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SCIENCES AND SCIENCES OF NATURE
AND LIFE
MATTER SCIENCES DEPARTMENT

Physics 2 Handout

Tutorials

1st year Earth and Cosmological Sciences, Geography and Regional Planning Specialization

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This handout of lessons in Physics 2 is aimed at first-year students of combined Earth and Cosmological Sciences specializing in Geography and Regional Development. Its goal is to acquire basic notions of Electricity and Magnetism, including Electrostatics, Electrokinetics, Electromagnetism, and relationships between radiation and magnetism (Photoelectric Effect, Compton Effect, and Materialization Effect).

This handout on Physics 2 consists of two chapters. Distributed each chapter as follows:

Chapter I: Electricity and magnetism:

1°- Electrostatics

- Electric field and potential

- Conductor balance

- Capacitors

2°- Electrokinetics

- Electrical conduction

- Ohm's law, Joule's law

- Electrical circuits

- Theorems of Thévenin and Norton

3°- Electromagnetism

- Definition of the magnetic field

- Current-field interaction (Laplace's law)

- Ampere formula

Chapter II: Radiation:

1°- Generality

- Electromagnetic radiation,

- Particle radiation

- Detection of radiation

- Energy spectrum of radiation

- Photoemissive Cell

2°- Production of X-rays

3°- Radiation – matter interactions

- Photoelectric effect

- Compton Effect

- *Materialization effect*
- *Attenuation – Protective screen.*

Lessons in Physics 2 will allow students to consolidate their abilities and practice applying the rules provided in the course reminders distributed. I hope this handout will be of valuable assistance to Earth and Cosmological Sciences students in understanding and mastering the Physics 2 unit and thus completing the first year of Geography and Regional Development.

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CHAPTER TWO : **Radiation**

Chapter I:

Electricity and magnetism

Introduction

Electricity and magnetism represent two of Western civilization's most profound areas of study. While early in human history, these subjects were thought to be independent of each other, it is clear now that they are intimately related. This subject encompasses an enormous number of experimental observations and theoretical developments, to the point that modern applications of electricity and magnetism cannot be imagined without them. Electric and magnetic fields, which in nature are simultaneously pervasive and subtle, permeate our everyday lives. However, physical phenomena as diverse as plasma displays, accelerators, fluorescent lights, absorption and emission spectra, and Hall voltage are no exception. Here, we begin our study of electricity and magnetism, focusing on the experimental facts and our basic search for mechanisms. We begin by exploring electric charge and force, symmetries in the law of electrostatics, and electric potential, among other topics. These basic principles will carry us through our detailed explorations. This subject is one of the most integrated with other fields in physics.

I.1°- Electrostatics

Electricity and magnetism represent two of Western civilization's most profound areas of study. While early in human history, these subjects were thought to be independent of each other, it is clear now that they are intimately related. This subject encompasses many experimental observations and theoretical developments. Electrostatic is a compound word called **electric**, meaning something to do with an electric charge and **static**, meaning stationary. Electrostatics is the study of the behavior of electric charges at rest. Unlike charges, when electric currents flow, they can cause a variety of exciting electrical and magnetic phenomena. Electrostatics is essential because many practical and vital devices and physical systems contain stationary electric charges that do not move.

The electric force analysis demonstrates that forces are vital for describing and analyzing electromagnetic systems. It is much more efficient to use a scalar field called the electric potential in place of electric force to analyze the performance of electrostatic systems. Therefore, the section on fundamental concepts of electricity and magnetism begins with electrostatics, dealing with how charges exert force on other charges via an electric field. The following chapter provides an overview of the material.

I.1.1°- Electric field and potential

I.1.1.a°- Coulomb's law

Consider two point charges q_1 and q_2 placed in a vacuum. The first exerts a force proportional to its charge q1 on the second. Conversely, the second exerts a force proportional to its charge q2 on the first. We deduce that the force between two-point charges called electrostatic force is proportional to the product of their charges q_1 q_2. which is expressed by:

$$\overrightarrow{F_e} = K.\frac{q_1.q_2}{r^2}.\vec{U} \dots\dots\dots\dots\dots\dots\dots..(I.1)$$

This expression is Coulomb's law.

With r: the distance separating the two charges.

The relation defines K in the international system:

$K = \frac{1}{4\pi\varepsilon_0}$ where ε_0 represents the permittivity of vacuum, including its experimental value:

K= 8.9875 109 Nm ^{2} C $^{-2}$

We will often use the approximate value: 9.10^9

$\vec{U}$: unit vector of direction joining the charge q_1 to the charge q_2 , directed from q1 to q2 such that:

$$\vec{U} = \frac{\vec{r}}{r}$$

Application: Calculate the force exerted by the charge $q_1 = 3.10^{-3}$ C on a charge $q_2 = - 5.10^{-4}$ C separated by a distance of 20 mm.

Solution:

$$\overrightarrow{F_e} = K.\frac{q_1.q_2}{r^2} = 9.10^9\frac{3.5.10^{-7}}{4.10^{-4}} = 33{,}75.10^6 N$$

I.1.1.b°- Electric field

By definition, we say that there is an electric field ($\vec{E}$) at a given point in space if there is a charge Q_0 and if this charge is subjected to a force $\overrightarrow{F_e}$ such that:

$$\vec{E} = \frac{\overrightarrow{F_e}}{Q_0} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (I.2)$$

In the international system unit of [E], it is N.C^{-1}.

$\vec{E}$ is parallel to $\overrightarrow{F_e}$.

The meaning of $\vec{E}$ depends on the sign of Q_0:

If $Q_0 > 0 \Longrightarrow \vec{E}$ and $\vec{F_e}$ same direction.

If $Q_0 < 0 \Longrightarrow \vec{E}$ and $\vec{F_e}$ are opposite in direction.

- **The field created by a point charge:**

When a charge Q is at point O, it then creates, at any point M in the space surrounding it, a vector field, called an electrostatic field, expressed by the relation:

$$\overrightarrow{E_M} = \frac{\overrightarrow{F_e}}{q_0} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Q}{r^2} \vec{U} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (I.3)$$

- Q: the charge present at point O.
- q_0: a test charge placed at point M, it undergoes the action of force $\overrightarrow{F_e}$.

- **The electric field is created by a set of point charges:**

Now, let us consider n charges qi located at points P i. What would then be the electric field produced by this set of charges at point M?

As with forces, the superposition principle is also valid for electric fields. The total field $\overrightarrow{E_{MT}}$ is the vector sum of all contributions due to each of the charges (Figure I.1). We therefore have:

$$\overrightarrow{E_{MT}} = \sum_{i=0}^{n} \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_i}{r_i^2} \overrightarrow{U_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (I.3)$$

Figure I.1: Composition of fields at a point (M).

- **A continuous distribution of charges creates the electric field:**

Consider a continuous distribution of charges within a certain volume, on a surface, or along a straight line.

- **Volume case:**

The distribution is characterized at each point P of volume by the data of the volume charge density $\rho(P) = \frac{dq}{dV}$, where dq denotes the electric charge contained in the volume element dV surrounding point P. In the case where the charge distribution is uniform,

dq is sufficiently small to be considered as punctate; therefore, the field $\overrightarrow{dE}$ created at a point M by the charge dq has the expression:

$$\overrightarrow{dE} = \frac{1}{4\pi\varepsilon_0}.\frac{dq}{r^2}\vec{U} \ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(I.4)$$

$$\overrightarrow{dE} = \frac{1}{4\pi\varepsilon_0}.\frac{\rho dV}{r^2}\vec{U} \ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(I.5)$$

With $r = \overline{PM}$ and $\vec{U} = \overrightarrow{PM}/r$. We therefore write for the entire distribution:

$$\Rightarrow \vec{E} = \frac{1}{4\pi\varepsilon_0}.\oiiint \rho\frac{dV}{r^2}\vec{U} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(I.6)$$

- **Surface case:**
  For a surface distribution of charges characterized by the data of the surface density $\sigma = dq/dS$ at each point of a surface S, we will write similarly:

$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\oiint \sigma\frac{dS}{r^2}\vec{U} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(I.7)$$

- **Case of a straight line:**
  For a linear load distribution characterized at each point of a curve by the linear density $\lambda = dq/dl$:

$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\oint \lambda\frac{dq}{dl}\vec{U} \ldots\ldots\ldots\ldots\ldots\ldots..(I.8)$$

➢ **Field lines:**

An electrostatic field line is a curve tangent at each point to the electrostatic field vector defined at that point.

The set of field lines defines a mapping of the field.

Properties:

1. Two field lines never intersect at a point M unless the field E is zero at M.
2. An electrostatic field line is not closed. It starts from a charge q and ends on a charge of opposite sign.
3. To know the direction of the field at point M of a field line, you have to place a positive charge there and look at the direction and sense of the electrostatic force it undergoes. These directions and senses are the same as those of the field.

In the case of a point charge, the field lines are half-lines that intersect at the point where the charge is located. If the charge is positive, the field is directed outwards; it is said to be outgoing. The same goes for the field lines. The opposite is true for the negative charge; the field lines converge towards the charge, and the field, in this case, is directed towards the charge (Figure I.2).

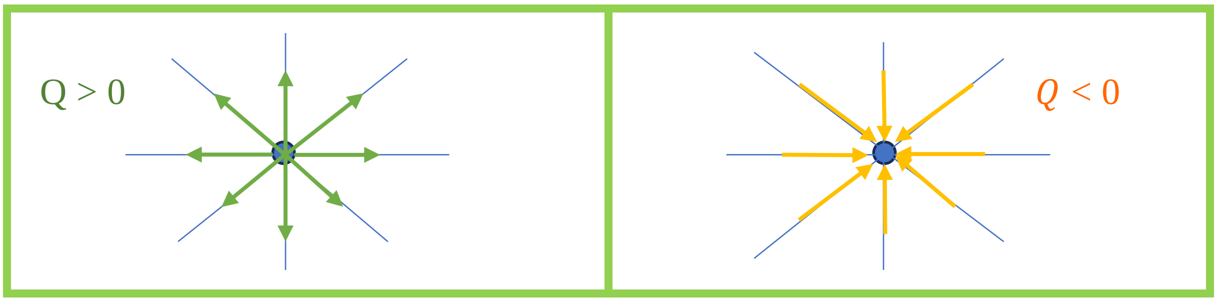


Figure I.2 Field lines for the two types of separated charges.

I.1.1.b°- Electrostatic potential:

- **Circulation of the electric field of a point charge:**

  Consider a region of space where an electric field prevails. Any charged particle q_0 in this field is subject to an electric force. $\vec{F} = q_0\vec{E}$

  The elementary work dW to move the charge q_0 an elementary displacement dl is:

$$dW = \vec{F}.\overrightarrow{dl} \Rightarrow dW = q_0.\vec{E}.\overrightarrow{dl}$$

  If we want to move the charge q_0 along any path ab, we must provide work W_{ab}:

$$W_{ab} = \int_a^b \vec{F}.\overrightarrow{dl} \Rightarrow W_{ab} = q_0 \int_a^b \vec{E}.\overrightarrow{dl} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(I.9)$$

The integral $\int_a^b \vec{E}.\overrightarrow{dl}$ is called the circulation of the electric field along the entire curve from a to b.

- **Electrical potential:**

  In the example shown in Figure I.3, we have

$$\underset{C_1}{\int_a^b \vec{E}.\overrightarrow{dl}} = \underset{C_2}{\int_a^b \vec{E}.\overrightarrow{dl}} = \underset{C_3}{\int_a^b \vec{E}.\overrightarrow{dl}}$$

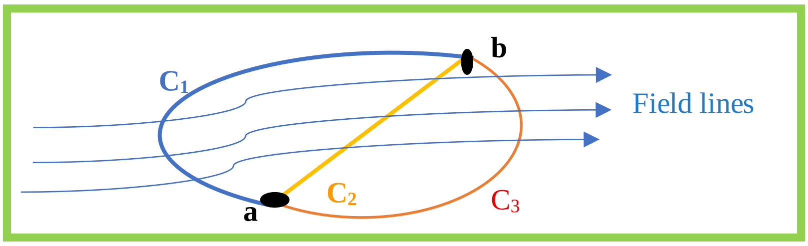


Figure I.3: Work independent of the path followed by the load

This means that the work required to move the charge from point a to point b is independent of the path followed. When the flow of the field along the curve does not depend on the path followed but depends only on the starting point and the arrival point, we say that this field is conservative in this case. We set $dV = -\vec{E}.\overrightarrow{dl}$ More generally, in Cartesian coordinates,

$$\vec{E}\left(-\frac{\partial V}{\partial x}, -\frac{\partial V}{\partial y}, -\frac{\partial V}{\partial z}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (I.10)$$

More concisely,

$$\vec{E} = -\overrightarrow{grad}V \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (I.11)$$

V is a scalar quantity called electric potential; in this case, we say that the electric field derives from the potential V. The energy required to move q_0 between **a** and **b** is therefore:

$$W_{ab} = -\int_a^b q_0\, dV = -q_0 V = -(V_b - V_a)q_0 \dots\dots\dots\dots\dots\dots\dots (I.12)$$

The quantity $V_b - V_a$ is called voltage or potential difference between points b and a, U_{ab} notes it, such that:

$$U_{ab} = V_b - V_a = \frac{W_{ab}}{q_0} \dots\dots\dots\dots\dots\dots\dots\dots\dots (I.13)$$

This brings us to the definition of potential difference.

Definition: The potential difference $(U_{ab} = V_b - V_a)$ equals the work provided to the unit charge transporting it from point a to point b.

- **The electric potential produced by a point charge:**

  We have seen that the field E produced by a charge q is radial:

$$E(r) = \frac{1}{4\pi\varepsilon_0}.\frac{q}{r^2}$$

To obtain the potential V, we first calculate the circulation of the field along any ray.

We have $dV = \vec{E}.\overrightarrow{dr}$

$$dV = -\frac{q}{4\pi\varepsilon_0}.\frac{dr}{r^2} \Rightarrow V = -\frac{q}{4\pi\varepsilon_0}\int\frac{dr}{r^2} = \frac{q}{4\pi\varepsilon_0 r} + C_{st} \dots\dots (I.14)$$

Assuming V = 0 when r tends towards infinity we will have C_{st} = 0 volts.

We obtain:

$$V = -\frac{q}{4\pi\varepsilon_0}.\frac{1}{r}\dots\dots\dots\dots\dots\dots\dots\dots(I.15)$$

The potential is constant on spheres of radius r whose center is the charge q. We say that these spheres constitute equipotential surfaces.

- **The potential created by several distinct point charges:**

We start from the link between E and the potential V, more precisely from the differential relation:

$$V(r) = \overrightarrow{E(M)}.\overrightarrow{dl}$$

For a set of charges q_i concentrated at bridge M and using the superposition theorem:

$$dV = -\overrightarrow{E(M)}.\overrightarrow{dl} = -\sum_{i=1}^{N}\left[\overrightarrow{E_\imath(M)}\right].\overrightarrow{dl} = \sum_{i=1}^{N}\left[-\overrightarrow{E_\imath(M)}\right].\overrightarrow{dl} = \sum_{i=1}^{N} dV_i$$

The sum of a set of differentials being the differential of the sum:

$$dV = \sum_{i=1}^{N} dV_i = d\left[\sum_{i=1}^{N} V_i\right]$$

$$V(M) = \sum_{i=1}^{N} V_i = \frac{1}{4\pi\varepsilon_0}.\sum_{i=1}^{N}\frac{q_i}{r_i}\dots\dots\dots\dots\dots(I.16)$$

Where r_i is the distance between qi and point M. The charge q_i can be positive or negative, which is why it must be taken with its sign.

- **The electric potential created by a continuous distribution of charge:**

In this case, we must carry out an integration after having chosen a corresponding elementary charge, with the same procedure as that of the electric field for a similar case.

$$dV = \frac{1}{4\pi\varepsilon_0} \cdot \frac{dq}{r}$$

$$V(M) = \frac{1}{4\pi\varepsilon_0}\int \frac{dq}{r} \dots\dots\dots\dots\dots\dots (I.17)$$

In general, it is preferable to calculate the potential first and then deduce the electric field by derivation. We assume that the charge distribution is uniform throughout our study.

a) If the distribution is volumetrically concentrated at point P:

$$V(M) = \iiint \frac{\rho dV}{4\pi\varepsilon_0 r} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (I.18)$$

ρ volume density

b) If the distribution is surface:

$$V(M) = \iint \frac{\sigma dS}{4\pi\varepsilon_0 r} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (I.19)$$

σ surface density.

c) If the distribution is linear:

$$V(M) = \int \frac{\lambda dl}{4\pi\varepsilon_0 r} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (I.20)$$

λ linear density.

I.1.1.d°- Applications:

- **Field and potential created by a ring:**

A ring with center O and radius R, carries a charge q distributed uniformly with a linear density $\lambda > 0$.

1. Calculate the potential created at point M on the (oy) axis and located at distance y from O.
2. Deduce the field vector at point M.

Solution:

The quantities r, y, and R are constant for the given point M. Starting from Figure I.4 and setting $K = \frac{1}{4\pi\varepsilon_0}$ we can write:

$$dV = K\frac{dq}{r} \rightarrow \int dV = \frac{K}{r}\int dq \rightarrow V = \frac{Kq}{r} + C_{st}$$

In the figure we can see that: $r = \sqrt{R^2 + y^2}$

After replacing K and q = λ. 2π R we arrive at the expression:

$$V = \frac{\lambda}{2\varepsilon_0} . \frac{R}{\sqrt{R^2 + y^2}} + C_{st}$$

It now remains to determine the module E. To do this, it is sufficient to derive the expression of V for y by exploiting the relation:

$$\vec{E} = \frac{dV}{dy} \rightarrow \vec{E} = \frac{\lambda R}{2\varepsilon_0} . \frac{y}{\sqrt[3]{R^2 + y^2}} \vec{U}$$

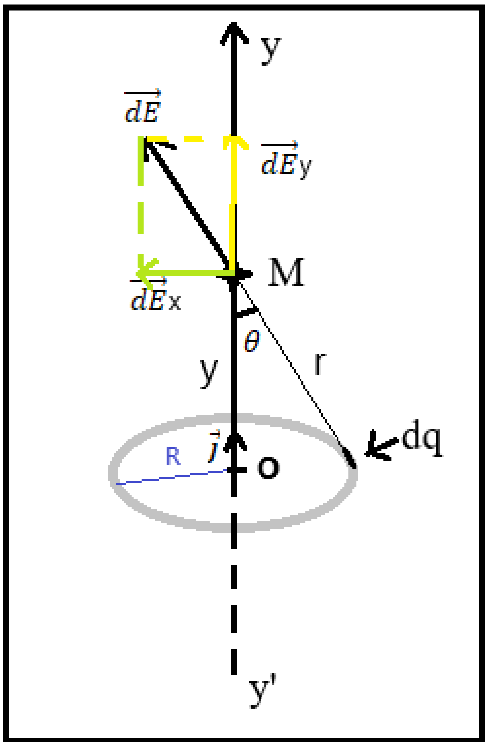


Figure I.4: Electrostatic field created by a charged ring at point M

- **Field and potential created by a disk:**

Let us consider a disk with center O, radius R, uniformly charged on the surface. The surface charge density is σ (σ>0) (figure I.5).

1. Calculate the electric field and the potential created by this distribution, at a point M on the axis (Oz).

Solution:

To do this, let us decompose the disk into radius ρ and width $d\rho$ rings. Let P be a point on the ring and P' the symmetric of P for O.

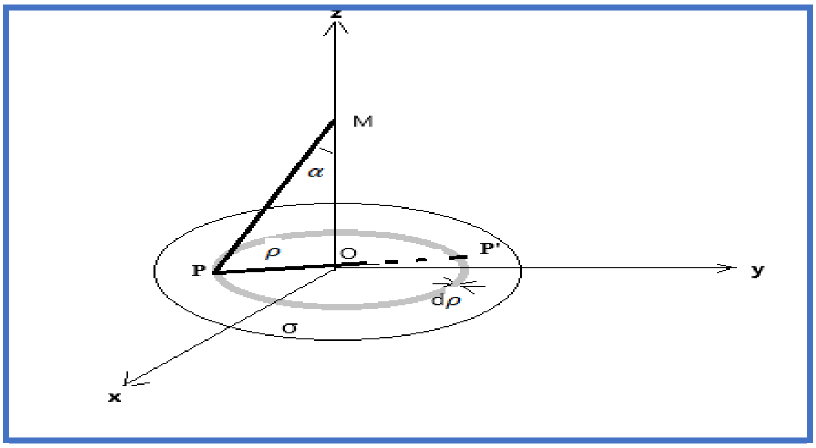


Figure I.5: Electrostatic field created by a charged disk at point

Let us first examine the symmetry of the problem: the distribution has a symmetry of revolution around OZ. Any plane containing the OZ axis is a plane with even distribution symmetry. Therefore the field E at point M on the OZ axis is carried by $\vec{k}$:

$\vec{E} = E(0,0,z) = E(Z).\vec{k}$

A charge element dq = σ dS, centred at P (figure I.5), creates at a point M on the axis of the disk an elementary field $\overrightarrow{dE}$ given by:

$$\overrightarrow{dE} = \frac{1}{4.\pi\varepsilon_0}.\frac{dq}{r^2}.\vec{U}$$

With, dS= $\rho d\rho d\theta \ and \ r = \sqrt{\rho^2 + Z^2}$

the charged disk has a symmetry of revolution around its axis, for example the Z'Z axis, the field is then carried by this axis. We have:

$$\overrightarrow{dE} = \frac{\sigma}{4.\pi\varepsilon_0}.\frac{\rho d\rho d\theta}{\rho^2 + Z^2}.\vec{U}$$

$$\overrightarrow{dE_z} = \overrightarrow{dE}.\cos\alpha = \frac{\sigma}{4.\pi\varepsilon_0}.\frac{\rho d\rho d\theta}{\rho^2 + Z^2}.\cos\alpha\,\vec{U}$$

$$\overrightarrow{E(M)} = \frac{\sigma}{4.\pi\varepsilon_0}\iint \frac{\rho d\rho d\theta}{\rho^2 + Z^2}.\cos\alpha\,\vec{k} \qquad with \qquad \cos\alpha = \frac{Z}{r}$$

$$\overrightarrow{E(M)} = \frac{\sigma}{4.\pi\varepsilon_0}\iint \frac{\rho d\rho d\theta}{\rho^2 + Z^2}.\frac{Z}{\sqrt{\rho^2 + Z^2}}\vec{k}$$

$$\overrightarrow{E(M)} = \frac{\sigma.Z}{4.\varepsilon_0}.\int_0^R \frac{\rho d\rho}{\sqrt[3]{\rho^2 + Z^2}}(\int_0^{2\pi} d\theta)\vec{k}$$

$$\overrightarrow{E(M)} = \frac{\sigma.}{2.\varepsilon_0}\left(\frac{Z}{|Z|} - \frac{Z}{\sqrt{R^2 + Z^2}}\right).\vec{k}$$

When Z is large the field weakens, on the other hand, when R >>Z, M very close to the disk the field becomes:

$$\overrightarrow{E(M)} = \pm\frac{\sigma.}{2.\varepsilon_0}.\vec{k}$$

The potential at a point M is deduced from the field by integration:

$$\overrightarrow{E(M)} = -\overrightarrow{grad\,V(M)} = -\frac{dV}{Z}.\vec{k}$$

So,

$$V = \frac{\sigma.}{2.\varepsilon_0}.\left(Z - \sqrt{R^2 + Z^2}\right)$$

I.1.2°- Driver conductor:

Let us first recall that a conductor is a body inside which charges can move under the action of an electric field, even a feeble one.

I.1.2.1-**Definition:**

A conductor is said to be in electrostatic equilibrium if its charges are in a state of rest.

I.1.2.2- Properties of a conductor in equilibrium:

1- Since the charges inside the conductor in equilibrium are at rest, the force exerted on the charges must be zero, which means that the electric field inside the conductor is also zero.

$$\vec{F} = q.\vec{E} = \vec{0} \Rightarrow \vec{E} = \vec{0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(I.21)$$

2- The general relation $\vec{E} = -\overrightarrow{grad}V$ shows that the potential is constant inside the conductor and by continuity, on its surface. In other words, a conductor in equilibrium is an equipotential surface:

Vi = C_{st} which proves that the field is perpendicular to the conductor's surface.

3- The charge in the conductor in equilibrium is zero, it is concentrated on the surface of the conductor. Indeed, since the number of protons equals the number of electrons, the total charge inside the conductor is zero.

I.1.2.3°- Electrostatic pressure:

Let us now calculate the forces to which the electric charges located on the surface of a conductor in equilibrium are subjected. Many experiments show these forces are typically directed to these conductors' surfaces.

The expression of the elementary force df is applied to the external elementary surface dS of a conductor, which carries an elementary charge d q égal à , sigma on its surface carries on its surface an elementary charge $dq = \sigma.dS$ is:

$$\overrightarrow{df} = dq.\vec{E} = \sigma.\overrightarrow{dS}.\frac{\sigma}{2\varepsilon_0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(I.22)$$

From where:

$$\overrightarrow{df} = \frac{\sigma^2}{2\varepsilon_0}.\overrightarrow{dS} \Rightarrow \frac{\overrightarrow{df}}{\overrightarrow{dS}} = \frac{\sigma^2}{2\varepsilon_0} = P_{elec} \ldots\ldots\ldots\ldots\ldots\ldots..(I.23)$$

P_{elec} is the electrostatic pressure, it is a scalar quantity, it is always positive.

This pressure can also be considered as the force capable of tearing the charges from the conductor.

I.1.2.4- Capacity of a conductor:

Consider an isolated conductor in electrostatic equilibrium, placed at a point O in space and carrying a charge Q, distributed on its external surface with a surface density σ such that:

$$Q = \iint \sigma.dS \dots\dots\dots\dots\dots\dots (I.24)$$

If the charge Q increases, the surface density σ increases proportionally:

This is due to the linearity of the equations governing the problem of conductor equilibrium.

The potential created by Q, at a point M in space such that $\overline{OM} = r$, is written

$$V = K.\iint \sigma\frac{dS}{r} \quad either \quad V = K.Q\iint \alpha\frac{dS}{r} \dots\dots\dots\dots\dots\dots\dots (I.25)$$

This result remains valid for any point on the surface of the conductor. The integral depends only on the geometry and dimensions of the conductor.

We deduce that the ratio between the charge and the potential to which the conductor is carried,

$$C = \frac{Q}{V} \dots\dots\dots\dots\dots\dots. (I.26)$$

depends only on the geometry of the conductor, it is called the conductor's capacitance. The expression gives this:

$$Q = C.V \dots\dots\dots\dots. (I.27)$$

The capacitance C is a positive quantity, with its unit called the Farad (F). The farad is defined as the capacitance of an isolated conductor with a potential of 1 volt when receiving a charge of 1 coulomb. The farad is a very large unit, so smaller subunits are typically used:

- Microfarad: 1 μF = 10^{-6} F
- Nanofarad: 1 nF = 10^{-9} F
- Picofarad: 1 pF = 10^{-12} F

Example :

The case of a spherical conductor, placed in a vacuum, of radius R, if it carries the charge Q, the potential inside the sphere is:

$$V = \frac{1}{4\pi\varepsilon_0}.\frac{Q}{R}$$

which identifies with the general relation Q = C V provides the expression of C:

$C = 4\pi\varepsilon_0 . R$

For the earth, considering that the radius is R = 6400 km, its capacity is C = 70 µF.

For a sphere of radius r = 10cm, the potential V = 1000V relative to the earth, and its capacity is C = 10 pF.

I.1.2.5- Phenomena of influence :

- **Partial influence :**

  Consider an electrically neutral conductor A (figure I.6). Let us approach the latter, a positively charged conductor B, as shown in the figure. Conductor B creates an electric field $\overrightarrow{E_B}$ in space, particularly in conductor A.

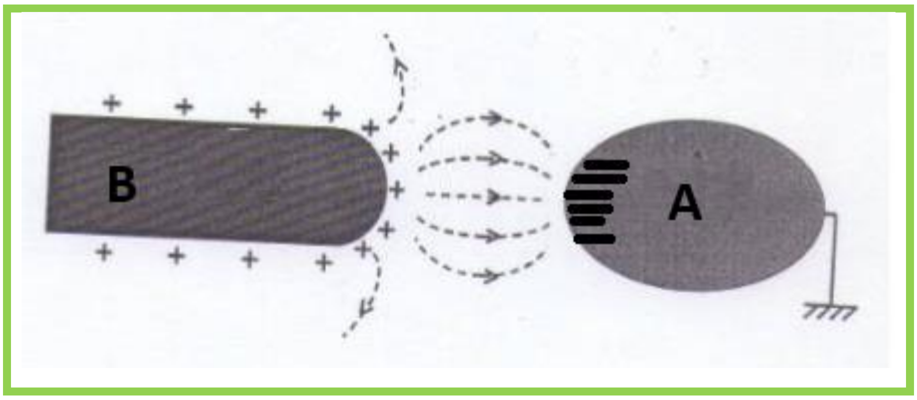


Figure I.6: Partial influence

The free electrons of conductor A will, under the action of this field, move in the opposite direction of $\overrightarrow{E_B}$. These electrons gradually accumulate on the face opposite B and form negative charges at equilibrium, resulting in –Q. Conversely, positive charges, the resultant of which is +Q, will appear on the other face due to a lack of electrons, as shown in the figure. These charges, which result from electrification by influence, contribute to the electric field inside and outside the conductor. They create an induced field $\overrightarrow{E_{in}}$, which opposes the inducing field $\overrightarrow{E_B}$ and thus reduces the total field. The free electrons stop their movement inside conductor A when the total electric field is zero. The system formed by the two conductors then reaches a state of equilibrium.

Field lines: The topography of the electric space, represented in the figure, shows that only certain field lines, which emanate from the inducing body B, end at the conductor A. By the theorem of corresponding elements, it follows that the charge Q created by influence is less than the inducing charge of the conductor B. This type of influence is said to be partial.

- **Total influence :**

  We speak of total influence when all the field lines start from B and end at A. This is obtained when A surrounds B (figure I.7).

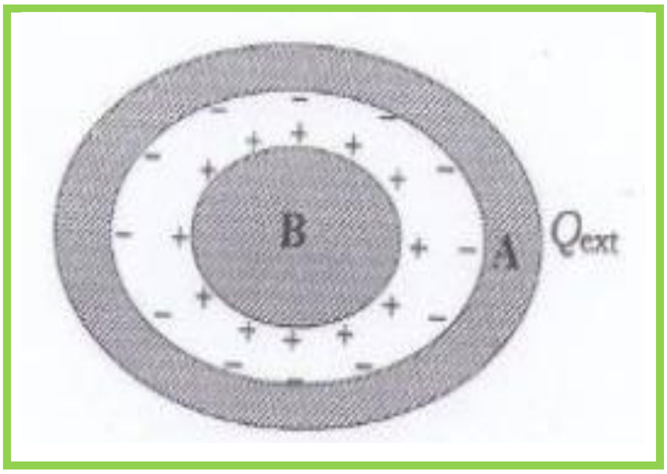


Figure I.7: Total influence.

Applying the corresponding element theorem shows that the charge appearing on the internal surface of A is equal and opposite to the charge on conductor B.

$$Q_B = Q_{int}$$

I.1.3°- Capacitors:

I.1.3.1°- Introduction:

A *capacitor* is a device comprising two conductive plates separated by an insulating material (called a dielectric). When a voltage is applied, the capacitor stores electric charge on its plates, creating an electric field between them. The electrical symbol represents it .

Capacitors of one sort or another are included in almost any electronic device. Physically, there is a wide variety of shapes, sizes, and construction, depending on their application.

In addition to their practical uses in electronic circuits, more importantly, they help students understand the concepts of and the relationships between electric fields E and F, potential difference, permittivity, energy, and so on.

➢ Capacitance (C)

If a potential difference is maintained across the two plates of a capacitor (for example, by connecting the plates across the poles of a battery), a charge +Q will be stored on one plate and −Q on the other. The ratio of the charge stored on the plates to the potential difference V across them is called the capacitance C of the capacitor.

- **Definition**: Capacitance is the ability of a capacitor to store charge per unit voltage applied across its plates. It's measured in **farads (F)**.
- **Formula**: $C = {}^{Q}/_{V}$, where:
  - C is the capacitance,
  - Q is the charge stored (in coulombs, C),
  - V is the voltage across the plates (in volts, V).

For example, a capacitor with 1 farad of capacitance stores 1 coulomb of charge when 1 volt is applied across it.

➢ How Does a Capacitor Work?

- **Charging:** When a voltage source (like a battery) is connected to a capacitor, electrons accumulate on one plate while the other loses electrons. This separation of charge creates an electric field.
- **Discharging:** When the capacitor is connected to a circuit without a voltage source, it releases the stored charge, providing current to the circuit.

➢ Series and Parallel Capacitors

- **Series:** The charge is the same on each, and the potential difference across the system is the sum of the potential differences across the individual capacitances. Hence :

$$\frac{1}{C_{Total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \dots\dots\dots\dots\dots\dots (I.28)$$

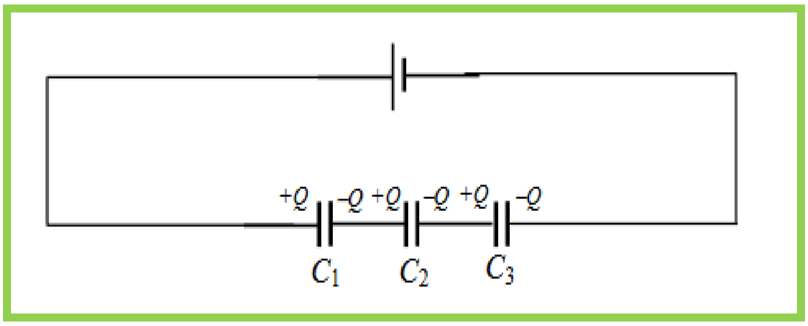


Figure I.8: Capacitors in Series.

- **Parallel**: The potential difference is the same across each, and the total charge is the sum of the charges on the individual capacitor. Therefore:

$$C_{Total} = C_1 + C_2 + C_3 \dots\dots\dots\dots\dots\dots\dots (I.29)$$

➢ Energy Stored in a Capacitor:

Let us imagine (figure I.7) that we have a capacitor of capacitance C, which sometimes has a charge of +q on one plate and a charge of −q on the other. The potential difference across the plates is then $\frac{q}{C}$. Let us now take a charge of +δq from the bottom plate (the negative one) and move it up to the top plate. We have to do work to do this, in the amount of $\frac{q}{C}.\delta q$. The total work required, then, starting with the plates completely uncharged until we have transferred a charge Q from one plate to the other is $\frac{1}{C}\int_0^Q qdq = \frac{Q^2}{2C}$ This is, then, the energy E_{energy} stored in the capacitor, and, by application of Q = CV it can also be written, $E_{energy} = \frac{1}{2}Q.V$ or, more usually.

$$E = \frac{1}{2}.CV^2 \dots\dots\dots\dots\dots\dots\dots (I.30)$$

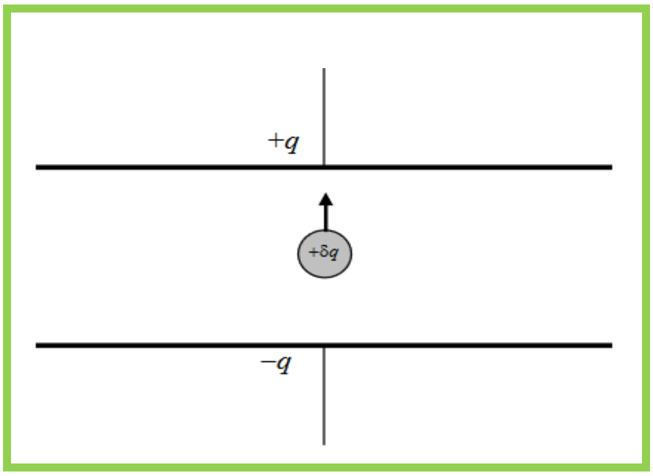


Figure I.9: the energy E_{energy} stored in the capacitor

I.2°- Electrokinetics:

Electrokinetics is the study of electric currents, electric charges moving in material media called conductors, and electrical circuits and networks.

Example :

You are given three capacitors of values 1, 3, and 6 Farads. You connect them as shown in Figure I.10. Find the total capacitance of the circuit and the charge on each capacitor.

1) We can add the ”6” and ”3” that are in series first, then add the result in parallel with the 1. Adding the series capacitors gives

$$\frac{1}{C_{36}} = \frac{1}{3} + \frac{1}{6} \quad \rightarrow \quad C_{36} = 2F$$

Adding this combination with the ”1” in parallel yields $C_{Total} = 2 + 1 = 3F$

2) Since there is 6 volts across the ”1” Farad capacitor, the plates have a net charge of

$$Q_1 = C.V = 1.(6) = 6C$$

The net charge on the plates of the series ”3” and ”6” Farad capacitors is $Q_{36} = CV = 2.(6) = 12\ C$

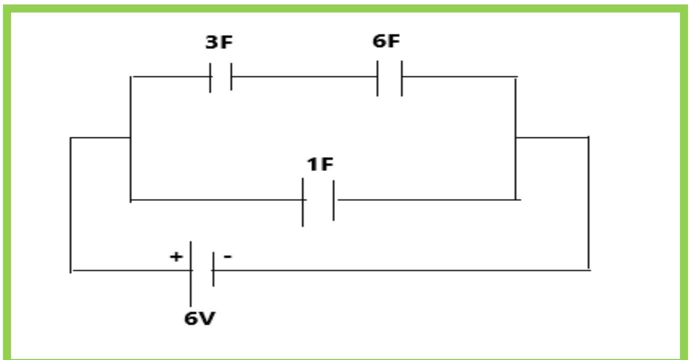


Figure I.10: Series of mixed-connected capacitors

Note that the total charge supplied by the battery is $Q = CV = (2+1).(6) = 3(6) = 18\ C$, also equals (6+ 12) Coulombs.

I.2.1°- Electrical conduction:

Electrical conduction in solids involves the movement of electrons or ions under the influence of an electric field. This movement generates an electric current. For conduction by electrons, when an electric field is applied, the electrons accelerate, colliding with atoms and statistical imperfections, and lose energy, thus giving out a part of it to the atoms. The atoms then make an oscillation. This ion oscillation is nothing but the lattice vibration of the material. Electrons can be treated as free by the system when they interact weakly. When the electrons interact only weakly, they collide many times while traversing a mean-free path. However, when they interact with each other, in many cases, there are not too many collisions with the impurities. Although this sounds very unusual, it effectively represents a metal's conduction process. On the other hand, in semiconductors and insulators, the number of impurities is low, and the electron-electron interactions are not considered.

Conductive materials include metals, electrolytes (or ionic solutions) and plasmas. Since perfect conductors do not exist, ohmic conductors are used, the best of which are silver, gold and aluminum.

I.2.1.1°- Electric current:

Electric current is a collective and organized movement of charge carriers (electrons or ions). This flow of charges can occur in a vacuum (electron beams in cathode ray tubes, etc.), or in conductive matter (electrons in metals, or ions in electrolytes). An electric current appears in a conductor when a potential difference is established between its terminals.

Intensité du courant électrique :

- **Intensity of electric current:**

  Electric current intensity describes the flow of electric charge through a given surface, such as the cross-section of an electric wire.

$$I(t) = \frac{dq(t)}{dt} \dots\dots\dots\dots\dots (I.31)$$

  - Where: I is the current intensity.
  - q the electric charge.
  - t the time.

The International System of Units measures current intensity in amperes, a base unit whose standard symbol is A. One ampere corresponds to a charge flow of one coulomb per second.

The intensity is measured using an ammeter that must be connected to the circuit in series.

- **Current density:**

Current density is a vector describing the electric current on a local scale. Its direction indicates the movement of charge carriers (but its direction can be opposite for negative carriers), and its norm corresponds to the intensity of the current per unit area. It is related to the electric current by:

$$I = \int \vec{j}.\overrightarrow{dS} \dots\dots\dots\dots\dots (I.32)$$

where: I is the current intensity; S is the surface area, J is the current density; and dS is the elementary surface vector.

In the international system of units, current density is measured in amperes per square meter (A.m $^{-2}$).

I.2.2°- Ohm's law, Joule's law:

I.2.2.1°- Ohm's law:

The potential difference or voltage U (in volts) across a resistor R (in ohms) is proportional to the intensity of the electric current I (in amperes) flowing through it (figure I.11).

$$U = R.I \dots\dots\dots\dots\dots\dots.(I.33)$$

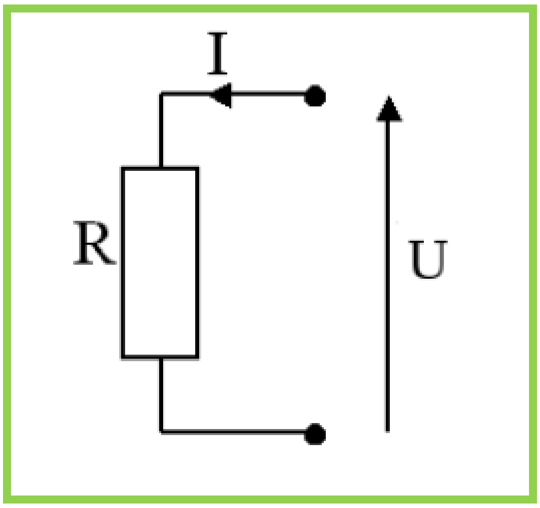


Figure I.11: Resistance crossed by a current I under a voltage U.

Resistance is the body's opposition to the passage of an electric current, measured in ohms.

I.2.2.2°- Joule's law:

The Joule effect is a heat production effect that occurs when an electric current passes through a conductor with resistance. It manifests itself by an increase in the thermal energy of the conductor and its temperature. Indeed, this type of conductor transforms electrical energy into heat energy (energy dissipated in the form of heat). The power dissipated by this conductor is equal to:

$$P = RI^2 \dots\dots\dots\dots\dots (I..34)$$

The unit of power is the watt (W).

R: the resistance of the conductor.

I: the intensity of the current flowing through the conductor.

According to the definition of energy, we deduce that the energy consumed by a resistor during time t is equal to:

$$E = U.I.t = R.I^2.t = \frac{U^2}{R}.t \dots\dots\dots\dots\dots (I..35)$$

The unit of energy is the joule (J).

- **Grouping of resistors:**

  There are two cases for grouping resistors:

  - **Grouping in series:**

All resistors **R_i** are traversed by the same electric current **I**, and each of them has only one end in common with another resistor (figure I.12). The voltage U_{AB} = U is equal to the sum of the voltages of the resistors.

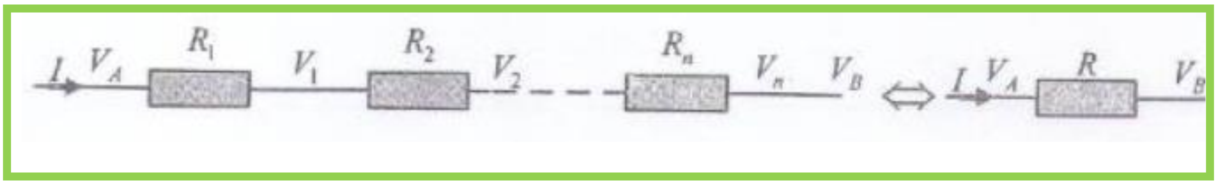


Figure I.12: Series grouping of resistors

$$U = U_1 + U_2 + U_3 + \cdots \ldots.. + U_n = R_{eq}.I \ldots \ldots.. \ldots \ldots \ldots \ldots \ldots (I.36)$$

$$U = R_1.I + R_2.I + R_3.I + \cdots \ldots R_n.I = R_{eq}.I \ldots \ldots \ldots \ldots \ldots \ldots (I..37)$$

Thus, we obtain the equivalent resistance of all the resistances grouped in series.

$$R_{eq} = \sum_{i=1}^{n} R_i \ldots \ldots \ldots \ldots \ldots \ldots (I..38)$$

- **Parallel grouping:**

This grouping is characterized by all the resistors having common terminals, two by two (figure I.13). The voltage is the same between the ends of any resistor **R_i**.

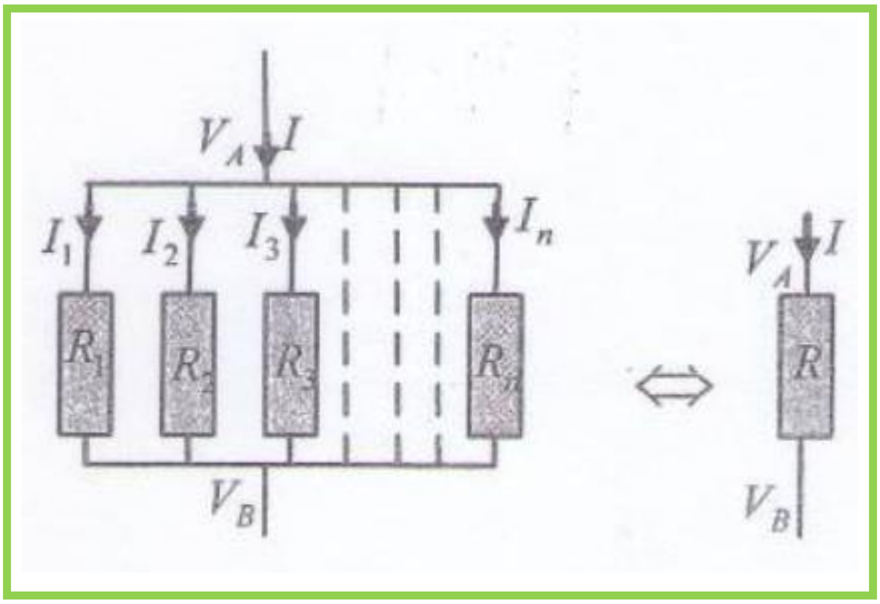


Figure I.13 : Parallel grouping of resistors

The electric current that supplies the circuit portion is distributed between the resistors, such that:

$$I = I_1 + I_2 + I_3 + \cdots + I_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (I.39)$$

$$I = \frac{U}{R_{eq}} = \frac{U}{R_1} + \frac{U}{R_2} + \frac{U}{R_3} + \cdots + \frac{U}{R_n} \Rightarrow \frac{U}{R_{eq}} = \left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}\right] U \ldots\ldots\ldots\ldots (I.40)$$

Thus, we obtain the equivalent resistance, in this case, is always smaller than that of the smallest of the resistors mounted in the derivation:

$$\frac{1}{R_{eq}} = \left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}\right] \Rightarrow \frac{1}{R_{eq}} = \sum_{i=1}^{n} \frac{1}{R_i} \ldots\ldots\ldots\ldots\ldots\ldots (I..41)$$

I.2.3°- Electrical circuits:

An electrical circuit is a set of conductors (wires) and electrical components (sockets, switches, ...) or electronic components (household appliances, ...) through which an electric current flows.

The electrokinetic study of an electrical circuit consists of determining the intensity of the current and the voltage at each location.

- ***Elements of the electrical circuit:***

The electrical circuit is essentially composed of the following elements (figure I.14):

1 The node: is a point where more than two conductors end.

2 The branch: a portion of the circuit inserted between two nodes.

3 The mesh: any closed contour formed by a series of branches.

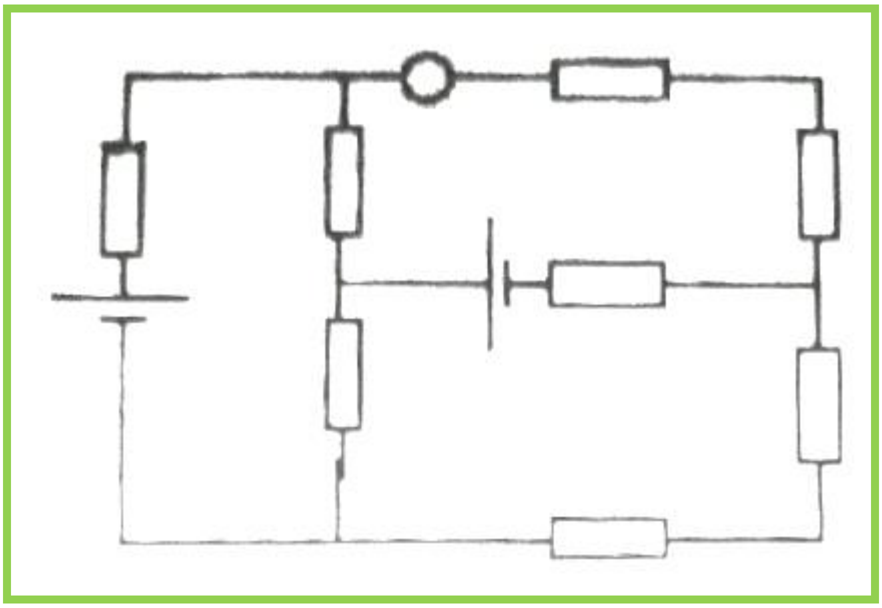


Figure I.14: Any electrical circuit.

- **Generators:**

Energy must be supplied to the circuit to obtain a continuous electric current in a closed circuit. Devices called generators do this. They are sources of electromotive forces that transport charges.

There are two types of generators:

1. **Generators or voltage sources:**

The voltage source, or voltage generator, is a dipole characterized by a constant voltage between its terminals, regardless of the variable current it supplies. In what follows, we will focus mainly on direct current (DC) generators. This type of generator is characterized by an electromotive force (e) and a low internal resistance (r) (Figure I.15).

It is possible to replace a voltage generator, with characteristics (e, r), with an ideal source with an electromotive force (e) in series with an ohmic conductor with resistance (r), as shown in Figure I.15.

The electromotive force of a voltage generator is equal to the potential difference between its terminals when it is not supplying any current:

$$I = 0 \Rightarrow e = U_{AB}$$

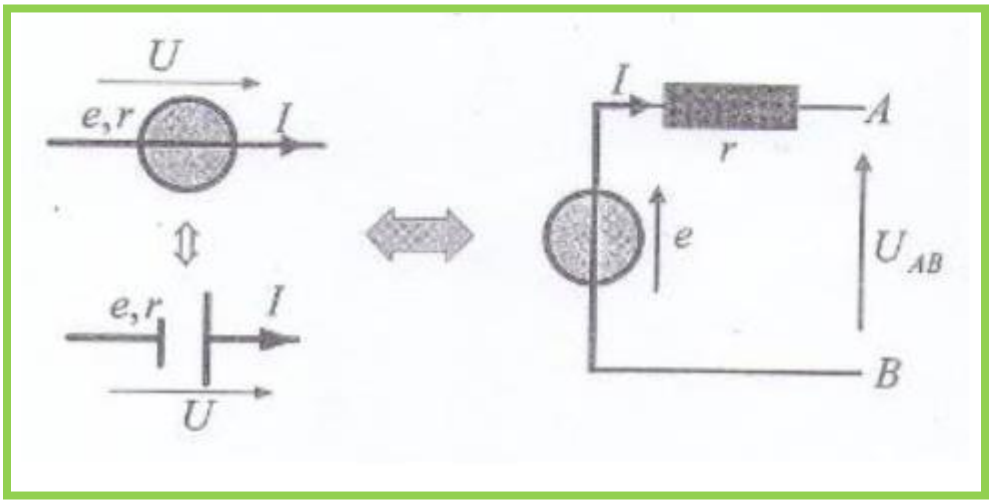


Figure I.15: representation of the voltage generator.

2. **Generators or current sources:**

The current source, or current generator, is a dipole that supplies a constant current, regardless of the variable potential difference between its terminals. In what follows, we will focus mainly on direct current (DC) generators. The diagram in Figure I.16 represents this type of generator. A current generator can be replaced by an ideal current that supplies a constant current and is connected in parallel with an ohmic conductor with resistance, as shown in Figure I.16.

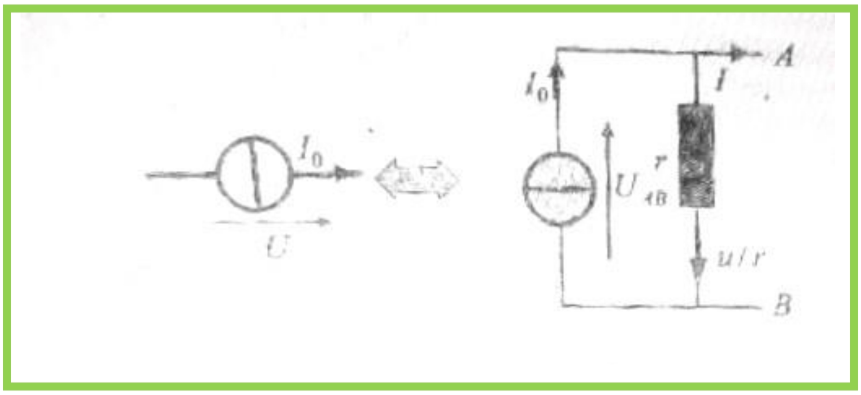


Figure I.16: representation of the current generator.

Example :

This combination of resistors can be broken up into parallel and series sections (see Figure I.17). This is nice because one can calculate the equivalent resistance of the whole circuit and find the current delivered by the battery. Once this is done, one can go piece by piece to determine the currents and voltages across the resistors.

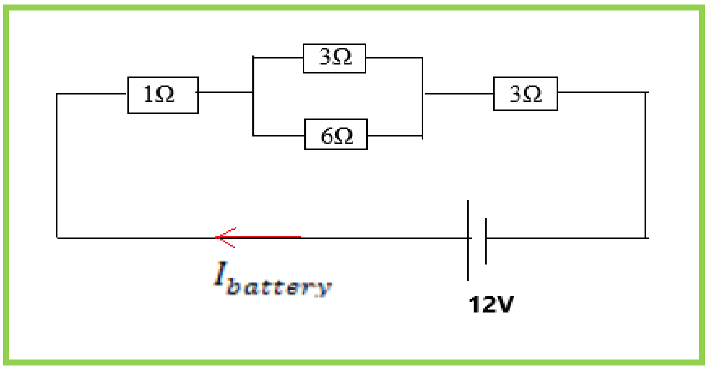


Figure I.17: Series of mixed-connected resistances

First, we determine the resistance of the whole circuit. The 6Ω and 3Ω resistors in parallel are equivalent to $\frac{1}{R_{36}} = \frac{1}{3} + \frac{1}{6} \rightarrow R_{36} = 2\Omega$

This 2Ω parallel combination is in series with the other two resistors, so the total resistance of the circuit, R_T , is $R_T = 1 + 2 + 3 = 6\Omega$

The current that is supplied by the battery is $I = V/R_T$, or $I_{battery} = 12/6 = 2A$

Thus, 2A flows through the 1Ω resistor and the 3Ω resistor in series. Now the voltages across all the resistors can be determined. Across the 1Ω resistor, V = IR = 2(1) = 2 V. Across the 3Ω resistor in series with the battery, V = IR = 2(3) = 6 V. The voltage across the 3Ω and 6Ω resistors in parallel are V = 12 − 2 − 6 = 4 V. The current through the 6Ω resistor is therefore I = V/R = 4/6 = 2/3 A. The current through the 3Ω resistor (in the parallel combination) is I = V/R = 4/3 A.

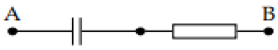
I.2.4°- Kirchhoff's laws

I.2.4.1°- Components of a circuit

An electric circuit is simply an assembly of dipoles (electrical components) connected by conductive wires.

- **Branch**

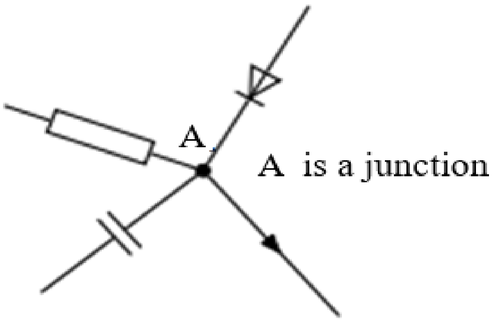
A branch is a portion of a circuit that does not contain any branches (or the components are simply in series one after the other).



A node is a point in the circuit where several branches meet. AB is a branch, all the components of the same branch are traversed by the same current.

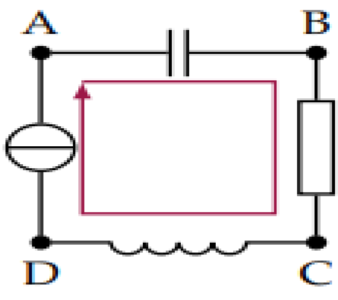
- **Junction**

A junction is a point in the circuit where several branches meet.



- **Loop**

A loop is a series of branches that return to the same starting point.



Loop ABCD. An arrow specifies the direction of travel of a loop.

I.2.4.2°- Kirchhoff's first law

Circuit network analysis can be carried out using Kirchhoff's laws. Kirchhoff's first law applies to currents at a junction in a circuit. It states that at a junction in an electrical circuit, the sum of currents flowing into the junction is equal to the sum of currents flowing out of the junction.

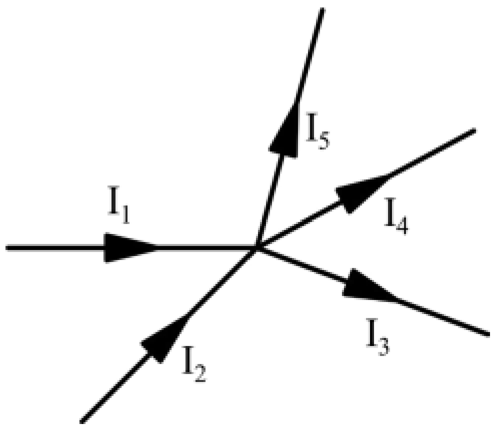


Figure I.18: Currents of known direction of flow into and out of a junction

In Figure I.18 the directions of the currents are known. Kirchhoff's first law states that:

$$\mathbf{I_1 + I_2 = I_3 + I_4 + I_5}$$

Not: *current cannot flow into the junction from all directions without current flowing out.*

I.2.4.3°- Kirchhoff's second law

Kirchhoff's second law applies to voltage drops across components in a circuit. It states that around any closed loop in a circuit, the directed sum of potential differences across components is zero. The meaning of 'directed sum' in this definition is explained in Figure I.19.

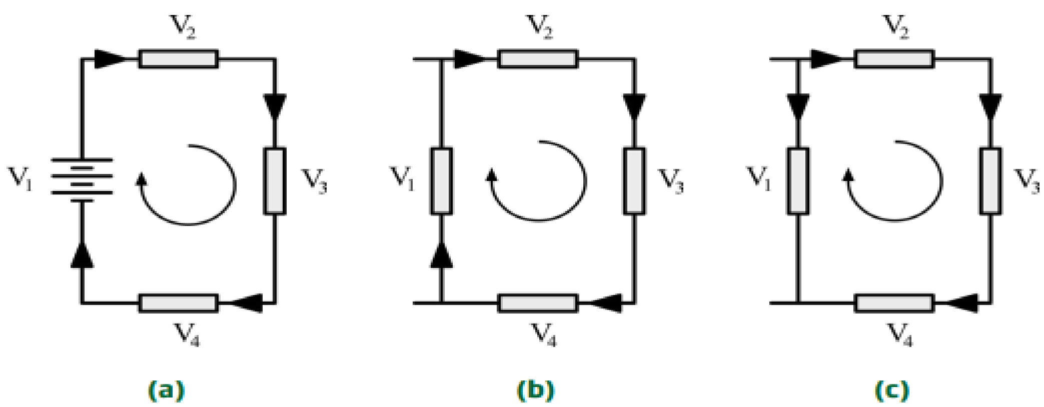


Figure I.19: Two closed loops with a power supply (**a**), without a power supply assumed current direction (**b**) and without a power supply with actual current direction (**c**).

Remember:

• For cells, the assumed positive is where the current flows out of the cell.

• For components, the assumed positive is where it flows into the component.

In Figure **I.19 (**a), Kirchhoff's second law states:

$V_1 - V_2 - V_3 - V_4 = 0$

The same principle applies in Figure **I.19 (**b), where an assumed current flow has been added. In this case, the diagram has added wires to indicate that it is joined to a larger circuit. This helps clarify that in this case, as there is no dc supply, current must enter and exit the loop.

$V_1 + V_2 + V_3 + V_4 = 0$

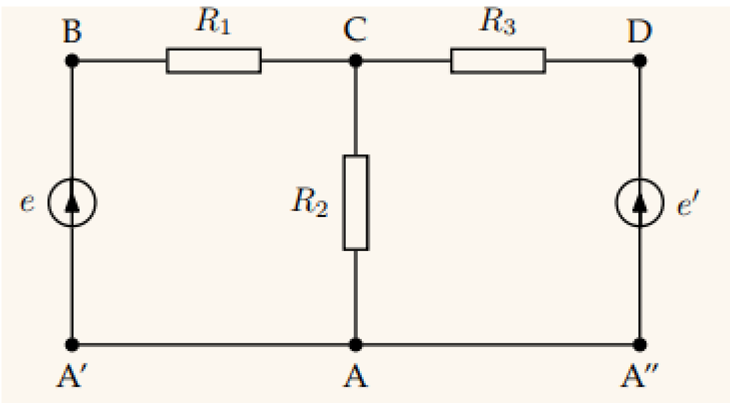
Note, for the above to be true either all the values must be zero (which means your circuit isn't turned on or is made of exotic superconductors!), or at least one of the values must be negative, for example, the current flows in the opposite direction to that shown by arrow in that (or those) components.

For the case where $V_2 = V_3 = V_4 = 2$ V, V_1 must be −6 V, indicating that the current flowing through the resistor associated with V1 is as shown in Figure **I.19 (**c), rather than **I.19 (**b).

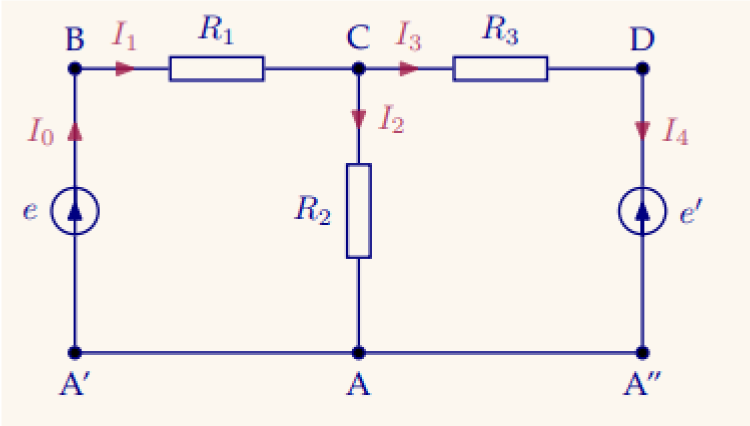
Exercise:

In the circuit below, determine the current flowing in each resistor

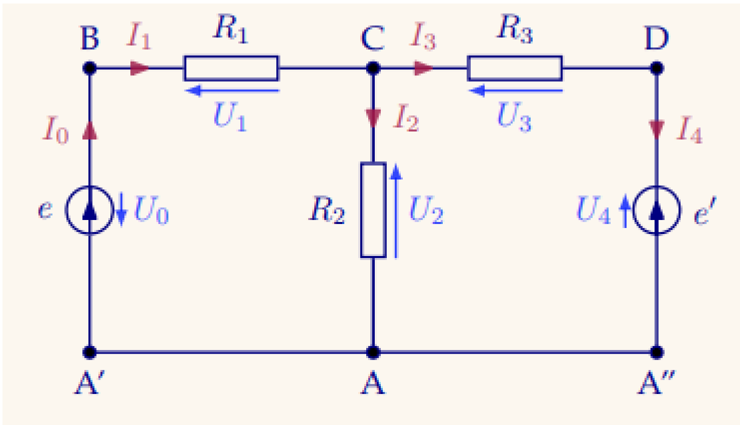
We have e = 17V, e' = 6V, R1 = 1Ω, R2 = 4Ω and R3 = 3Ω.



We start by choosing a direction and a name for the current in each of the branches (this choice is arbitrary, you can choose something different):



We then name the voltages at the terminals of each dipole, we orient them in the direction opposite to the current.



We use the characteristics associated with each dipole to relate current and voltage in each component.

· $U_0 = -e$

· $U_1 = R_1I_1$

· $U_2 = R_2I_1$

· $U_3 = R_3I_3$

· $U_4 = e'$

• We use the Node Law in B, C, D (we can also apply it in A, A' and A", but this does not provide any new information):

- $I_0 + (-I_1) = 0 \Rightarrow I_0 = I_1$

· $I_3 = I_4$

· and finally: $I_1 = I_2 + I_3$ …………..(1)

• We use the law of loops on AA'BC and ACDA'':

·• Following AA'BC:

$U_{AA'} + U_{A'B} + U_{BC} + U_{CA} = 0$

$0 - U_0 - U_1 - U_2 = 0$

$e - R_1I_1 - R_2I_2 = 0$…………………. (2)

• Following ACDA":

$U_{AC} + U_{CD} + U_{DA"} + U_{A"A} = 0$

$U_2 - U_3 - U_4 + 0 = 0$

$R_2I_2 - R_3I_3 + e' = 0$ ………………..(3)

• Finally (1), (2) and (3) form a linear system with 3 equations and 3 unknowns, which we solve to find:

$$I_2 = \frac{e + \frac{R_1}{R_3}e'}{R_1 + R_2 + \frac{R_1R_2}{R_3}} = 3A$$

$$I_3 = \frac{R_2e + \frac{R_1R_2}{R_3}e'}{R_1R_3 + R_2R_3 + R_1R_2} + \frac{e'}{R_3} = 2A$$

$$I_1 = I_2 + I_3 = 5A$$

I.2.4°- Theorems of Thevenin and Norton:

Thévenin's and Norton's theorems are applied to simplify the analysis of complex electrical circuits. Thévenin's theorem replaces a multi-element circuit with a single voltage source and a resistor, while Norton's theorem uses a current source and a resistor. These theorems facilitate the understanding of the behaviour of a circuit by reducing it to a more straightforward form.

I.2.4.1°- Theorems of Thevenin:

Thévenin's theorem allows us to transform a circuit composed of multiple loops, multiple voltage sources, and multiple current sources into a single-loop circuit consisting of an equivalent resistance (Thévenin resistance R_{th}) and an equivalent voltage source (Thévenin voltage V_{th}).

- **Calculating Thévenin Voltage:**

  To calculate the Thévenin voltage of a circuit, mentally remove the load resistance, and then calculate the voltage across R_L.

  In a practical setup, remove the load resistance (R_L) and place a voltmeter in its place. This way, **the Thévenin voltage** is measured as the **open-circuit voltage** of the setup.

  Make sure that the value of R_L is much lower than the input impedance of the voltmeter. For reference, the input impedance of a voltmeter is typically in the MΩ range.

- **Calculating Thévenin Resistance:**

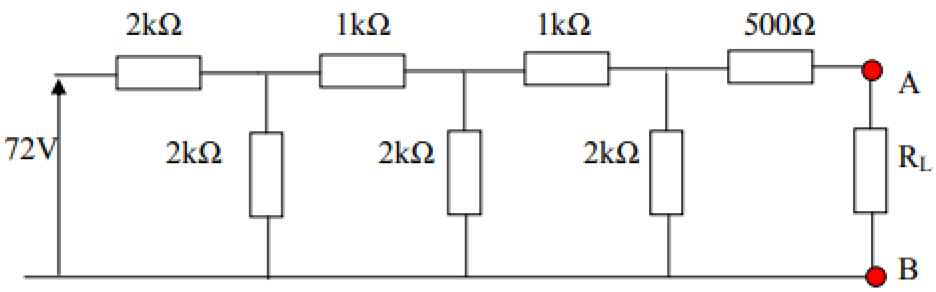
To calculate Thévenin resistance:

- Remove the current sources and replace them with open circuits.
- Remove the voltage sources and replace them with short circuits.
- Remove the load resistance R_L.

Next, calculate the equivalent resistance of the setup, which is the Thévenin resistance R_{th}. In a practical setup, use an ohmmeter to measure the resistance as seen from the load resistance terminals.

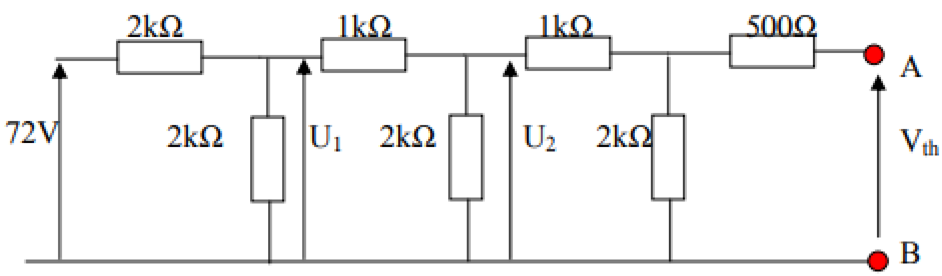
Example 1:

How to mount it:

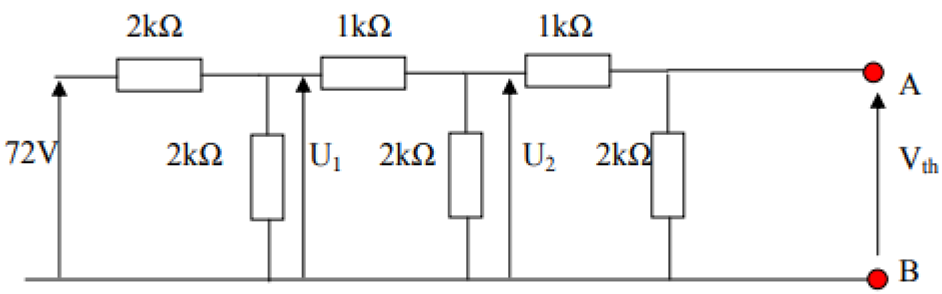


Thévenin tension calculation

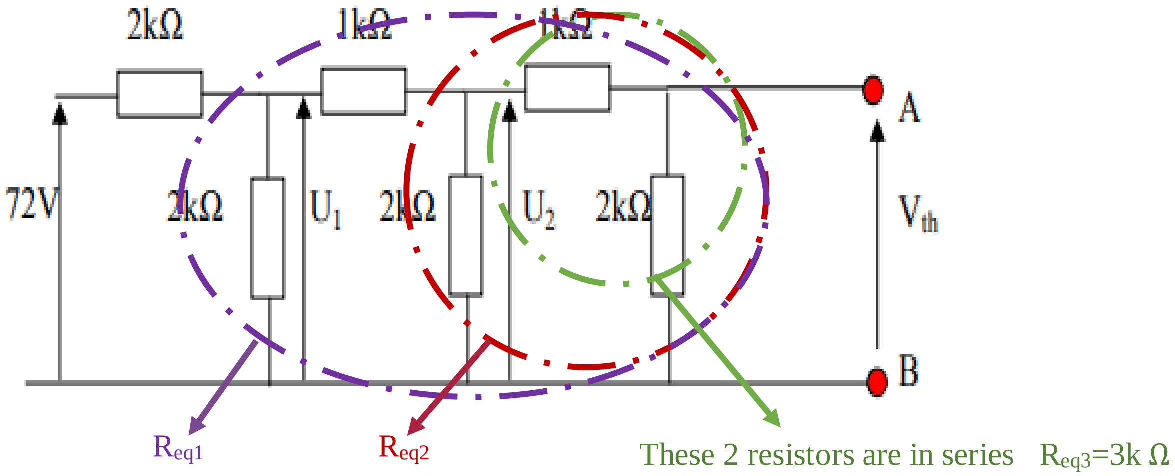
When the charge is withdrawn, we will leave the circuit at once:



The voltage resistance is higher than that of the 500 Ω. When using the different scheme:



After this calculation, the calculations U_1 puis U_2



$$R_{eq2} = \left[\frac{1}{2} + \frac{1}{3}\right]^{-1} = 1.2k\Omega$$

$$R_{eq1} = \left[\frac{1}{2} + \frac{1}{1 + R_{eq2}}\right]^{-1} either\ R_{eq1} = \left[\frac{1}{2} + \frac{1}{2.2}\right]^{-1} = 1.04762k\Omega$$

We have: $U_1 = \frac{R_{eq1}}{2+R_{eq1}}.72\ either\ U_1 = \frac{1.04762}{2+1.04762}.72 = 24.75V$

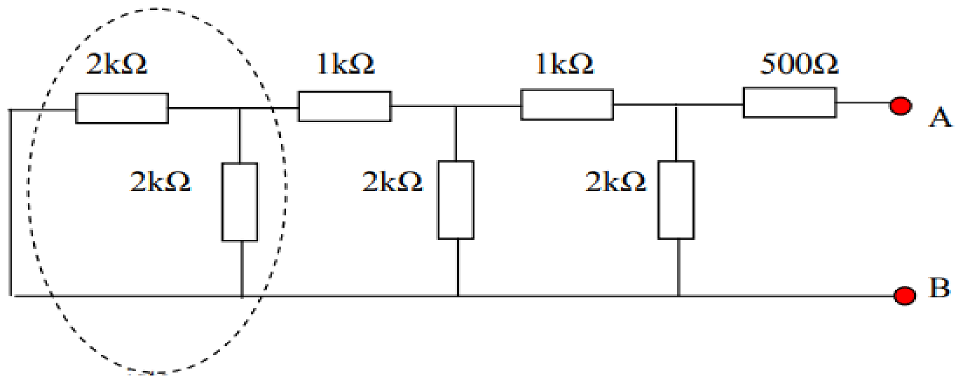
In the same way, we have $U_2 = \frac{R_{eq2}}{1+R_{eq2}}.U_1\ either\ U_2 = 24.45.\frac{1.2}{2.2} = 13.5V$

We can calculate the Thévenin tension: $U_{th} = \frac{2}{1+2}.U_2 = 9V$

Calculation of Thévenin resistance

We replace the voltage source (72V) with a short circuit and remove the load resistance R_L.

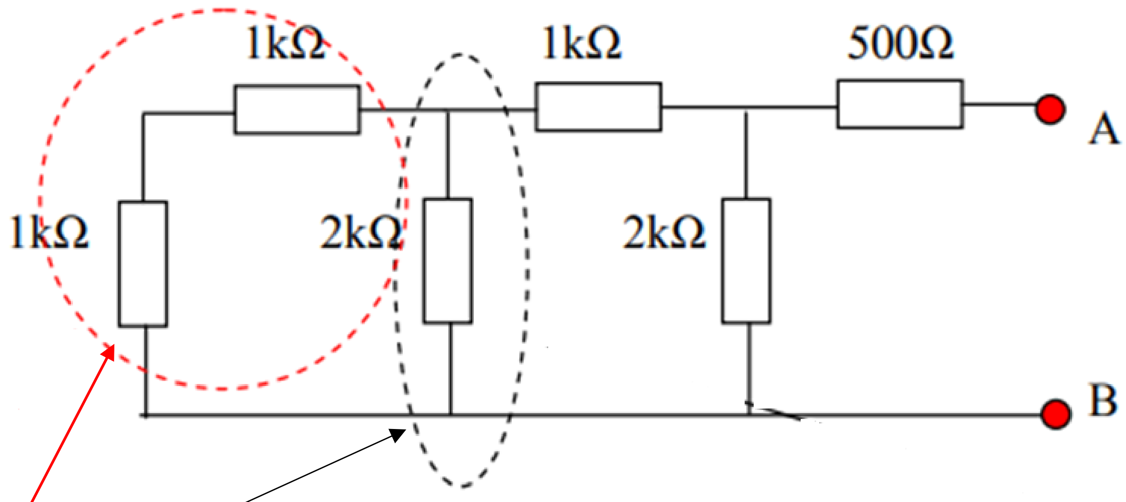
We have the following circuit:



These 2 resistors are in parallel

The equivalent resistance is R_{eq}=1kΩ

The diagram becomes:



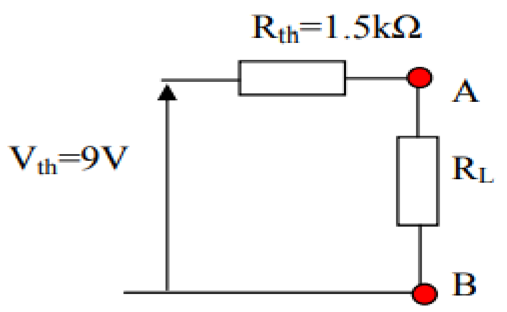
The two resistors are in series 1kΩ. We have an equivalent resistor of 2kΩ, parallel to the **2kΩ** resistor. The equivalent resistance is 1kΩ.

The schema becomes

In the same way as before we have an equivalent resistance of 1kΩ. The Thévenin resistance is 1+0.5 or 1.5kΩ.

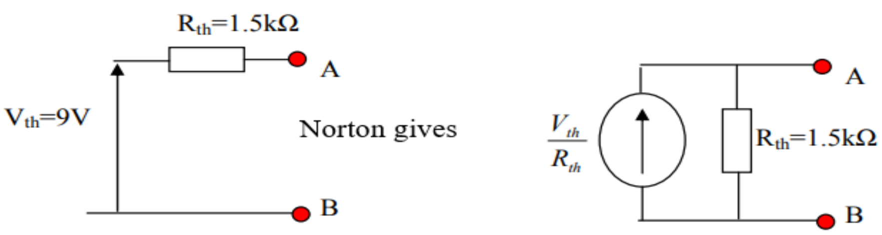
R_{th}=1.5KΩ

The equivalent diagram of our circuit is:



I.2.4.2°- Theorems of Norton:

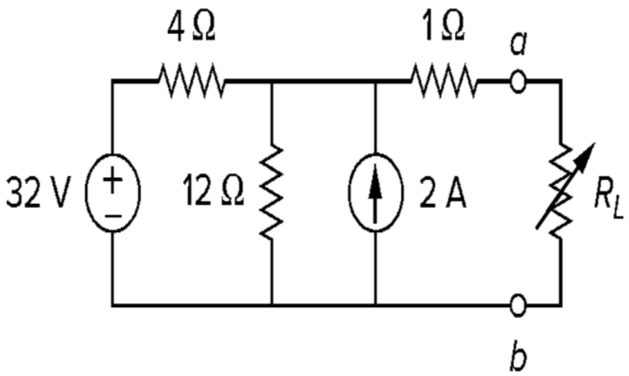
Norton's theorem is derived from Thévenin's theorem.



We note that Norton's resistance is identical to Thévenin's resistance. Finally, we replace Thévenin's voltage with Norton's pure current source. This current source supplies a current (I) such that $I = \frac{V_{th}}{R_{th}}$.

Example 2:

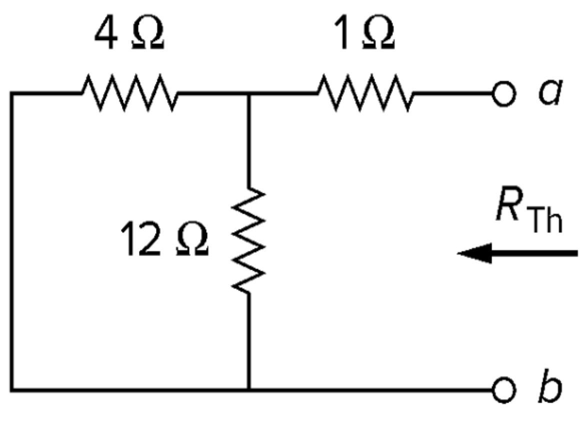
Find the Thevenin equivalent of the circuit shown below across terminals a-b. Then find the current through R_L = 6Ω and 36Ω respectively.



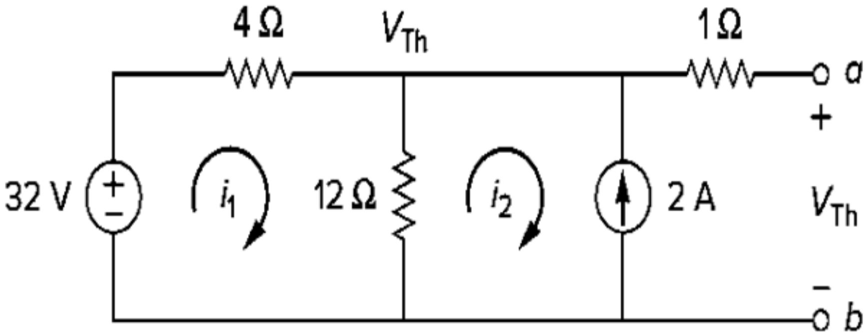
Soln:

Step 1: Find R_{Th} by turning off the 32V voltage source (replacing it with a short circuit) and the 2A current source (replacing it with an open circuit).

$$R_{Th} = \frac{4.12}{16} + 1 = 4\Omega$$



Step 2: Make a-b open circuit. Find V_{Th} by applying mesh/node analysis.



$-32 + 4\ i_1 + 12(i_1 - i_2) = 0;\ i_2 = -2A\ \rightarrow i_1 = 0.5A$

$V_{Th} = 12((i_1 - i_2) = 12(0.5 + 2) = 30V \rightarrow V_{Th} = 30V$

Step 3: Finding current through R_L

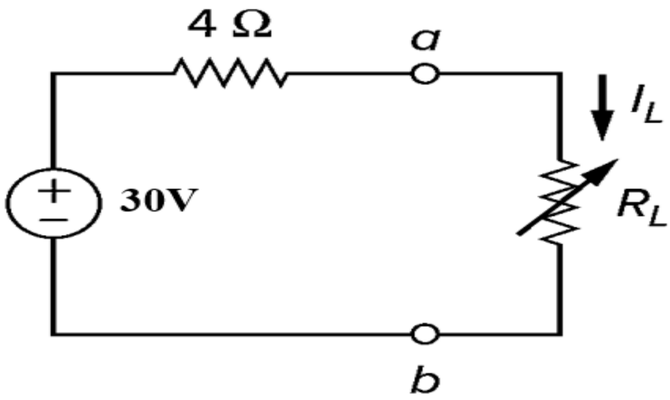
$$I_L = \frac{V_{Th}}{R_{Th} + R_L}$$

a) When $R_L = 6\Omega$

$$I_L = \frac{30}{4 + R_L} = \frac{30}{10} = 3A$$

b) When $R_L = 36\Omega$

$$I_L = \frac{30}{4+R_L} = \frac{30}{40} = 0.75A$$



Thevenin equivalent circuit

I.3°- Electromagnetism

The word "magnetism" derives from the name of the region "Magnesia," located on the western coast of present-day Turkey, where the magnetic phenomenon was observed a long time ago. This region contained deposits of the mineral called "magnetite," which has specific properties. Indeed, it was observed that two pieces of this mineral (called magnets) either attract or repel each other and can also transfer their properties to a nearby piece of iron. This magnetic phenomenon remained unexplained until the year 1819. In that year, the Swedish physicist Ørsted demonstrated for the first time the effect of an electric current on a magnet: a straight conductor wire was placed above and parallel to a magnetized needle mounted on a pivot; when an electric current passed through the conductor, the needle oriented itself perpendicular to the wire, and the direction of the orientation changed with the direction of the current. This proved the existence of a magnetic force resulting from the passage of electric current. This experiment showed that a wire carrying an electric current acquires magnetic properties very similar to those of a natural magnet.

I.3.1°- Definition of the magnetic field

Whatever magnetic effects are observed at a point in space, a single quantity is necessary to describe them: a vector field called the magnetic field, which we will denote by B (also referred to as the magnetic induction field).

Compared with the electric field, a charge or a group of moving charges creates a magnetic field in the region where they are located. This magnetic field acts on an external electric charge q with a force $\overrightarrow{F_B}$. The same applies to an electric current since by definition, it consists of a group of charges.

Like the electric field $\vec{E}$, the magnetic field is also a vector quantity, and it is characterized by the vector $\vec{B}$.

The unit of magnetic induction in the International System of Units (SI) is the Tesla (T).

- **Superposition Property:**

  If multiple magnetic fields: $\overrightarrow{B_1}, \overrightarrow{B_2}, \dots \dots \dots, \overrightarrow{B_n}$.act simultaneously on a moving electric charge or on a magnetized needle, the equivalent magnetic field $\vec{B}$.is equal to the vector sum of all the acting fields.

  $\vec{B} = \overrightarrow{B_1} + \overrightarrow{B_2} + \dots \dots \dots . + \overrightarrow{B_n}$

- **Magnetic field lines**

The magnetic field lines are a visual and intuitive realization of the magnetic field.

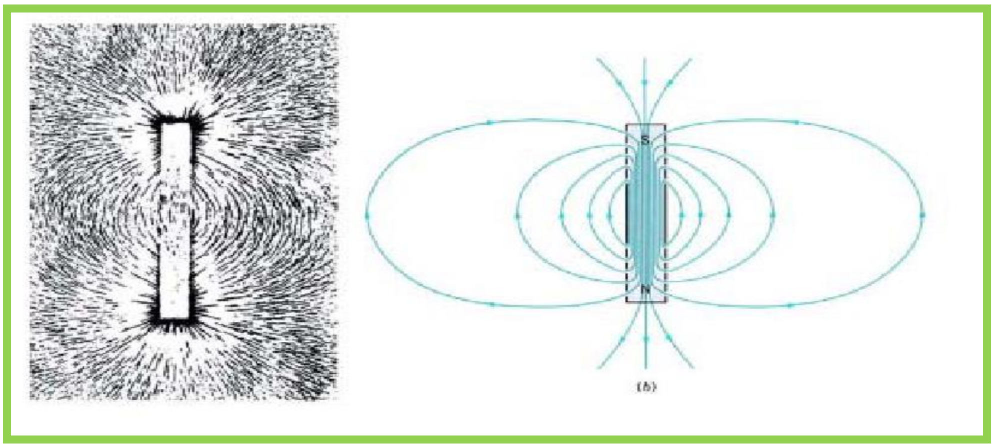


Figure I.18: The magnetic field lines

- **Properties of magnetic field lines:**

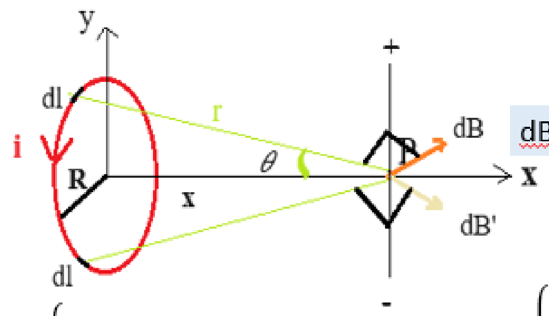
1- Magnetic field lines form a closed loop.

2- The tangent to the field lines at a given point represents the direction of the net magnetic field B at that point.

3- Closer the field lines, the stronger is the magnetic field $\vec{B}$.

4- Magnetic field lines never intersect each other.

- **Magnetic field at point P is present on the axis of the solenoid**



$$\vec{dB} = \frac{\mu_0 . i . (\vec{d\ell} \otimes \vec{r})}{4\pi \|\vec{r}\|^3}$$

dB.sinθ along axis x

$$\vec{dl} x \vec{r} = dl.r.sin\theta$$

$$\sin\theta = \frac{R}{r}$$

$$r = \sqrt{R^2 + X^2}$$

R=r.sinθ

$$\Rightarrow \begin{cases} dB_x = \int dB.sin\theta \\ dB_y = 0 \end{cases} \Rightarrow dB.sin\theta = \frac{\mu_0}{4\pi}\frac{i.dl.R}{r^3} \Rightarrow \begin{cases} \int dl = l = 2\pi R \\ \int dB.sin\theta = \int \frac{\mu_0}{4\pi}\frac{i.dl.R}{r^3} = B_T \end{cases} \Rightarrow \begin{cases} B_T = \frac{\mu_0}{4\pi}\frac{i.R}{r^3}\int dl \\ \int dl = 2\pi R \end{cases}$$

$$B_T = \frac{\mu_0}{4\pi}\frac{i.R.2\pi.R}{(R^2+X^2)^{\frac{3}{2}}} \Rightarrow \boxed{B_T = \frac{\mu_0}{2}\frac{i.R^2}{(R^2+X^2)^{\frac{3}{2}}}}$$

- **The direction of the magnetic field:**

‘’Right-hand thumb rule ‘’

Curl lingers on the right hand in the direction of the current.

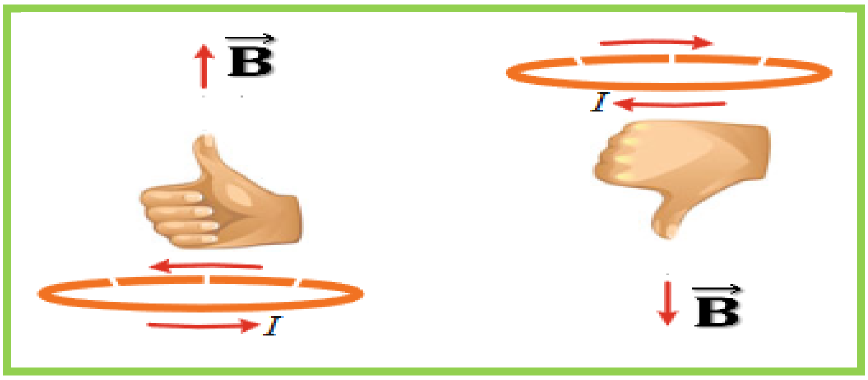


Figure I.19: The direction of the magnetic field

I.3.2 °- Current-field interaction (Laplace's law)

Laplace’s law describes the force experienced by a current-carrying conductor placed within a magnetic field. This interaction, also called the **Lorentz force** when considering electric charges in motion, is fundamental in electromagnetism and underpins many applications, such as in electric motors.

I.3.2.1 °- Mathematical Formulation Laplace's Law

The mathematical formulation of **Laplace's Law** describes the force exerted on a current-carrying conductor placed within a magnetic field. The law quantifies the **magnetic force** $\vec{F}$ acting on the conductor segment $\vec{F}$ (where L is the length of the conductor within the field) and relates it to the current I and magnetic field $\vec{B}$ as follows:

$$\vec{F} = I(\vec{L}\Lambda\vec{B}) \ldots\ldots\ldots\ldots\ldots..(I.42)$$

- $\vec{F}$: The magnetic force (in newtons, N) acting on the conductor.
- I: The electric current (in amperes, A) passing through the conductor.
- $\vec{L}$: A vector representing the length and direction of the conductor within the magnetic field.
- $\vec{B}$: The magnetic flux density or magnetic field (in teslas,T).

- **Cross Product:**

The force direction is determined by the **right-hand rule** for the cross product $\vec{L}\Lambda\vec{B}$:

1. Point your right hand's fingers along the direction of $\vec{L}$ (conductor length).
2. Rotate your fingers toward $\vec{B}$ (magnetic field direction).
3. Your thumb then points in the direction of $\vec{F}$.

- **Magnitude of the Force:**

The magnitude of $\vec{F}$ can be expressed as:

$$F = I.L.B.sin\theta \ldots\ldots\ldots.(I.43)$$

where:

- F is the magnitude of the force.
- θ is the angle between $\vec{L}$ and $\vec{B}$.

This formulation shows that the force is strongest when $\vec{L}$ is perpendicular to $\vec{B}$ (θ=90°, sin(90∘)=1) and zero when $\vec{L}$ is parallel to $\vec{B}$ (θ=0°, where sin(0°)=0).

I.3.2.2 °- Lorentz force

Dutch physicist Hendrik Lorentz gives the expression for the force $\vec{F}$exerted on a point charge q, moving at speed $\vec{V}$ in electric and magnetic fields $\vec{E}$and $\vec{B}$:

$$\vec{F} = q.\left(\vec{E} + \vec{V}\wedge\vec{B}\right) \dots\dots\dots\dots\dots\dots\dots\dots (I.\ )$$

In the presence of only the magnetic field $\vec{B}$ ($\vec{E}$= $\vec{0}$), the Lorentz force becomes:

$$\vec{F} = q.\left(\vec{V}\wedge\vec{B}\right) \dots\dots\dots\dots\dots\dots\dots\dots (I.\ )$$

A magnetic field is a region of space where, in the absence of the electric field $\vec{E}$, a charge q moving at a speed $\vec{V}$, is subjected to the action of a force:

$$\vec{F} = q.\left(\vec{V}\wedge\vec{B}\right)$$

This new definition of the magnetic field is obtained from the Lorentz force. This force:

1- has the following modulus: $F = q.V.B\left|\sin(\vec{V},\vec{B})\right|$

2- its direction is perpendicular to the plane formed by $\vec{V}$ and $\vec{B}$

3- Its meaning is such that, in the case of a positive charge, the vectors $\vec{V}$,$\vec{B}$ and $\vec{F}$ form a direct trihedron (right-hand rule). When the charge is negative, the force changes direction.

The meaning of this force is also given by Ampere's stickman rule:

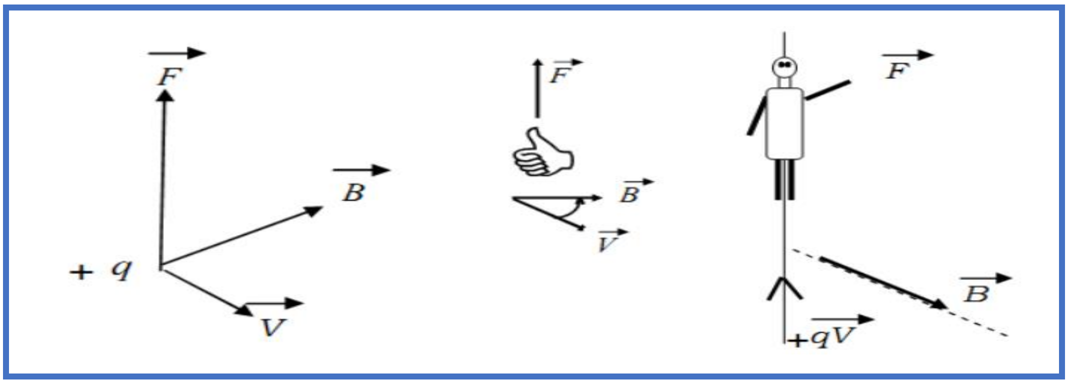


Figure I.**:** The figure shows Ampère's man, crossed from head to toe by the charge (+q) animated by a speed V, seeing the field lines flee, and the force to his left.

I.3.2.3 °- Movement of a particle in a magnetic field

A particle, of mass m carrying an electric charge q, moves in a uniform magnetic field B with a constant speed V perpendicular to B. It is therefore subject to a force whose expression is:

$$\vec{F} = q.\left(\vec{V} \wedge \vec{B}\right)$$

This force is **perpendicular** to $\vec{V}$ and $\vec{B}$ and its modulus is:

F = q.V.B (1)

It remains perpendicular to $\vec{V}$ during the movement. There is therefore no tangential acceleration. The acceleration being centripetal ($a=a_N$);

The fundamental relationship of dynamics allows the modulus of the force to be expressed in the form:

$$F = m\frac{V^2}{R} \qquad (2)$$

R is the radius of the circular path. With (1) and (2), it comes:

$$\mathrm{q.V.B} \quad = m\frac{V^2}{R}$$

From this expression, we obtain:

- The radius of the circle described by the particle: $\mathrm{R} \quad = \frac{mV}{q.B}$

Note that the more intense the magnetic field, the smaller the trajectory radius.

- The modulus of the angular velocity of the movement $\omega = \frac{V}{R}$ which is written: $\omega = \frac{q}{m}.B$ depends only on the ratio q/m and the intensity of the magnetic field B.

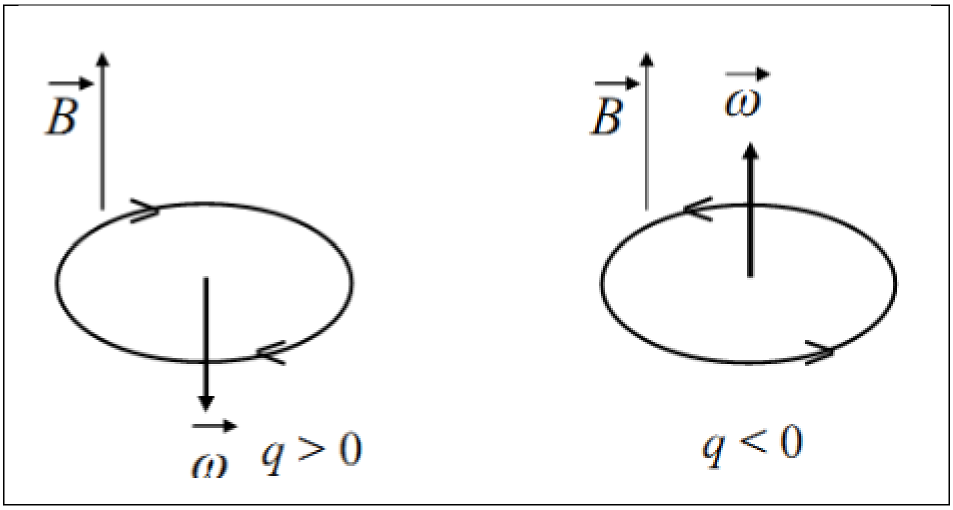
- **Direction of angular velocity**:

  In a uniform circular motion, the fundamental relation of dynamics is written:

$$\vec{F} = m.\vec{a} = m\left(\vec{\omega} \wedge \vec{V}\right)$$

$$m(\vec{\omega}\wedge\vec{V}) = q(\vec{V}\wedge\vec{B})\ either\ \vec{\omega}\wedge\vec{V} = -\frac{q}{m}(\vec{B}\wedge\vec{V})$$

From where $\vec{\omega} = -\frac{q}{m}(\vec{B})$



mFigure I.**:** Direction of angular velocity

- If the particle's charge is positive (q > 0) ω and B have opposite directions.
- Otherwise (q < 0) ω and B have the same direction.

❖ **Case where the initial velocity is not perpendicular to the field:**

In this case, we break down the speed into two components: $\vec{V} = \overrightarrow{V_{//}} + \overrightarrow{V_{\perp}}$

$\overrightarrow{V_{//}}$ is parallel to $\vec{B}$: this component is not affected by $\vec{B}$, the particle takes a rectilinear and uniform motion. $\overrightarrow{V_{\perp}}$ is perpendicular to $\vec{B}$: the motion of the particle is circular and uniform.

The resulting motion is helical

✓ The trajectory is a **helix**.

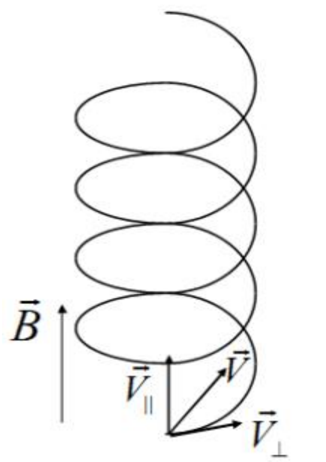


Figure I. : Movement helical

I.3.2.4 °- The magnetic field created by a current

- **Biot and Savart's law**

French physicists Biot and Savart found the expression for the magnetic field obtained during Oersted's experiment.

A straight conductive wire of infinite length, carrying a current I, creates, at a point M in space located at a distance r from the wire, a magnetic field whose:

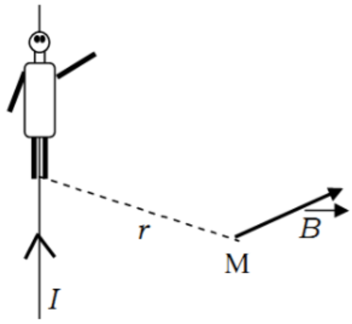
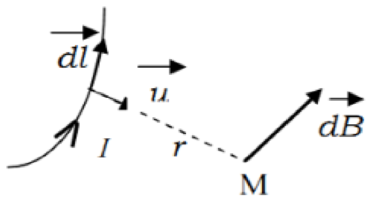


Figure I. : Oersted's experiment.

- The direction is such that the field lines are circles centred on the wire.
- Ampère's stickman rule gives the direction: when he is traversed by I, from the feet to the head, he sees in M the field to his left (**figure I.**).
- - the modulus is: $B = \frac{\mu_0}{2\pi} . \frac{I}{r}$

where μ_0 is the magnetic permeability of the vacuum.
In the MKSA system, $\mu_0 = 4\,\pi 10^{-7}$ henry per meter: H/m.
In the case of a closed circuit of any shape, each current element. I dl, creates in M an elementary field: $\overrightarrow{dB} = \frac{\mu_0}{4\pi} . \frac{I.\overrightarrow{dl} \wedge \vec{u}}{r^2}$

This is the expression of the Biot and Savart law in the general case.
The vector $\vec{u}$ is oriented, as shown in the figure, from the source to point M.



I.3.3 °- *Ampere formula:*

Ampère's formula, often used in the context of Ampère's Law, relates the integrated magnetic field around a closed loop to the current passing through the loop. It is fundamental to understanding how currents generate magnetic fields.

I.3.1°- Ampère’s Law

The mathematical form of Ampère’s Law is:

$$\oint \vec{B}.\vec{dl} = \mu_0 . I_{Enc}$$

where:

- $\oint \vec{B}.\vec{dl}$ represents the line integral of the magnetic field $\vec{B}$ around a closed path.
- μ_0 is the permeability of free space ($4\pi\times10^{-7}$ T.m/ A).
- I_{Enc} is the total current enclosed by the path.

I.3.2°- Applications of Ampère's Law

1. **Magnetic Field Around a Straight Current-Carrying Wire**
    - For a long, straight wire carrying a current **I**, Ampère's Law gives:

$$B = \frac{I\mu_0}{4\pi r}$$

where:

- B is the magnetic field at a distance r from the wire.
- r is the radial distance from the wire.

➢ **Diagram**: Magnetic field lines form concentric circles around the wire, with the direction given by the right-hand rule (curl your fingers in the direction of the field lines, and your thumb points in the direction of the current).

2. **Magnetic Field Inside a Solenoid**

- A solenoid is a coil of wire with many turns, creating a nearly uniform magnetic field inside when current flows through it.
- Ampère's Law gives:

$$B = \mu_0 . n . I$$

where:

- B is the magnetic field inside the solenoid.
- n is the number of turns per unit length.
- I is the current flowing through the solenoid.

- **Diagram**: The magnetic field lines inside the solenoid are parallel and evenly spaced, indicating a uniform magnetic field. Outside the solenoid, the field lines spread out and are much weaker.

I.3.3°- Using Ampère's Law in Symmetric Cases

Ampère's Law is particularly useful for calculating magnetic fields in cases with a high degree of symmetry, such as:

- ✓ A long, straight conductor
- ✓ A solenoid or toroid
- ✓ A coaxial cable

Important Note: Ampère's Law is analogous to Gauss's Law in electrostatics. While Gauss's Law relates electric fields to enclosed charges, Ampère's Law relates magnetic fields to enclosed currents.

Example: Magnetic Field Around a Long, Straight Wire

Problem: Calculate the magnetic field B at a distance r from a long, straight wire carrying a steady current I.

Setup and Assumptions

1. We assume the wire is infinitely long, which ensures that the magnetic field $\vec{B}$ is the same at every point equidistant from the wire.
2. By symmetry, the magnetic field lines are circular, centered around the wire, and perpendicular to the wire.
3. We choose a circular path of radius r around the wire as our Amperian loop.

Diagram:

The wire runs vertically, and the magnetic field lines form concentric circles around it. We use the right-hand rule: if you point the thumb of your right hand in the direction of the current, your fingers curl in the direction of the magnetic field.

I.3.4°- Applying Ampère's Law

Ampère's Law states:

$$\oint \vec{B}.\vec{dl} = \mu_0 . I_{Enc}$$

Since the magnetic field $\vec{B}$ is tangential to the Amperian loop and has the same magnitude at every point on the loop, the dot product $\vec{B}.\vec{dl}$ simplifies to $B\,dl$, where B is the magnitude of the magnetic field, and dl is the infinitesimal length along the loop.

Thus, the line integral becomes:

$$\oint \vec{B}.\overrightarrow{dl} = B \oint dl = B.(2\pi r)$$

where $2\pi r$ is the circumference of the circular loop.

I.3.5°- Calculating the Magnetic Field

Substituting into Ampère's Law:

$$B.(2\pi r) = \mu_0.I$$

Solving for B:

$$B = \frac{\mu_0.I}{2\pi r}$$

Explanation

1. The magnetic field BBB decreases as you move further from the wire (B$\propto\frac{1}{r}$).
2. The right-hand rule gives the direction of the magnetic field: if you wrap your right hand around the wire with your thumb pointing toward the current, your fingers curl toward the magnetic field lines.

Numerical Example

Suppose the wire carries a current of 10 A, and you want to find the magnetic field B at a distance of 0.1m from the wire.

1. Given:

   - I=10A
   - r=0.1 m

   - $\boldsymbol{\mu_0}$= 4π×10^{-7} T m/A

2. Calculation:

$$B = \frac{\mu_0.I}{2\pi r} = \frac{(4\pi.10^{-7}).10}{2\pi.0,1}$$

   Simplifying:

$$B = \frac{4.10^{-6}}{0,2} = 2.10^{-5}T$$

$$\Longrightarrow B = 20\mu T$$

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Chapter II:

Radiation

II.1°- Generality

Radiation is the process by which energy is emitted or transmitted in the form of waves or particles through space or a medium. It can occur in various forms, including electromagnetic waves (such as light or radio waves) and particle radiation (such as alpha and beta particles). Radiation is an essential phenomenon in many fields, including physics, medicine, and environmental science.

- **Types of Radiation**
  Radiation is typically classified into two main categories:

  - **Ionizing Radiation**: Radiation with enough energy to remove tightly bound electrons from atoms, thus creating ions. Examples include X-rays, gamma rays, and high-energy particles.
  - **Non-Ionizing Radiation**: Radiation that doesn't have enough energy to ionize atoms but can still excite electrons to higher energy states. Examples include radio waves, microwaves, and visible light.

II.1.1°- **Electromagnetic radiation (EMR)**

II.1.1.1°- Definition and Characteristics

Electromagnetic radiation consists of oscillating electric and magnetic fields propagating through space at the speed of light. This type of radiation does not require a medium to travel and includes a broad spectrum of frequencies, from low-energy radio waves to high-energy gamma rays.

- Electromagnetic (EM) radiation is a form of energy propagated through free space or a material medium through electromagnetic waves. EM radiation is so-named because it has electric and magnetic fields that simultaneously oscillate in planes mutually perpendicular to each other and to the direction of propagation through space.

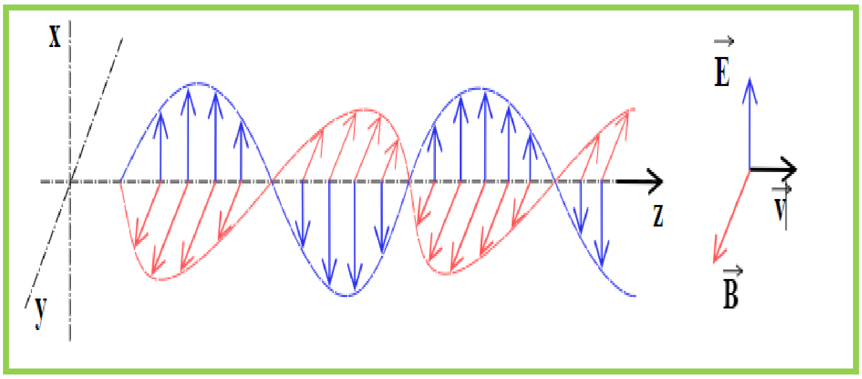


Figure II.1: Electromagnetic waves.

- **Waves** are characterized by **frequency**, **wavelength**, **speed**, and **phase**.
- **Frequency** is the number of waves (cycles) per second that pass a given point in space (symbolized by $\bar{\nu}$).
- **Wavelength** is the distance between two consecutive peaks or troughs in a wave (symbolized by the λ)

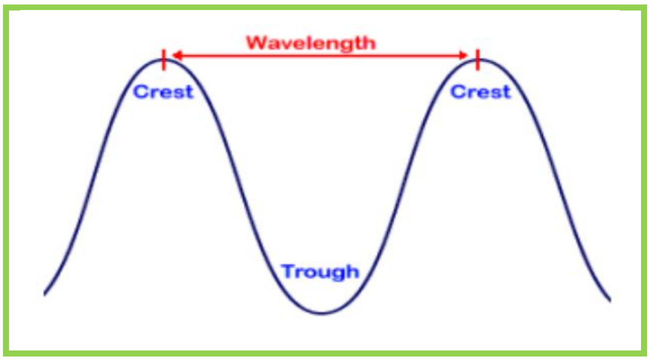


Figure II.2: Wavelength

❖ **Relation between λ and $\bar{\nu}$:**

$$\lambda.\bar{\nu} = c \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (II.1)$$

- Since all types of electromagnetic radiation travel at the speed of light, short-wavelength radiation must have a high frequency.
- Unlike the speed of light and wavelength, which change as electromagnetic energy is propagated through media of different densities, the frequency remains constant and is a more fundamental property.
- Wavenumber is defined as a count of the number of wave crests (or troughs) in a given unit of length (symbolized by ν):

$$\nu = \bar{\nu}/c = 1/\lambda \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .(II.2)$$

- Wavenumber units: inverse length (often in cm-1)
- Frequency units: unit cycles per second 1/s (or s-1) is called hertz (abbreviated Hz)

II.1.1.1°- Electromagnetic Spectrum

The electromagnetic spectrum is divided based on wavelength and frequency:

- **Radio waves**: are used in broadcasting and communications.

- **Microwaves:** Applied in radar and cooking technologies.

- **Infrared Radiation:** Utilized in thermal imaging and remote sensing.

- **Visible Light:** The narrow range detectable by the human eye.

- **Ultraviolet (UV) Light:** Used in sterilization and chemical processes.

- **X-rays and Gamma Rays:** High-energy radiation used in medical imaging and cancer treatment.

II.1.2°- Particle Radiation

II.1.2.1°- Nature of Particle Radiation

Particle radiation consists of subatomic particles that carry energy through space, such as protons, neutrons, and electrons. Unlike electromagnetic radiation, particle radiation requires a medium to travel and is often produced by radioactive materials or nuclear reactions.

- **Types of Particle Radiation**

- **Alpha Particles:** Heavy, positively charged particles emitted by certain radioactive elements.
- **Beta Particles:** High-speed electrons or positrons emitted during radioactive decay.
- **Neutrons:** Uncharged particles released in nuclear reactions, especially in fission processes.

Each type of particle radiation has unique properties and varying penetration capabilities, influencing its application in fields like medicine, industry, and nuclear energy.

II.1.3°- Detection of Radiation

- ***Techniques and Instruments***

etecting radiation is essential for monitoring and measuring radiation in various settings, from medical facilities to nuclear plants. Critical detection devices include:

- **Geiger-Müller Counters**: Detect ionizing radiation by measuring gas ionization within a tube.
- **Scintillation Counters**: Use scintillating materials that emit light when radiation strikes, which is then converted into an electrical signal.
- **Photographic Film**: Historically used in dosimeters to measure accumulated radiation exposure by detecting changes in film opacity.

Each detector is tailored to specific types of radiation, whether ionizing or non-ionizing, and is crucial for maintaining safety and regulatory compliance.

II.1.4°- Energy Spectrum of Radiation

The electromagnetic (EM)spectrum is the distribution of electromagnetic radiation according to energy or, equivalently, according to the wavelength or frequency. The members of the Electromagnetic spectrum in order are:

Radio, TV, Microwaves, Infra-Red, Visible Light, Ultraviolet, X-Rays and Gamma Rays.

Increasing Frequency

Increasing Wavelength

Radio waves have the longest wavelength and the lowest frequency of any member and Gamma Rays have the highest frequency and the shortest wavelength.

Gamma Rays are the highest energy electromagnetic (EM) waves as they have the highest frequency.

Every electromagnetic (EM) spectrum member travels at the same speed in a vacuum. They all travel at the speed of light in the air.

II.1.4.1°- The Visible Spectrum

Visible light is the only member of the EM spectrum which can be seen without special equipment. All other members of the visible spectrum are invisible and have another detection method. This part of the spectrum is the only part the human eye can see. The colors in order are: Red, Orange, Yellow, Green, Blue, Indigo, and Violet.

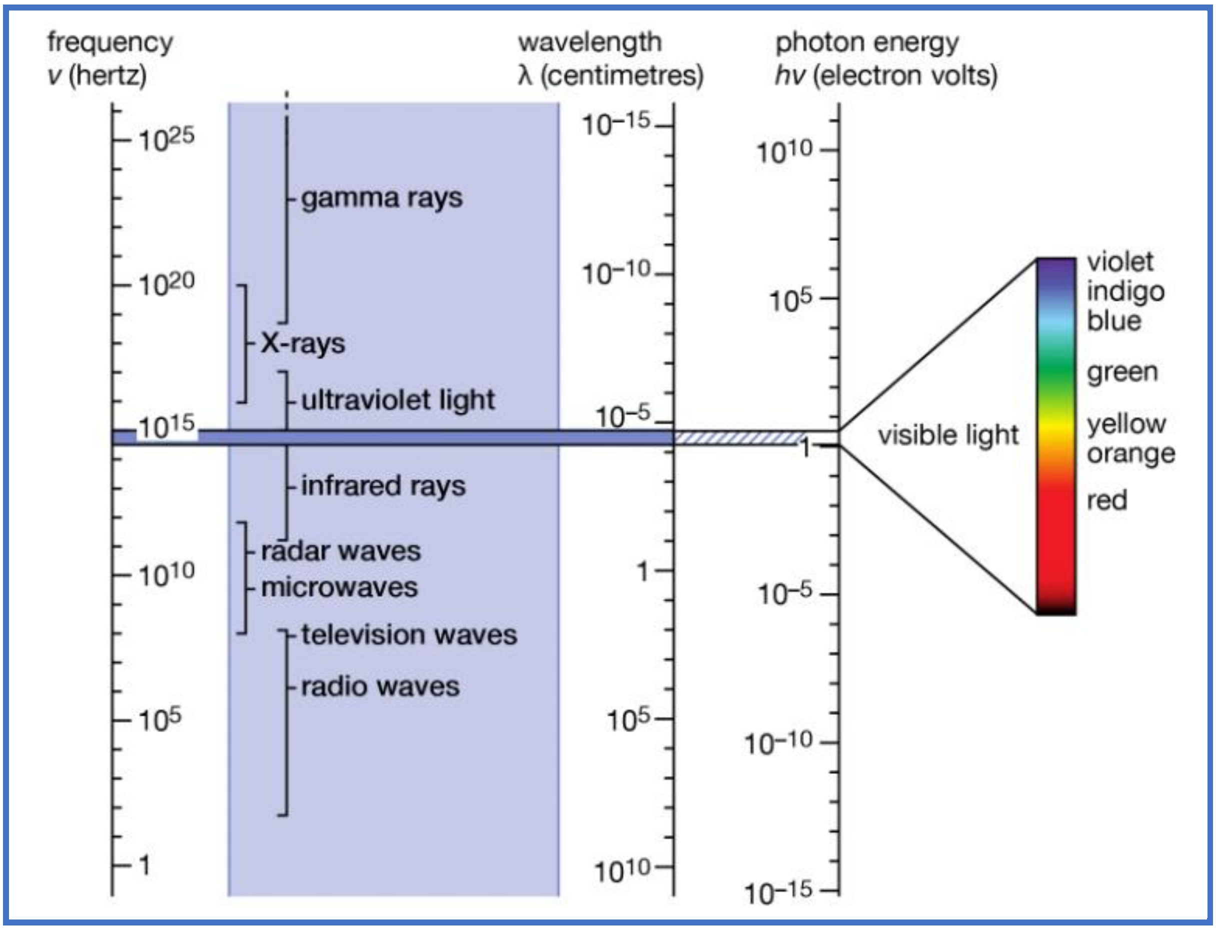


Figure II.3: Schematic representation of the radiation (electromagnetic) spectrum.

NOTE: In remote sensing, the sensor's spectral bands in the visible are often called by their color (e.g., blue, green, and red channels).

Red light has the longest wavelength.

Violet light has the shortest wavelength.

As you go from Red to Violet light, the wavelength decreases, and the frequency and energy increase.

Note: It is referred to as the Visible Spectrum and not a **Rainbow**!!

- **Particulate nature of radiation:**

Radiation can also be described in terms of energy particles called photons. The energy of a photon is given as: $\boldsymbol{\varepsilon}_{Photon} = h\bar{\nu} = {}^{hc}/_{\lambda} = hc\nu$

where h is Plank's constant (h = 6.6256x10^{-34} J s).

• This equation relates the energy of each photon of the radiation to the electromagnetic wave characteristics ($\bar{\nu}$ and λ).

• Photon has energy but it has no mass and no charge.

Example 1: A light bulb of 100 W emits at 0,5 µm. How many photons are emitted per second?

Solution 1: The energy of one photon is $\varepsilon_{Photon} = {}^{hc}/_{\lambda}$, thus, using that 100 W = 100 J/s, the number of photons per second, N, is:

$$\varepsilon = N\varepsilon_{Photon} \Longrightarrow N = {}^{\varepsilon}/_{\varepsilon_{Photon}} = \frac{\varepsilon}{\frac{hc}{\lambda}} \Rightarrow N = \frac{\varepsilon(\mathrm{J.}s^{-1})\lambda(\mathrm{m})}{h(\mathrm{J.s})c(m.\mathrm{s}^{-1})} =$$

$$\Rightarrow N(s^{-1}) = \frac{100.0{,}5.10^{-6}}{6{,}6256.10^{-34}.2{,}9979.10^{8}}$$

$$\Rightarrow N = 2{,}517x10^{20}$$

Example 2: Another light bulb at a wavenumber of 2 µm^{-1} and the number of photons is 3,187.10^{+21}. What is the energy of a light bulb?

Solution 2:

The energy of a light bulb is

$$\boldsymbol{\varepsilon} = \boldsymbol{N\varepsilon_{Photon}} = \mathrm{N}.\frac{hc}{\lambda}$$

$$\Longrightarrow \varepsilon = \ 3{,}187.10^{+21}.6{,}6256.10^{-34}.2.10^{+6}\ 2{,}9979.10^{+8}$$

$$\Longrightarrow \quad \varepsilon = 1266\ \mathrm{J}$$

Example 3:

A third light bulb for 110 J.s^{-1} energy and the number of photons per second is $2{,}89.10^{+20}$. What is the wavelength of a light bulb?

Solution 3:

the wavelength of a light bulb is

$$\varepsilon = N.\varepsilon_{photon} = \mathrm{N}.\frac{hc}{\lambda} \Longrightarrow \lambda = \frac{N.h.c}{\varepsilon}$$

$$\Longrightarrow \lambda = \frac{2{,}89.10^{20}.6{,}6256.10^{-34}.2{,}9979.10^{8}}{110}$$

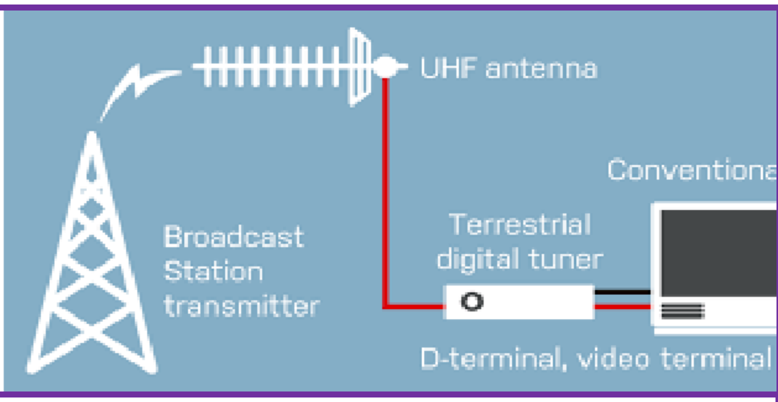
$$\Longrightarrow \lambda = 0{,}518\mu m$$

II.1.4.2°- Practical Uses of Electromagnetic Radiation:

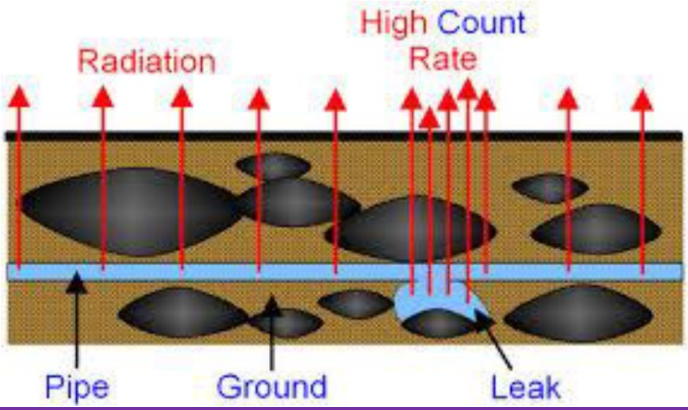
Electromagnetic Radiation	Application
Radio waves	Radio Telescopes. Wireless radio transmission.
TV waves	Terrestrial TV signals.
Microwaves	Cooking food. Speaking on mobile phones.
Infra-Red	Thermal imaging cameras for the Police and Fire Services. Physiotherapists are used to treat muscle Injuries.
Visible Light	Needed to see anything.
Ultraviolet	Used to treat skin conditions. Vitamin D3 for the brain. Security markings on property.
X-Rays	Checking for broken bones. Scanning airport luggage.

Gamma rays ($\gamma - Rays$)	Radioactive tracers in medicine and leaking underground pipes. Sterilizing hospital equipment.

Examples of these electromagnetic radiation applications are shown below:

	Radio and TV transmission.
	Microwave Oven cooking
	A firefighter uses an Infrared
	A UV pen can be used on property. This marking can only be seen when illuminating with a UV light.

A person going through airport security and having their baggage scanned by an X-Ray machine.



Putting Gamma Radiation through a cracked water pipe to find the location of a leak.

II.1.4.3°- EM Radiation Detectors:

Visible light is the only member of the EM spectrum which can be seen without special equipment. All other members of the spectrum are invisible and have another method of detection.

Radiation	***Detector***
Radio & TV	Aerial, Radio Telescope
Microwaves	Aerial, Radio Telescope
Infrared	Thermometer, Skin
Visible Light	Eyes, Solar Cell
Ultraviolet	Photographic Film
X-Rays	Photographic Film
Gamma Rays	Geiger – Muller Tube

Examples of these electromagnetic Radiation Detector applications are shown below:

	Radio Telescopes are used to pick up radio, TV and microwaves.
	Solar cells will convert (visible) light energy into electrical energy.
	A Geiger – Muller Tube and counter. This will detect ionising radiation such as Gamma Rays.

II.1.4.4°- Safety Precautions with Electromagnetic (EM) Radiation:

Gamma Radiation should not be handled with your bare hands, tongs or forceps should be used. It should not be pointed at your body, particularly your eyes.

Radiographers stand behind a lead-glass screen when they are taking an **X-ray**. This is to reduce their exposure to the radiation emitted.

Too much exposure to **ultraviolet radiation** over some time can lead to skin cancer.

Looking directly into sunlight **(visible light)** can damage your sight.

Too much exposure to **Infrared radiation** (heat radiation) can burn bare skin.

Microwaves used in mobile telephone communication can affect sperm levels. It is recommended that men do not walk about with their mobile phones in their trouser pockets.

II.1.5°- Photoemissive Cell

Photoemissive cells are of two types (a) vacuum type and (b) gas-filled type.

The features in photoemissive cells are.

(i) A sensitive surface for the cathode

(ii) The anode at high potential

(iii) A suitable gas for the gas-filled photoelectric cells.

The vacuum-type photo-emissive cell consists of a thin glass or quartz bulb that is highly evacuated and contains a semi-cylindrical plate C coated with potassium or cesium which serves as a photocathode and a nickel or platinum wire A which serves as the anode. The positive potential is applied to the anode by the battery B which is connected between the anode and cathode through a rheostat R and a galvanometer (or microammeter) G. When light of frequency greater than the threshold frequency is incident on photocathode C, photoelectrons are emitted and attracted by the anode A. The photoelectric current thus produced in the circuit is tiny and detected by the galvanometer G. As the potential of the anode is increased, the photoelectric current increases until saturation occurs. As the number of electrons emitted depends upon the intensity of incident light, the variation in light intensity produces a corresponding change in the photoelectric current.

The vacuum cells are extremely accurate in their response to incident light and the photoelectric current is proportional to the intensity of the incident beam. Such cells are generally employed for photoelectric measurements, where no lag of time should occur between the incidence of light and the response of the photoelectric cells. They are suitable for the accurate comparison of intensities of light and are used in television and photometry.

In a vacuum-type cell, the photoelectric current is usually minimal. To enhance this current, the cell can be filled with an inert gas, such as helium or neon, at a pressure ranging between 0.1 to 1 mmHg. In gas-filled photoelectric cells, the presence of the gas amplifies the current due to the ionization process that occurs when ejected photoelectrons collide with gas molecules, generating additional electrons. However, a limitation of these cells is that the photoelectric current does not always vary linearly with light intensity, which can affect measurement accuracy.

In industrial applications, gas-filled cells with cesium oxide are commonly preferred for their superior sensitivity. These cells consist of a cylindrical silver cathode with a thin layer of cesium, approximately one molecule thick, applied in an oxygen atmosphere. The anode is a rod positioned parallel to the cylinder’s axis, optimizing the cell’s response to light exposure.

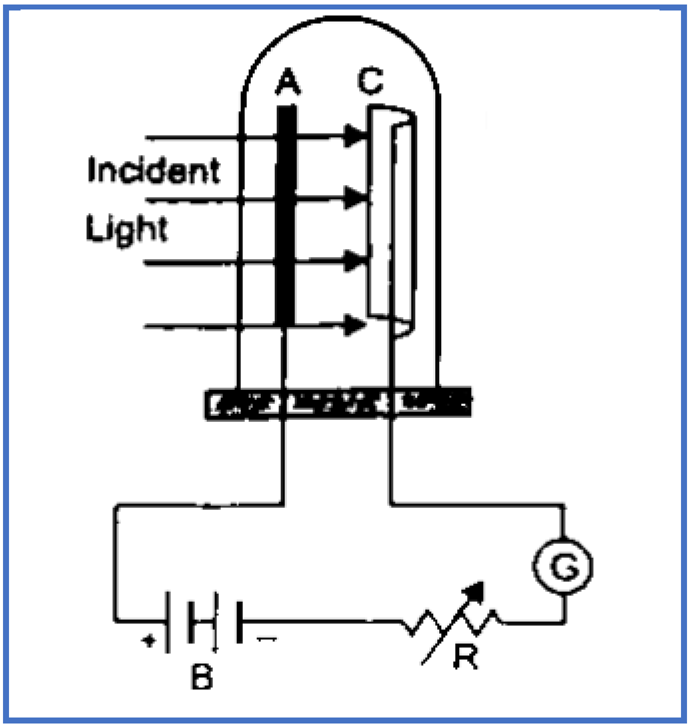


Figure II.4: Schematic representation of the Photoemissive Cell

II.1.5.1°- Principle and Function

A photoemissive cell is a device that converts light into an electric current by exploiting the photoelectric effect. When photons strike a photoemissive material, they can transfer enough energy to electrons to cause their emission, generating a current that can be measured.

II.1.5.2°- Applications of Photoemissive Cells

- Photometry: Measuring light intensity for various scientific and industrial applications.
- Automatic Lighting: Used in light-sensitive switches for street lighting.
- Photomultipliers: Used in scientific instruments to amplify weak light signals, crucial in fields such as astronomy and particle physics.

II.2°- Production of X-ray

*II.2.*1°- Discovery of X-ray

• Discovered in 1895 by a German physicist named Wilhelm Conrad Röntgen.
• while studying cathode rays (stream of electrons) in a gas discharge tube.
• He observed that another type of radiation was produced (presumably by the interaction of electrons with the glass walls of the tube) that could be detected outside the tube.

• This radiation could penetrate opaque substances, produce fluorescence, blacken a photographic plate, and ionize a gas.

• He named his discovery "x rays" because "x" stands for an unknown.

*II.2.*2°- Properties of X-ray

✓ X-rays are invisible.
✓ X-rays have no mass.

✓ X-rays travel at the speed of light in a vacuum

✓ X-rays travel in straight lines.

✓ They have a very short wavelength

✓ They are unaffected by electric and magnetic fields

✓ They cannot be refracted.

✓ They cause ionization (adding or removing electrons in atoms and molecules)
✓ They are transmitted by (pass through) healthy body tissue

✓ They affect photographic film in the same way as visible light (turning it black)

✓ They are absorbed (stopped) by metal and bone

✓ They can cause photoelectric emission

✓ They are produced when a beam of high-energy electrons strikes a metal target

• **These properties make X-rays very useful for medical diagnosis and treatment.**

*II.2.*3°- X-ray Tube

• X-rays are produced in the X-ray tube, which is located in the x-ray tube head.

• X-rays are generated when electrons from the filament cross the tube and interact with the target.

• The two main components of the X-ray tube are the **cathode** and the **anode**.

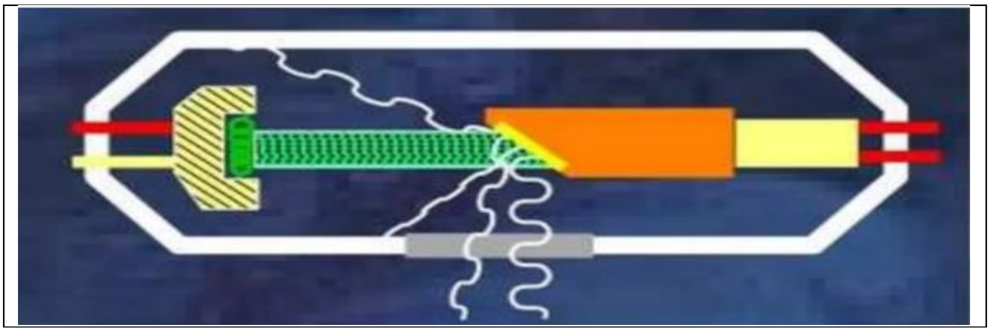


Figure II.5: Schematic representation of the X-ray Tube

II.2.3.1°- Cathode

• The cathode is composed of tungsten filament centered in a focusing cup.

• Electrons are produced by the filament and are focused on the target of the anode where the X-rays are produced.

• The focusing cup has a negative charge, like the electrons and helps direct the electrons to the target (focuses them, electrons can be focused -ray cannot).

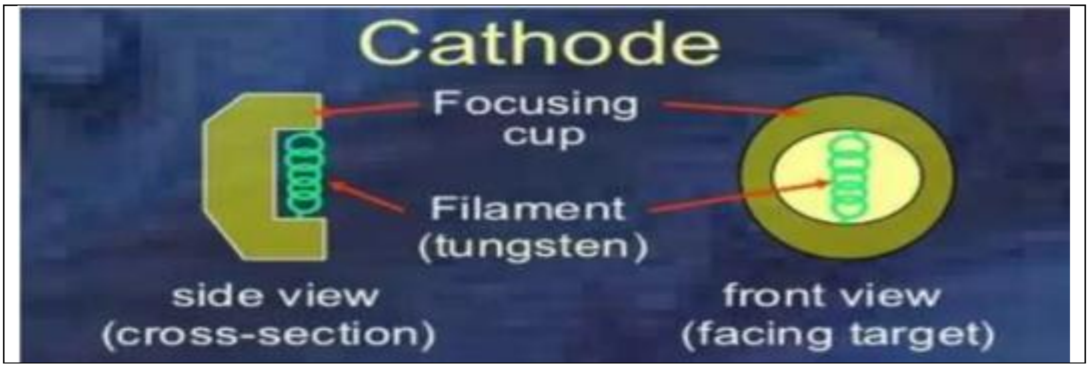


Figure II.6: Schematic representation ***Cathode*** of the X-ray Tube

II.2.3.1°- Anode

• The anode in the X-ray tube is composed of a tungsten target embedded in a copper stem.

• When electrons from the filament enter the target and generate X-rays a lot of heat is produced.

• The copper helps to take some of the heat away from the target so that it doesn't get too hot.

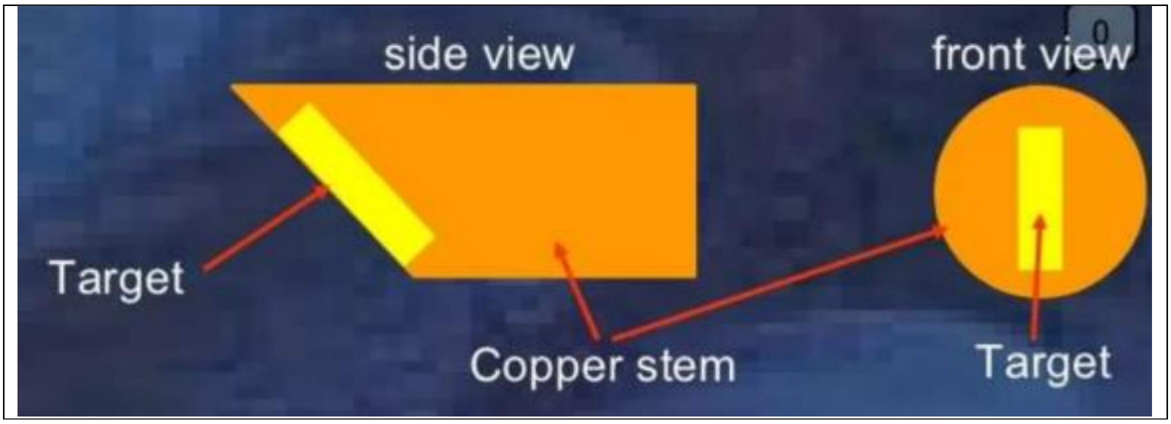


Figure II.7: Schematic representation ***Anode*** of the X-ray Tube

II.2.4°- Why Tungsten?

• The choice of tungsten as the target material in conventional X-ray tubes is based on the criteria that the target must have a high atomic number and high melting point.

• The efficiency of X-ray production depends on the atomic number, and for that reason, tungsten with Z = 74 is a good target material.

• It has a melting point of 3370°C and is the element of choice for standing intense heat produced in the target by the electronic bombardment.

II.2.5°- Production of X-rays

■ X-rays are produced when rapidly moving electrons accelerated through a potential difference of order 1 kV to 1 MV strike a metal target.

■Electrons from a hot element are accelerated onto a target anode.

■The source of electrons is the cathode or negative electrode. Electrons are stopped or decelerated by the anode or positive electrode. Electrons move between the cathode and the anode because there is a potential difference in charge between the electrodes.

■ When the electrons suddenly decelerate on impact, some kinetic energy is converted into EM energy, such as X-rays.

Less than 1% of the energy supplied is converted into X-rays during this process. The rest is converted into the target's internal energy.

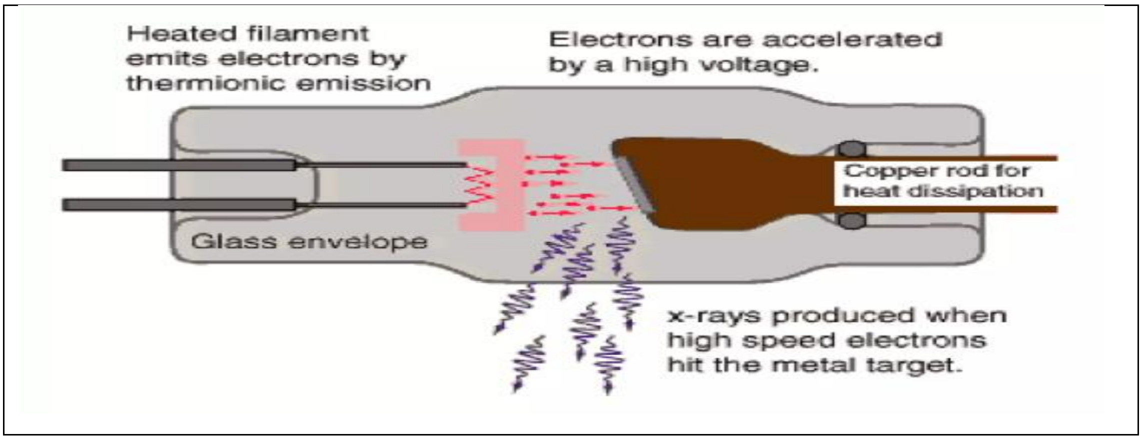


Figure II.8: Schematic representation of the *production of X-rays*

II.2.6°- Characteristics X-ray

• When the energy of an electron incident on the target exceeds the binding energy of an electron of a target atom, it is energetically possible for a collision interaction to eject the electron and ionize the atom.

• The unfilled shell is energetically unstable, and an outer shell electron with less binding energy will fill the vacancy.

• As this electron transitions to a lower energy state, the excess energy can be released as a characteristic x-ray photon with an energy equal to the difference between the binding energies of the electron shells

• With higher-atomic-number targets and the transitions involving inner shells such as K, L, M, and N.

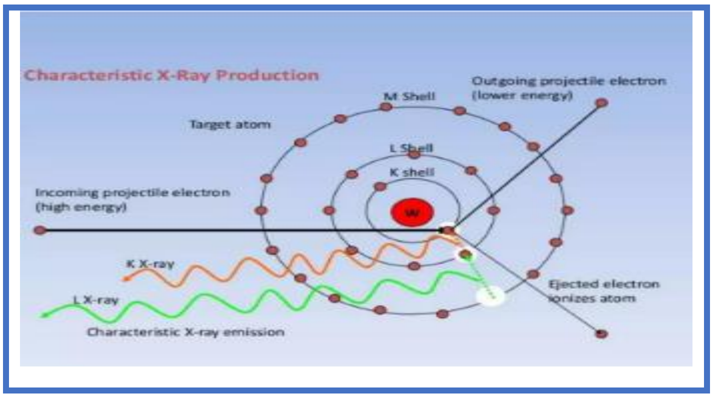
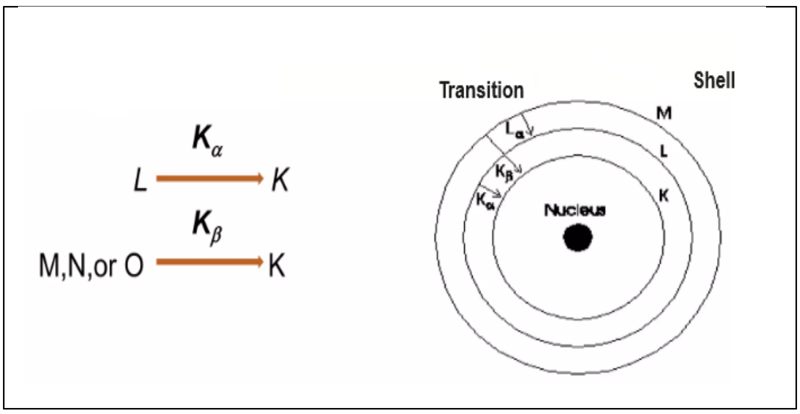


Figure II.9: Schematic representation of the production of X-rays as electrons transition

➢ Characteristic Cascade

• The shell capturing the electron designates the characteristic x-ray transition, and a subscript of α or β indicates whether the transition is from an adjacent shell (α) or nonadjacent shell (β).



• A K_β x-ray is more energetic indices K_α an x-ray.

• Within each shell (other than the K shell), there are discrete energy sub-shells, which result in the fine energy splitting of the characteristic x-rays.

• For tungsten, three prominent lines on the Bremsstrahlung spectrum arise from the $K_{\alpha 1}$, $K_{\alpha 2}$ and $K_{\beta 1}$ transitions.

• The filtered spectrum of Bremsstrahlung and characteristic radiation from a tungsten target.

• The specific characteristic radiation energies from K_α and K_β transitions.

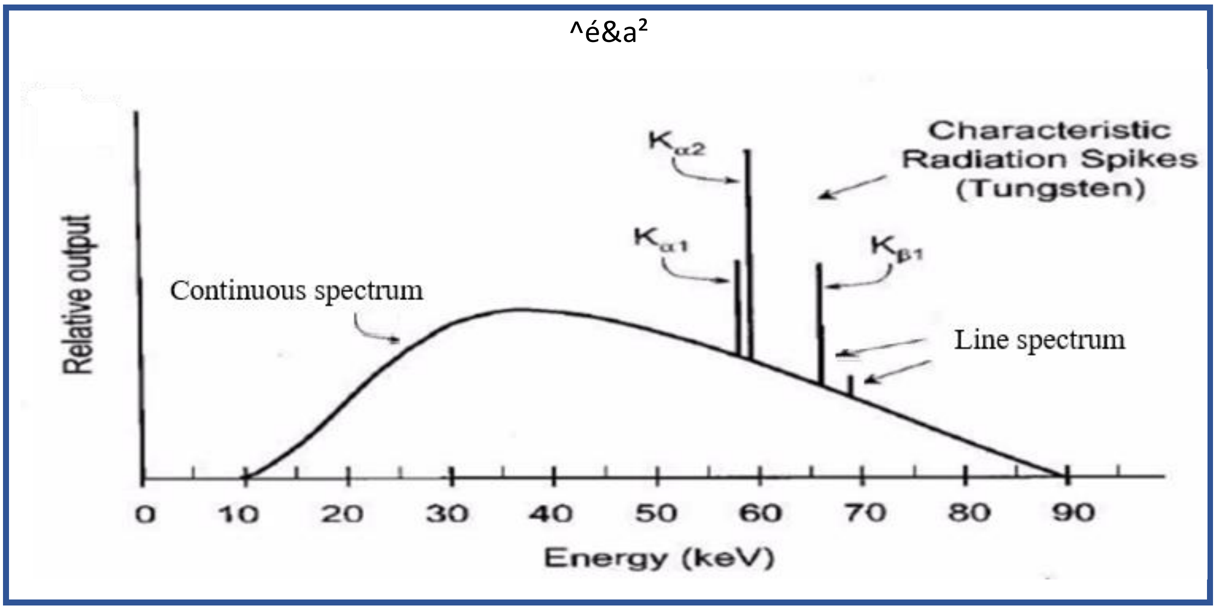


Figure II.10: Plot of the characteristic radiation energies for K_α and K_β transitions.

The spectral study of the emitted X-rays shows that they are formed by the superposition of a continuous spectrum and a line spectrum. These two components correspond to two very distinct emission mechanisms.

- Interaction of accelerated electrons with the target nuclei (continuous spectrum or Bremsstrahlung spectrum).

- Ionization of the deep layers of the target atoms (line spectrum).

➢ **The Continuous X-ray Spectrum**

Imagine an electron with an initial kinetic energy of E_0 colliding with (interacting with) one of the target atoms, as shown in Figure 3. The electron may lose energy ΔE, which can result in the emission of an X-ray photon that radiates away from the collision site. (There is very little energy transferred to the recoil of the atom because of its relatively large mass so it can be neglected.) This continuous X-ray spectrum is called the Bremsstrahlung.

- **The spectrum of characteristic rays (line spectrum)**

These peaks are generated in a two-part process. First, an energetic electron hits an atom of the target and expels an electron from a deep shell (low value of n) of the atom during its scattering. If the electron of the atom were in the shell defined by n = 1 (called for historical reasons the K shell), it would leave a hole in this shell. Second, an electron in one of the higher energy shells fills the hole in the K shell. During this transition, the atom emits a characteristic X-ray photon.

If the electron that fills the K shell vacancy comes from the shell where n = 2 (called the L shell), the radiation emitted is the K_α line; if it comes from the shell where n = 3 (called the M shell), it produces the K_β line ...etc. The hole left in the L or M layer will be filled by an electron coming from a higher layer of the atom, figure II.9.

II.2.7- Tungsten 74

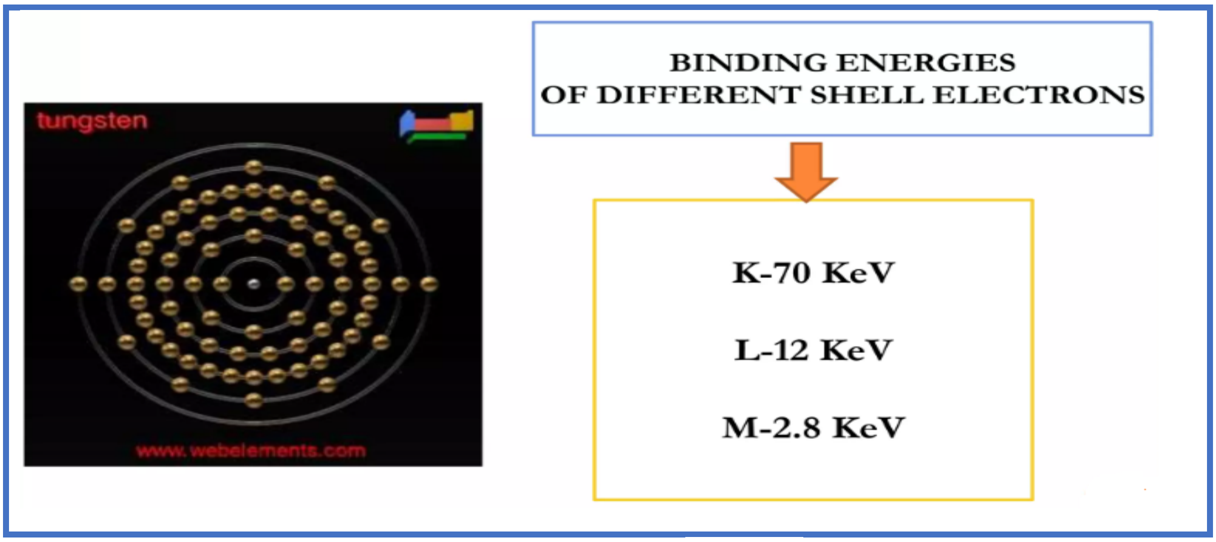
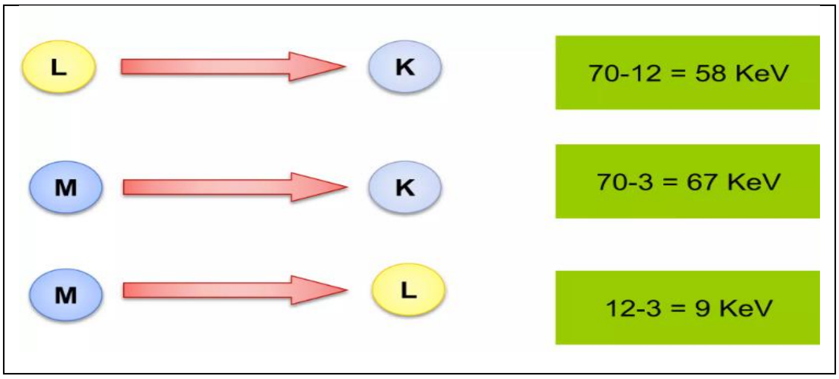


Figure II.11: Schematic representation of the Tungsten 74 and binding energies.



$$E_{P\,Xray} = E_K - E_L$$

II.2.8°- X-ray Emission Spectrum

- If a relative number of x-ray photons were plotted as a function of their energies we can analyze the x-ray emission spectrum.
- Understanding the X-ray emission spectra is key to understanding how changes in kV, mA, time, and filtration affect the optical density and contrast of the radiograph..

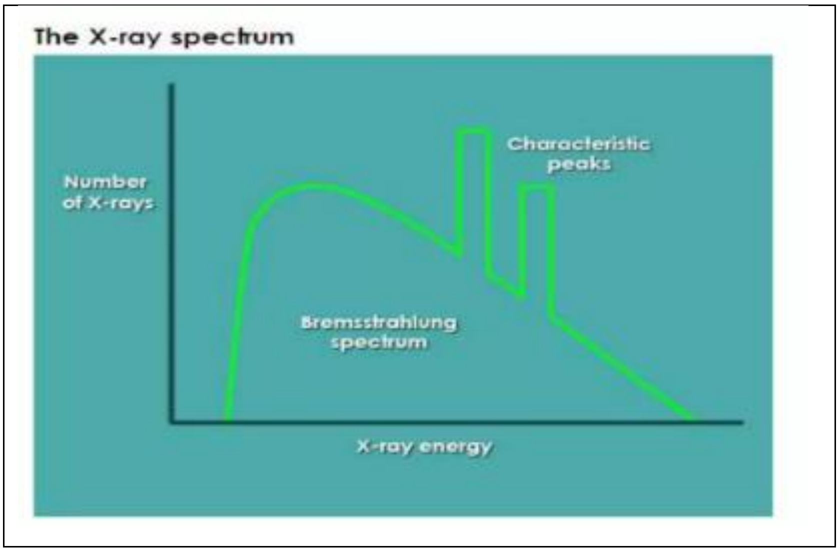
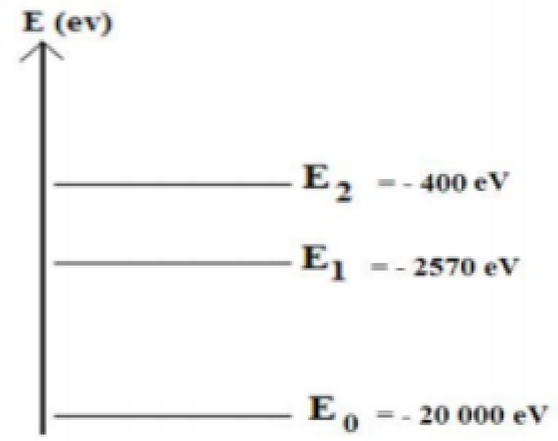


Figure II.12: Plot of the X-ray spectrum.

Exercise

X-rays

A metal emits an X-ray photon due to specific electronic transitions between two energy levels. The energy level diagram of molybdenum is given below.



1. Electronic transitions.

1.a. Reproduce the diagram above and indicate with arrows all the Possible transitions that are accompanied by the emission of a photon.

1.b. Calculate in electron volts (eV) the energy variations corresponding to these transitions.

2 The energy E transported by an X-ray photon associated with radiation of frequency v is given by the Planck relation: $E = h.v$.

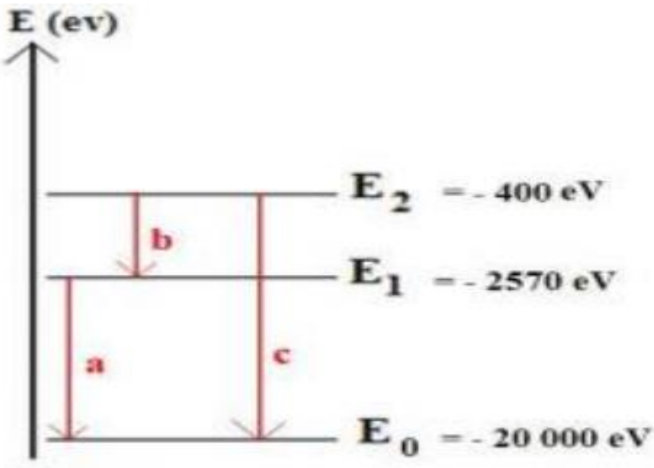
2.a. Knowing the energy E transported by an X-ray photon gives the relation allowing the wavelength 2 of the associated radiation to be determined.

2.b. Which of the transitions is considered to produce the X-ray photon associated with the radiation with the smallest wavelength? Justify.

2.c. Calculate the value of this wavelength.

Solution:

1.a. All the Possible transitions that are accompanied by the emission of a photon.



1.b. We calculate in electron volts (eV) the energy variations corresponding to these transitions

a: $Ea_{h\nu} = E_1 - E_0 = 17430 eV$

$b: Eb_{hv} = E_2 - E_1 = 2170eV$

$c: Ec_{hv} = E_2 - E_0 = 19600eV$

2.a. We give the relation allowing the wavelength

$$E = h\nu = \frac{hc}{\lambda} \Longrightarrow \lambda = \frac{h.c}{E}$$

2.b The smallest wavelength corresponds to the highest energy since a is inversely proportional to E. It is therefore that of the transition $c: Ec_{hv} = E_2 - E_0 = 19600eV$

2.c $Ec_{hv} = 19600eV = \mathrm{h.c}\ 19600\mathrm{x}1.6\ \mathrm{x}10^{-19} = 3.14\ 10 - 15\ \mathrm{J}$

therefore $\lambda = \frac{h.c}{E} = 6.3\ \mathrm{x}10^{-11}\mathrm{m}$

Note: This is an X-ray photon since $5\ .10^{-12}\mathrm{m} < \lambda < 10^{-8}$ m

II.2.8°- Industrial applications of X-rays

Let us recall their main uses:

- X-ray generators and gamma graphs are used for non-destructive testing of parts, welded structures, or engineering structures;
- accelerators are used in particular for sterilizing medical products, modifying polymer properties, initiating the polymerization of resins, sterilizing food;
- gamma irradiators are mainly used for food preservation.

Numerous other applications involve artificial radioelements, so only a few examples will be given here.

- **Thickness measurements**

Thickness measurements are carried out using equipment that can use two different techniques, depending on the applications:

- beta or gamma transmission,
- beta or gamma backscattering.

In the first case, the source and the detector are on either side of the part to be tested; in the other, they are on the same side. Transmission measurement is the most commonly used. The other is generally used only when there is difficulty in accessing both sides of the sample or when measuring deposit thicknesses. The most frequently used radioelements are cobalt 60, krypton 85, strontium 90, caesium 137, promethium 147 and americium 241. Activities can vary from 1 GBq to a few hundred GBq or tens of millicuries to a few curies.

- **Level measurements**

A gamma radiation source and a detector are placed on either side of the container whose level is to be controlled. The intensity of the radiation received by the detector decreases when the container's contents are located between the source and the detector, which makes it possible to trigger the desired actions, such as an alarm, stopping the filling, or starting a manufacturing process. More sophisticated systems make it possible to create high- and low-level servo controls or alarms.

Level measurements involving radioactive sources are used in the implementation of very varied processes when:

- high precision in level measurement is required (bottling of beverages, perfumes);
- the containers are opaque (chemical industry, filling of gas tanks, filling of metal cans with beverages, ...etc.);
- the levels are challenging to assess by conventional means (solid material hoppers).

➢ **Soil moisture and density measurement**

Americium-beryllium sources emit neutrons, and cesium-137 sources emit gamma rays, determining the nature of soils in civil engineering or subsoils in prospecting activities. The neutrons emitted by Am-Be sources are slowed down by collisions with light atoms present in the environment, mainly hydrogen. Their detection makes it possible to determine the presence of water or hydrocarbons. The detection of gamma rays emitted by cesium makes it possible to determine the density of soil or rocks.

➢ **X-ray fluorescence alloy analyzers**

X-ray fluorescence analyzers are widely used in the field to determine the composition of alloys and sort them quickly. They are also used in the laboratory for sample assays, particularly for impurity detection, given the devices' high sensitivity and high precision when adapted to a particular problem. These devices are based on detecting X-ray lines characteristic of atoms whose fluorescence is excited by low-energy photons. Therefore, the energies of the detected X-ray lines indicate the elements present in the analyzed sample, while the heights of the peaks give the quantities present.

➢ **Electron capture detectors**

Electron capture detectors are widely used in gas chromatography. The gas from the chromatograph passes into an ionization chamber that contains a source of nickel-63 or tritium, which emit beta rays. When a compound with a high affinity for electrons passes through the chamber, the ionization current drops.

➢ **Various uses of radionuclides in sealed sources**

Some applications, such as smoke detectors or surge protector tubes, are widespread since several hundred thousand devices are sold yearly. Smoke detectors are equipped with a harmless source of americium 241 of about 37 kBq (1 u.Ci) in a device placed on the ceiling of a room. However, to keep these devices under control, their sale to the general public is prohibited.

- **Use of radionuclides in unsealed sources**

The use of unsealed sources in the non-medical field is highly varied, both in research and industrial or earth science applications. They can be used as markers to carry out hydrology studies, process controls in the chemical industry, monitor the wear of mechanical parts or search for pipeline leaks.

II.3°- Radiation–matter interactions (Photon-matter interaction)

When a beam of photons penetrates matter, we see that the number of photons that constitute it decreases. Photons interact with electrons in matter. During a photon-electron interaction, part of the photon's energy is transferred to the electron. The processes concerning the fate of the electron, which recedes, will be described subsequently: collision and braking. The remaining energy is found in the form of scattered photons, which are different from the energy and direction of the incident photons.

These absorption and attenuation phenomena are the basis of the applications of X-ray and Y-ray beams, whether in radiodiagnosis or radiotherapy. We will first study the different modes of photon-electron interaction and then the associated probabilities.

***II.3.1*°- Photoelectric effect**

It is a process of absorption by an atom of the entire energy of the incident photon. This energy E_{ν} is correlated and communicated to a deep electron of connection energy E_{ci} which is ejected from its electronic shell. The excess energy if accident there is an appeal form of kinetic energy E_k communicated to the electron:

$$E_k = E_{\nu} - E_{ci} \dots\dots\dots\dots\dots\dots\dots\dots\dots..(II.3)$$

The photoelectric effect can only exist if the energy provided by the photon is greater than the electron's binding energy, and it is all the more likely that these two energies are close. The ionization of the *layer* is followed by an atomic reorganization in which fluorescence X-ray photons and (or) Auger electrons are emitted.

As electrons have relatively short paths in matter, we can consider that their energy is completely deposited in the medium. Furthermore, the photons accompanying the atomic reorganization have relatively low energies and in any case in the range of binding energies of the electrons in the medium and have a significant probability of interaction. It is therefore possible to recover almost all or even all of the energy of the incident photon in the form of kinetic energy of electrons.

Photoelectrons are emitted in all directions in space, but with a preferential direction which depends on the energy hv of the incident photon. For low-energy photons, the distribution is practically symmetrical at about $\theta = 90°$, where θ is the angle between the direction of the incident photon and that of the emitted electron. As $h\nu$ increases, θ tends towards zero.

II.3.2°- Compton effect (incoherent diffusion)

The incident photon of energy E_ν interacts with a quasi-free electron (loosely bound) which carries away part of the incident energy. A scattered photon carries away the remaining energy.

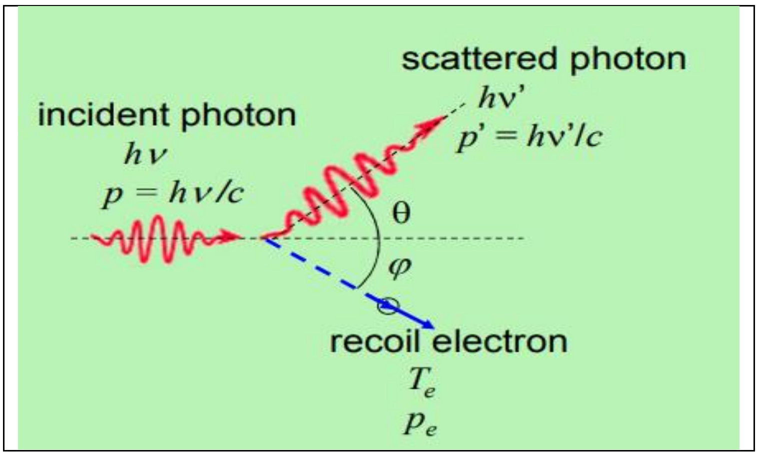


Figure II.13: Schematic representation of the Compton effect.

The conservation of energy and momentum allows us to derive practical formulas:

$$E_\nu = E_{\nu\prime} + T_e \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.4)$$

$$\overrightarrow{P_\nu} = \overrightarrow{P_{\nu\prime}} + \overrightarrow{P_e}$$

We set $E_o = m_e c^2$, we end up with:

$$\frac{E_0}{E_{\nu\prime}} - \frac{E_0}{E_\nu} = 1 - \cos\theta \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.5)$$

from where :

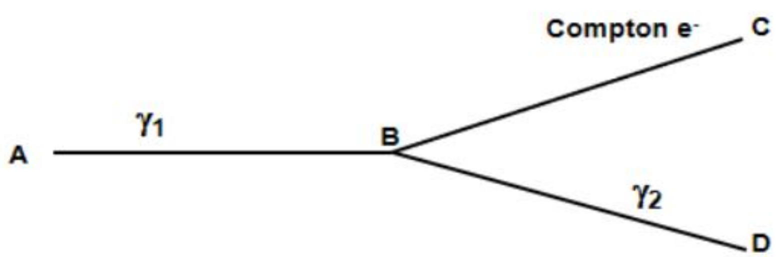
$$\frac{c}{\nu\prime} - \frac{c}{\nu} = \lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta) = \lambda_c\,(1 - \cos\theta)$$

With $\lambda_c = \frac{h}{m_e c}$ called Compton wavelength, aver $\lambda_c = 2.426\,.10^{-12} m$

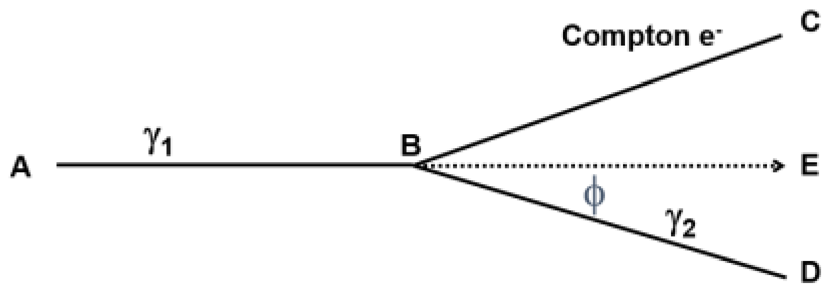
if $\theta = 0$ then Te = Ev - Ev = 0

if $\theta = \pi$ then $T_{e,max} = E_n u + E_{\nu\prime}$, in this case, we speak of retro diffusion of the photon to the electron.

Example: In the diagram below, which angle is an angle θ?



Answer: One must extend the incidence line from A to B to E (refer to the diagram below). The angle θ is between incidence (ABE) and deflection (ABD), that is, angle EBD. There is no reason to assume that angle EBC and angle EBD are equal, even though they appear in the diagram.



II.3.3°- Materialization effect

In the intense electric field that reigns near a nucleus, the photon can materialize as an electron and a positron, one with a positive charge and the other with a negative charge. The conservation of energy is then written as:

$$E_\nu = 2E_0 + T_{e^+} + T_{e^-} \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.6)$$

It is therefore necessary to verify E, ≥ 2Eo = 2×511 keV = 1.022 MeV. This reaction cannot take place in a vacuum.

This reaction cannot take place in a vacuum. The electron and positron then lose their kinetic energy in the medium. When the latter finds itself at rest, we then have a phenomenon of annihilation of the positron with an electron in the middle:

$$e^+ + e^- \longrightarrow 2\gamma\ (511keV)$$

There is then the emission of two photons of 511 keV at 180° from each other.

Quiz question 1: True/False: In Pair Production, the electron pair is emitted at a 180o angle to each other

Answer: False. The angle is indeterminate.

Quiz question 2: True/False: High kinetic energy positrons immediately annihilate electrons in matter

Answer: False. A highly energetic positron will collide with whatever is in its path, undergoing ionization events as it loses energy. It can undergo annihilation only when its kinetic energy has been reduced to a shallow level.

II.4°- Attenuation – Protective screen:

We are interested in the interaction of a set of photons (photon beam γ or X) with matter, by characterizing their attenuation as a function of thickness.

II.4.1°- Law of exponential attenuation:

In the case of a collimated monochromatic beam (thin, parallel) of γ or X rays, the number of emerging rays N(x) having undergone no interaction in crossing a *protective* screen of thickness x(cm) is linked to the number of incident rays N_0 by the relation:

$$\boldsymbol{N(x) = N_0 . e^{-\mu x}} \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.7)$$

1) μ is the linear attenuation coefficient, or: the probability of interaction per unit of length its unit is cm^{-1}.

μ depends on: The energy of the incident photons: the higher E, the higher μ of the nature of the material: **Z, ρ (bone ≠ water ≠ tissues…………).**

Remarks :

- ✓ The number of photons having interacted with matter is therefore:

$$N_{inter}(x) = N_0 - N_0 e^{-\mu x} = N_0(1 - e^{-\mu x})\boldsymbol{N(x) = N_0 . e^{-\mu x}} \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.8)$$

- ✓ Since the photons considered are monochromatic, an analogous relationship links the incident energy (I_0) of the beam and its energy after passing through a thickness x:

$$I_x = I_0 e^{-\mu x} \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.9)$$

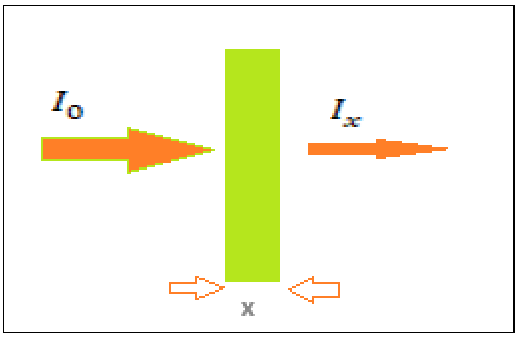


Figure II.14: Schematic representation of the *exponential attenuation*.

- ❖ If the beam passes through several media with different attenuation coefficients: $\mu_1, \mu_2, \mu_3 \dots\dots\dots, \mu_i$, over thicknesses $x_1, x_2, x_3 \dots\dots, x_i$, the number of emerging rays will be:

$$N(x) = N_0 . e^{-(\mu_1 . x_1 + \mu_2 . x_2 + \cdots + \mu_i . x_i)} \Longrightarrow N(x) = N_0 . e^{-\sum \mu_i . x_i} I_x = I_0 e^{-\mu x} \ldots\ldots\ldots\ldots (II.10)$$

2) Mass attenuation coefficient: To consider a material's density, it is practical to use the mass attenuation coefficient, which is the density of the material: μ / ρ where ρ is the density of the material. The mass attenuation coefficient can be independent of the material's solid, liquid, or gaseous state. In this case, the law of attenuation is written:

$$N(x) = N_0 . e^{-\frac{\mu}{\rho} m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots (II.11)$$

with $\rho . x$, mass per unit surface of the material considered (unit: kg.m^{-2})

Note: in a vacuum, a beam of electromagnetic radiation emitted from a source loses its intensity because of the divergence in space of this beam; at the distance d from the source, the intensity is:

$$I_x = \frac{I_0}{d^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (II.11)$$

II.4.2°- Half-attenuation layer:

We call the half-attenuation layer (**HAL**) or half-thickness ($x_{\frac{1}{2}}$, expressed in cm) the thickness of material necessary to attenuate by a factor of 2 (halve) the initial number of photons (or their energy initial) :

$$HAL = x_{\frac{1}{2}} = \ln 2 / \mu \quad (unit: m) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (II.12)$$

The thickness of the protective screen depends on its nature, the nature of the ionizing radiation (X or γ photons) and its energy.

II.4.3°- Other relation for attenuation law:

$$\begin{cases} N(x) = N_0 e^{-\mu x} \\ HAL = \ln 2 / \mu \end{cases} \Rightarrow \mu = \ln 2 / HAL \quad \Rightarrow N(x) = N_0 . e^{\ln 2 . x / HAL}$$

$$N(x) = N_0(e^{ln2})^{\frac{-x}{HAL}} = \frac{N_0}{(e^{ln2})^{\frac{x}{HAL}}}$$

$$\Rightarrow \quad \boldsymbol{N(x)} = \frac{\boldsymbol{N_0}}{\boldsymbol{2^{\frac{x}{HAL}}}} \dots\dots\dots\dots\dots\dots\dots\dots\dots..(II.13)$$

Example:

A laboratory technician is using an X-ray device that emits X-rays with an initial intensity I_0=1000 mR/h (milli-Roentgen per hour). The technician places a protective lead screen in front of the device to reduce the intensity of the X-rays.

The lead screen is 2 mm thick, and the half-attenuation layer (HAL) for the lead for X-rays is known to be 1.5 mm.

Calculate the remaining intensity I of the X-rays after passing through the lead screen.

If the technician wants to further reduce the intensity of the X-rays to 10 mR/h, what additional thickness of lead (or equivalent) must be placed in front of the device?

Solution:

1. Calculate the Remaining Intensity after The First Screen:

The intensity of radiation after passing through a material can be calculated using the formula:

$$I(x) = I_0 . e^{ln2.x}/_{HAL}$$

Where:

I_0 is the initial intensity.

x is the thickness of the material in mm.

HAL is the half-attenuation layer in mm.

Substitute the values provided into the formula to find the remaining intensity I after passing through 2 mm of lead.

$$I(2mm) = 1000. e^{ln2.2}/_{1.5} = 2519.8421\, mR/h$$

2. Determine Additional Thickness needed for Further Reduction:

To find the additional thickness needed to reduce the intensity from the obtained value to 10mR/h, rearrange the formula for (I):

$$\boldsymbol{I(x) = \frac{I_0}{2^{\frac{x}{HAL}}} \rightarrow 2^{\frac{x}{HAL}} = \frac{I_0}{I(x)} \rightarrow 2^{\frac{x}{0.5}} = \frac{1000}{10} = 100 \rightarrow 2^x = 100^{1.5} = 1000}$$

$$x = \frac{ln1000}{ln2} \rightarrow x \approx 10mm$$

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