense and very distant from one another in relation to their dimensions, and positively charged at the center of the atom: the atomic nuclei.

II.3.2.2. Eugène Goldstein's experiment (demonstration of the proton)

In 1886, Eugène Goldstein (1850-1930) was interested in electron-like radiation observed in a vacuum tube. Using equipment similar to that shown in the figure below, he studied the radiation passing through a cathode pierced with holes (Figure II.10). He noticed that rays were passing through the holes in the opposite direction to the cathode rays. He called them channel rays, because they pass through the holes as if through channels.

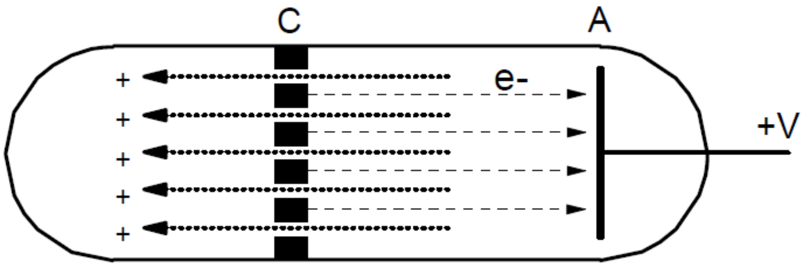

Figure II.10: Schematic diagram of a channel-beam tube, showing the rays emerging from the perforated cathode on the left.

In 1895, Jean Perrin suggested that they were made up of positively-charged corpuscles. This suggestion was later confirmed, as these rays can be deflected by a magnetic field.

In 1914, Rutherford established that the hydrogen ion is the hydrogen atom deprived of its electron and concluded that the hydrogen nucleus is a fundamental particle of any atomic nucleus. Rutherford would later call it the proton.

In 1919, Rutherford achieved the first nuclear reaction by bombarding nitrogen with particules□. He noticed the emission of a positively charged particle, the proton.

$$^{14}_{7}N + \propto \rightarrow \ ^{1}_{1}H + \ ^{17}_{8}O$$

This reaction shows that the proton is a constituent of the nitrogen atom. Characterization studies show that the proton is a particle with elementary charge +e and mass mp.

$+e = +1,602.10^{-19}$ coulomb

$m_p = 1,67265 \times 10^{-27}$ kg.

$= 1,0073$ u.m.a

II.3.2.3. Chadwick 1932 experiment (neutron detection)

Rutherford's discovery led to research into other types of transmutation. Research turned to light nuclei, since these were less likely to repel particles α. W. Bothe and H. Becker (1930) discovered extremely penetrating radiation from beryllium ${}_{4}^{9}Be$.

In 1932, Chadwick showed that this radiation must be composed of neutral particles with a mass similar to that of the proton. The action of the α particle on beryllium leads to the formation of the carbon-12 nucleus and emits ultra-penetrating rays (the neutron).

$${}_{4}^{9}Be + \propto \rightarrow {}_{6}^{12}C + {}_{0}^{1}n$$

He even declared that these particles had the same mass as a proton, but that their charge was zero. (m_n = 1,67495 $\times 10^{-27}$ kg = 1,0087 uma)

II.4. Rutherford's Planetary Model

Ancient Greeks were curious about the nature of matter. Empedocles of Agrigentum (around the 5th century BCE) proposed that matter was composed of four elements: water, air, earth, and fire. Democritus (460-370 BCE) suggested that matter was made up of tiny, indivisible particles which he called "atomos" (meaning indivisible in ancient Greek). In contrast, Aristotle (384-322 BCE) argued that matter was infinitely divisible. For philosophical reasons, Aristotle's theory dominated until the 19th century.

Analyses of air led Dalton (1808) to develop an atomic model:

• Each element is composed of indivisible particles: atoms.

• Atoms of an element have the same mass, while atoms of different elements differ in mass.

• Atoms cannot be created or destroyed in chemical reactions.

• During chemical reactions, atoms of different elements combine in fixed ratios.

Thomson (1897) envisioned the atom as a sphere filled with positively charged substance and studded with negatively charged electrons, resembling grapes in a cake.

Rutherford's model (1911) was later refined by Chadwick after the discovery of the neutron (1932). It is stated as follows:

1. **Electron Orbits:**
   - Atoms have electrons orbiting the nucleus in circular paths (orbits).
   - Electrons are negatively charged (-1).
2. **Nucleus Composition:**
   - Nucleus consists of protons (+1) and neutrons (no charge).
   - Protons and neutrons together are called nucleons.
3. **Mass and Mass Number:**
   - Protons and neutrons are much heavier than electrons.
   - Atom's mass is concentrated in the nucleus.
   - Mass number (A) is the sum of protons and neutrons.

4. **Empty Space:**

- Atoms are mostly empty space.

5. **Electric Neutrality:**

- Atoms are electrically neutral.

6. **Atomic Characteristics:**

- Atomic number defines the number of protons.
- Example: Helium (Z=2, A=4) has two protons, two neutrons, and electrons.

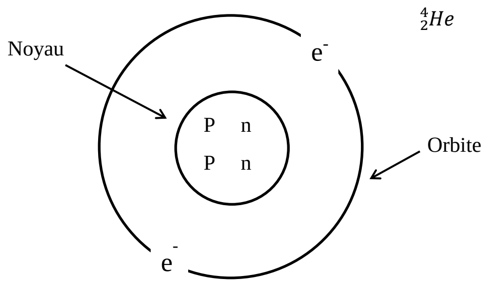

Figure II.11: Representation of the helium atom according to Rutherford's model. p: proton, n: neutron and e: electron.

The helium atom is symbolized by ^4_2He. This symbol is constructed as follows:

- He is the chemical symbol for helium
- The number 4 indicates the atomic mass of helium.
- Number 2 indicates the atomic number of helium

II.6. Isotope separation (Bainbridge Spectrometer 1933)

The Bainbridge spectrometer, also known as the Bainbridge mass spectrometer, is a type of mass spectrometer developed by Francis W. Aston and A. O. C. Nier in the 1920s. This instrument is designed for measuring the masses of isotopes with high precision.

Here are some key features and aspects of the Bainbridge spectrometer:

1. **Purpose:** The primary purpose of the Bainbridge spectrometer is to determine the mass-to-charge ratio (m/z) of ions. This is particularly useful in identifying isotopes of an element based on their different mass-to-charge ratios.

2. **Operation:** The spectrometer operates on the principles of magnetic and electric fields. Ions produced from a sample are accelerated through an electric field and then enter a magnetic field. The magnetic field causes the ions to move in circular or helical paths. The radius of the path is proportional to the mass-to-charge ratio of the ions.

3. **Mass Resolution:** One of the strengths of the Bainbridge spectrometer is its high mass resolution. This means it can distinguish between ions with very similar mass-to-charge ratios, allowing for precise measurement of isotopic masses.

4. **Isotope Analysis:** By measuring the radius of the ion paths, the instrument can determine the masses of isotopes present in a sample. This is particularly important in fields such as nuclear physics and chemistry (Figure II.12).

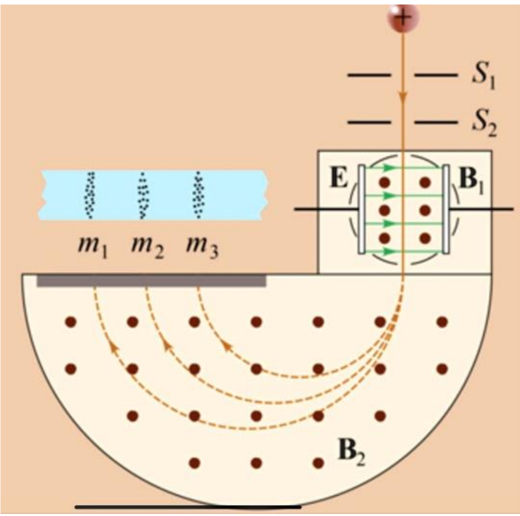

Figure II.12: Illustrative drawing of a mass spectrometer

In the magnetic field, the ions follow a circular path of radius r_i such that :

$r_i = \frac{m_i v}{q_B}$ et $d = 2(r_2 - r_1)$ d:impact distance

$d = 2\left[\frac{m_2 v}{qB} - \frac{m_1 v}{qB}\right] = \frac{v}{NA.q.B}(M_2 - M_1)$ (q=2e) $\Longrightarrow v = \frac{d.NA..B}{M_2 - M_1}$

Example

1)- Natural chlorine (Cl) is a mixture of two isotopes, ${}^{35}_{17}Cl$ ${}^{37}_{17}Cl$. The atomic molar mass of natural chlorine is 35.453 g/mol, and the molar masses of the isotopes are 34.9688 g/mol for ${}^{35}_{17}Cl$ et 36,9659 g/mol pour ${}^{37}_{17}Cl$. Provide the proportions of these isotopes in natural chlorine.

2)- To separate these isotopes, a Bainbridge-type mass spectrometer is used. In the ionization chamber, Cl^{2+} ions are formed.

2.a)- What should be the velocity of the ions at the exit of the velocity filter if we want to achieve a separation of their impact point by 1 cm after passing through a magnetic field with an intensity of 0.15 Tesla.

2.b)- What is the intensity of the electric field in the velocity filter if the magnetic field in the velocity selector has an intensity of 0.2 Tesla.

1)- The proportions of natural chlorine isotopes can be calculated using the formula for the average atomic molar mass:

M_{avg}= $\sum M_i x_i$ with $\sum x_i = 1$

where M_{avg} is the average molar mass of natural chlorine, Mi is the molar mass of isotope i, and xixi is the relative isotopic abundance of isotope ii in the natural mixture.

To obtain the proportions of isotopes

$$\left.\begin{array}{l} x_1 M_1 + x_2 M_2 = \bar{M} \\ x_1 + x_2 = 1 \end{array}\right\} \Rightarrow \quad x_2 = \frac{\bar{M} - M_1}{M_2 - M_1} \quad \text{soit} \quad x_2 = \frac{35{,}453 - 34{,}9688}{36{,}9659 - 34{,}9688} = 0.2425$$

$x_2 = 0{,}2425$ (24,25 %) $\quad x_1 = 0{,}7575(75{,}25)$

2a. In the magnetic field, the ions follow a circular path of radius r_i such that :

$r_i = \frac{m_i v}{qB}$ et $d = 2(r_2 - r_1)$ d:impact distance

$$d = 2\left[\frac{m_2 v}{qB} - \frac{m_1 v}{qB}\right] = \frac{v}{NA.q.B}(M_2 - M_1) \text{ (q=2e)} \Longrightarrow v = \frac{d.NA..B}{M_2 - M_1}$$

$$v = \frac{1.10^{-2}.6{,}02.10^{23}.1{,}6.10^{-19}.0.15}{(36{,}9659 - 34{,}9688).10^{-3}} = 7{,}24.10^4 \text{ m.s}^{-1}.$$

2.b)- In the speed filter, we have $v = \frac{E}{B} \Longrightarrow E = v.B$

$E = 7{,}24.10^4.0{,}2 \Longrightarrow E = 1{,}448.10^4$ V/m

II.7. Nuclear Energy

II.7.1. Mass and Energy: Einstein's Relation

During a nuclear transformation (whether natural or induced), the mass of the resulting products is always slightly less than the mass of the reactants. The loss of mass is denoted as Δm. Associated with this mass loss is a release of energy, and the value of ΔE is given by Einstein's relation.

$$\Delta \mathrm{E} = (\Delta \mathrm{m}) c_0^2$$

where c is the speed of light

II.7.2. Cohesion energy of a nucleus

The binding energy of a nucleus is the energy required to dissociate it into its individual nucleons. The greater the amount ΔE, the more stable the nucleus. This is why ΔE is called the cohesion energy (or binding energy) of the nucleus.

Precise measurements have shown that the mass of a particular atom is always slightly less than the sum of the individual masses of its components (neutrons, protons and electrons), this difference called the mass defect (Δm). The mass defect can be calculated using the following equation:

$$\Delta m = \left[Z * \left(m_p + m_e\right) + (A - Z) * m_n\right] - m_{\left({}_Z^A X\right)}$$

Δm: mass default

Z: atomic number (number of proton)

A: mass number (number of nucleons)

mp: proton mass

me: electron mass

mn: neutron mass

$m_{\left({}_Z^A X\right)}$: atomic mass

Exercise II.3

Calculate the mass default of lithium-7 ((_3^7)Li), its atomic mass being 7.016003 amu.

Proton mass = 1.00727 amu

Neutron mass = 1.00867 amu

Electron mass = 0.00054 uma

Solution**:**

$\Delta m = \left[Z * \left(m_p + m_e\right) + (A - Z) * m_n\right] - m_{\left({}^{A}_{Z}X\right)}$

$\Delta m = [3 * (1{,}007826) + (7 - 3) * 1{,}00867] - 7{,}016003$

$\Delta m = 0{,}0421335\ uma$

Exercise II.4

Calculate the mass default and binding energy for uranium-235. An atom of uranium-235 has a mass of 235.043924 amu.

Solution:

Step 1: Applying the mass defect equation

we obtain Δm=1.91517 amu

Step 2: Using the mass default and Einstein's equation, we can calculate the binding energy.

$\Delta \mathrm{E} = (\Delta \mathrm{m}) c_0^2 = 1{,}91517 \times 1.66054 \times 10^{-27} \times (2{,}9979 \times 10^8)^2$

This is constant

$1{,}4923 \times 10^{-10}$ J = 931254168 eV=931,2 MeV

$\Delta \mathrm{E} = \Delta \mathrm{m}(\mathrm{uma}) \times 931{,}2$

$\Delta \mathrm{E} = 1{,}91517 \times 931{,}2 = 1784$ MeV

II.7.3. Binding energy per nucleon

This is equal to the binding energy of the nucleus divided by the number of nucleons (A) present in the nucleus: $\frac{E_L}{A}$

Example :

The binding energy per nucleon of a uranium-235 nucleus is :

$$\frac{E_L}{A} = \frac{1784}{235} = 7{,}59 \text{ MeV/nucléon}$$

II.7.4. Core stability

II.7.4.1. Aston curve

The Aston curve represents the graph associated with -EL/A = f(A). It can be used to compare the stability of different atomic nuclei. The higher the average energy per nucleon, the more stable the nucleus, with the more stable nuclei at the bottom of the graph. Light nuclei will evolve by fusion, while heavy nuclei will evolve by fission.

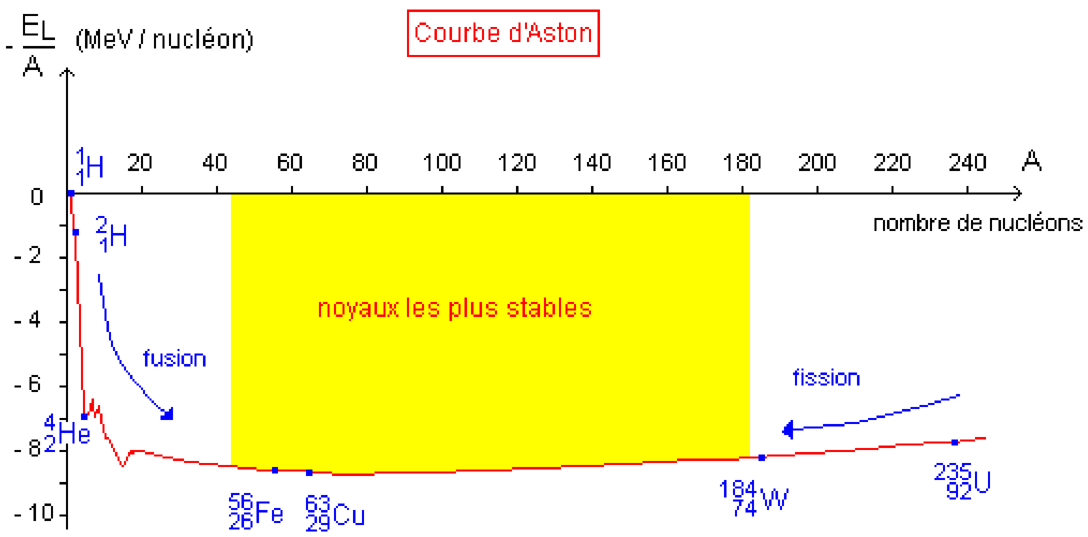

Figure II.16 : Aston curve

Example:

The binding energy of an oxygen-16 nucleus is 126 MeV, that of a uranium-238 nucleus is 1802 MeV.

To compare their stability, we need to calculate the binding energy per nucleon.

We find :

($^{16}_{8}O$)E_L/A = 126 /16 = 7,88 MeV/ nucleon

($^{238}_{92}U$) E_L/ A = 1802 / 238 = 7,57 MeV/ nucleon

The oxygen 16 nucleus is therefore more stable than the uranium 238 nucleus.

II.7.4.2. Valley of stability

The valley of stability designates the location of stable isotopes, when the atomic number is plotted on the abscissa and the number of neutrons on the ordinate of each isotope (nuclide map); the two axes are sometimes inverted on certain representations.

If we draw a diagram with the number of neutrons = f (Z: number of protons) (Figure II.16), we can see that light elements are stable when the number of neutrons and the number of protons are approximately equal (N = Z).

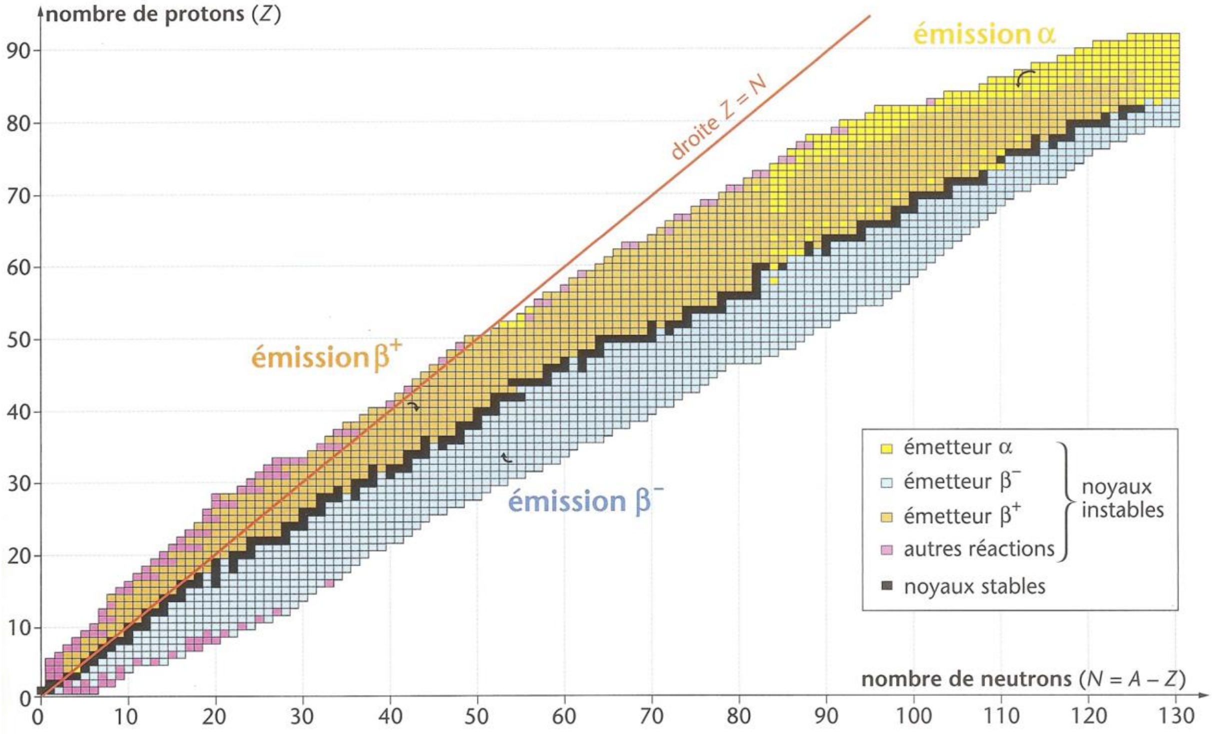

Figure II.17 : Diagramme des nucléides stables en fonction de leurs nombres de protons (Z) et de neutrons (N)

There are 4 different domains:

- The black area represents stable chemical elements (valley of stability). We can see that for light nuclei (A < 20), stable nuclei are on the bisector.

- Above that (A > 20), stable nuclei deviate from the bisector. They need more neutrons than protons to remain stable.
- The blue area represents unstable nuclei with an excess of neutrons. These nuclei return to the stability line through β^- decay.
- The orange area represents unstable nuclei with an excess of protons. These nuclei return to the stability line by β^+ decay or by electron capture, which transforms a proton into a neutron within the nucleus.
- proton-rich heavy nuclei return to the stability line by alpha decay.
- The yellow area represents unstable nuclei with excess mass, which tend to undergo fission reactions.