Republic of Iraq
Ministry of Education
General Directorate of Curricula

# PHYSICS 6

## Scientific Secondary

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**Second Translated Edition** **2023/1445**

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*Translated from 7th Arabic Edition*


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# Introduction

*Dear male students…*
*Dear female students…*

*This book represents support of pillars for developing the physics curriculum that works to achieve scientific and practical aims, and keep stride with the scientific development in information and communication technology. This book also achieves a link to the facts and concepts that student studies with the realities of his daily community life.*

*This curriculum aims at many objectives:*

1. *Providing the student with the methodology of scientific thinking and moving it from education based on memorization to self-learning mixed with fun and excitement.*
2. *Attempting to train the student in exploratory by developing the skills of observation, analysis, conclusion, and explanation.*
3. *Providing the students with skills Life and applied scientific capabilities.*
4. *Clarify the relation between science and technology in the field of science and its impact on development and link it to practical life.*
5. *Development of the concept of modern trends in preserving the ecological balance practically and globally.*

*This book includes ten chapters: (chapter one - Capacitors, chapter two - Electromagnetic Induction, chapter three - Alternating Current, chapter four - Electromagnetic Waves, chapter five - Physical Optics, chapter six - Modern Physics, chapter seven - Solid State Electronics, chapter eight - Atomic Spectra and Lasers, chapter nine - Relativity Theory, and chapter ten - Nuclear Physics), each chapter contains new concepts such as (do you know, remember, question and think) as well as a group of a large number of training and various activities for the student to get acquainted with the extent to which the objectives of that chapter have been achieved.*

*We extend our thanks and appreciation to Dr. Hanan Hassan Majeed Al-Allaf and the educational specialist Buthaina Mahdi Muhammad for their scientific review of the book. We also extend our thanks to each of the educational specialist Jalal Jawad Saeed and the educational specialist Intisar Abdul Razzaq Al-Obaidi and Mr. Abbas Naji Al-Baghdadi for their scientific contribution to complete this book in this form, as well as members of the Physics Curricula Division.*
*We ask God Almighty for the benefit to prevail through this book for all students. We ask Glory be to God, that this be the basis of our work, which pours in the love of our country and belonging to it, and God is the Grantor of success.*

*Authors*

## Environmental advice

- A clean environment means a better life.
- When the environment is a priority ... the environment survives.
- The water is a main source of life, it must be protected and kept safe from pollution.
- Environmental Protection is everyone’s responsibility, so let us all work to protect it.
- The environment belongs to you and the future generations, so you and the people around you need to protect it from pollution.
- Let’s work for a safe clean environment and a more beautiful country.
- For better beauty quality of the environment plant more and don’t cut.
- Maintain your environment’s safety and health for a better life.
- A human’s environment is a reflection of his or her conscience.
- Let us work together hand to hand to free Iraq from pollution.
- The environment is your life so contribute to making it clean and pure.
- The environment is our big home so let us work towards keeping it clean and healthy.

# CHAPTER 1

# Capacitors

Contents


1-1 Capacitor

1-2 The parallel - plate capacitor

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1-8 Some types of capacitors

1-9 Direct Current circuits consist of resistor and capacitor (RC-circuit)

1-10 Some practical applications of the capacitor


## Behavioural targets

**After studying this chapter, the student should be able to:**

- **Know the concept of the capacitor.**
- **Mention the types of capacitors.**
- **Explain the dielectric.**
- **Compere between polar and non-polar dielectrics.**
- **Learn the method of series combination.**
- **Learn the method of parallels combination.**
- **Compare between series and parallel connection method.**
- **Demonstrate an experiment how to charge the capacitor.**
- **Demonstrate an experiment how to discharge the capacitor.**
- **Mention some practical applications of the capacitor.**

## Scientific Terms

| | |
|---|---|
| Capacitance | السعة |
| Capacitor | المتسعة |
| Capacitors in Series Combination | ربط المتسعات على التوالي |
| Capacitors in Parallel Combination | ربط المتسعات على التوازي |
| Electric Charge | الشحنة الكهربائية |
| Parallel plates capacitor | المتسعة ذات الصفيحتين المتوازيتين |
| Dielectric | العازل الكهربائي |
| Permittivity Constant | ثابت السماحية |
| Electric Field | المجال الكهربائي |
| Electric Difference Potential | فرق الجهد الكهربائي |
| Electric Potential Energy | الطاقة الكامنة الكهربائية |
| Charging Capacitor | شحن المتسعة |
| Electric Potential Gradient | انحدار الجهد الكهربائي |
| Energy Density | كثافة الطاقة |
| Vacuum Permittivity | سماحية الفراغ |
| Electric Shock | صدمة كهربائية |
| Dielectric Constant | ثابت العزل الكهربائي |
| Polar Dielectric | عازل كهربائي قطبي |
| Dielectric Strength | قوة العزل الكهربائي |
| Non Polar Dielectric | عازل كهربائي غير قطبي |
| Equivalent Capacitance | السعة المكافئة |
| Relative Permittivity | السماحية النسبية |
| Discharging Capacitor | تفريغ المتسعة |

## 1-1 Capacitor

The spherical-shaped single insulated conductor can store a limited amount of electric charge. Adding more charges (Q) will inevitably lead to increase potential of conductor (V) in a specific distance (r) from the center of the charge, as in the following equation (which you previously studied):

$$V = \frac{1}{4\pi\varepsilon_0} \times \frac{Q}{r}$$

As you studied earlier, amount of proportionality constant(k) in Coulombs' law is:

$$k = \frac{1}{4\pi\varepsilon_0} = 9 \times 10^9 N.m^2/C^2$$

Therefore: $\varepsilon_0$ is permittivity of vacuum: $\varepsilon_0 = 8.85 \times 10^{-12} C^2/N.m^2$

The relation would be:

$$V = k\frac{Q}{r}$$

Therefore, the electric potential difference increases between the conductor and any other medium (such as air), then increase the electric field to extent that it discharges through the surrounding air, see figure (1). Therefore, the single conductor is rarely used in storing electrical charges.

Figure (1)

One might wonder, is it possible to build a device to store large amounts of electrical charges and store electrical energy?

To achieve this, a system of two conductors (of any shape) is used. These two conductors are separated by an insulator (either vacuum or air or an electric insulator).This device can store;

Positive charges on one conductor and negative charges on the other conductor. This system is called capacitor. see figure (2):

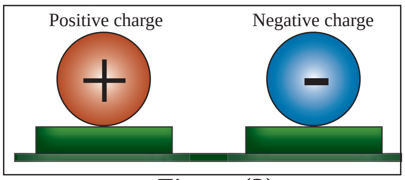


Figure (2)

The capacitor is a device used to store electrical charges and electric energy. It consists of a pair (or more) of conductive parallel plates separated by an insulator. Capacitors have various shapes such as; two parallel-plates capacitor, two cocentric cylinders capacitor and the two cocentric sphere capacitor. Capacitors are made in different shapes and size according to their applications. See figure (3). In this chapter; we will study the parallel-plate capacitor.

Figure (3)

## 1-2 The parallel - plate capacitor

The two conductors seperated by dielectric are usually plane and parallel in the form of parallel plates. This is the simplest and the most commonly used form of capacitors. In most practical applications, the plates are not charged initially. To charge them, one of the plates is connected to the positive terminal of the battery, so it shows a positive charge (+ Q). The other plate is connected to the negative terminal of the battery, so it shows negative charge (- Q) equal in magitude. Both charges lie on the opposite surfaces (inner surfaces) of the plates, because of attraction force among these charges, i.e both plates have equal and different charges. The net charge on the plates is zero. Figure (4) shows a capacitor consisting of two conductive plates, identical plane, isolated and parallel. The area of each is (A). These plates are separated by distance (d) and equally but oppositely charged called parallel- plate capacitor.

Figure (4) shows lines of electric field between the plates of two parallel-plane plates capacitor.

It is considered as a uniform electric field if the distance (d) between the plates is very small compared to the dimensions of the plate and irregularity of electric field lines at the edges is ignored. A capacitor in electric circuits is symbolized by ⊣⊢ or )⊢, this symbols applies to all capacitors.

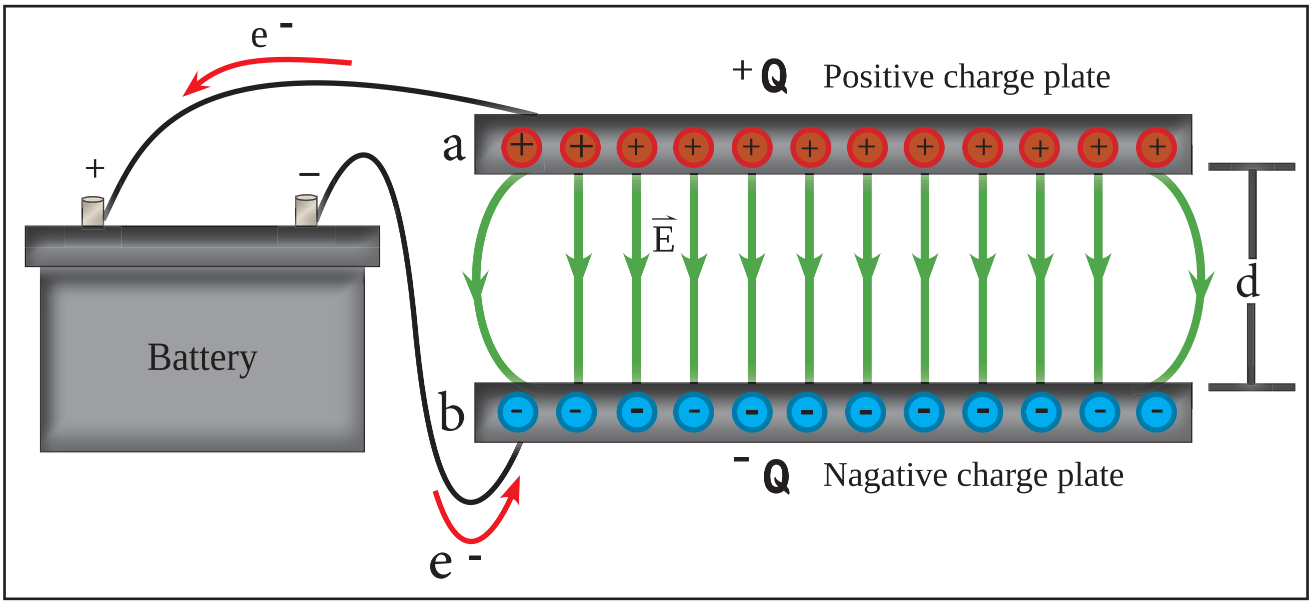


Figure (4) Uniform Electric Field

## 1-3 Capacitance

Since both plates of the capacitor are made by isolated conductor material, the charged capacitor has an equal potential on all points of each plate. An electric potential difference is generated between the higher potential (positive potential) plate and the lower potential (negative potential) plate. The potential difference between the charged plates is symbolized (ΔV). See figure (5).

It has been practically verified that the electrical potential difference (ΔV) between the charged plates is directly proportional to the amount of charge (Q) on each of the plates. This means that increase in charge (Q) would increase electric potential difference (ΔV) between the plates. Therefore, the capacitance of the capacitor is defined as "ratio of charge (Q) stored in any of the plates to the potential difference (ΔV) between the plates".

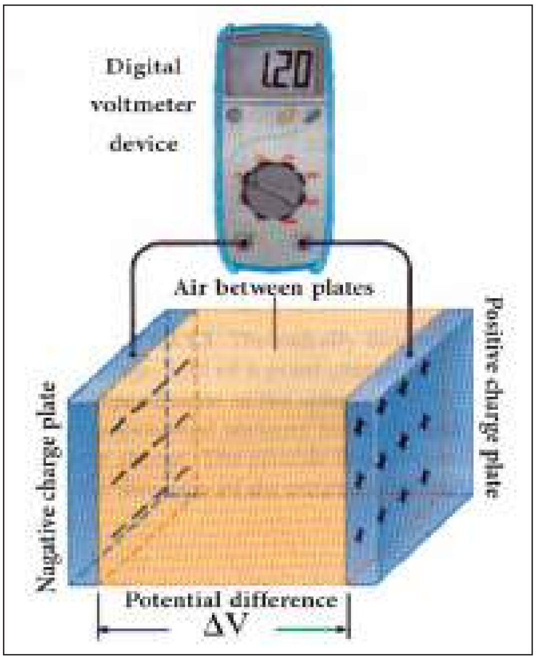

Figure (5)

$$\frac{Q}{\Delta V} = \text{Constant}$$

The fixed amount (constant) is called capacitance of the capacitor. Symbolized (C), so:

$$C = \frac{Q}{\Delta V}$$

Capacitance of the capacitor is a measure of the charge that needs to be placed on each plates to generate a particular electric potential difference. A capacitor with the larger capacitance means that it stores larger charge.

Capacitance of the capacitor is measured in the international system of units by:

$\left(\frac{\text{Coulomb}}{\text{Volt}}\right)$ it is called Farad (F).

**1 Farad = 1F = 1 Coulomb/volt**

The Farad is a very large unit for the most practical applications , the most stuitable units are the parts of Farad:

$$1\mu F = 10^{-6}F \quad , \quad 1nF = 10^{-9}F \quad , \quad 1pF = 10^{-12}F$$

## 1-4 Dielectric

As you previously studied, there are materials like wax paper, plastics and glass although being insulating at normal conditions (temperature and pressure), they decrease the amount of the electric field that is placed in. Therefore, they are called ***dielectric materials***.

**Dielectric material are classified into two types:**

**First type: Polar dielectrics:** Such as pure water, whose molecules have permanent bipolar electric moments. The distance between centers of their negative and positive charges is constant (this molecule is called dipole molecules have permanent bipolar). See figure (6) which illustrates the random directions of the poler dielectric particles in the absence of external electric field. When this dielectric is inserted between the plates of a charged capacitor, the electric field between plates will affect the dipoles and align them along the field. See figure (7).

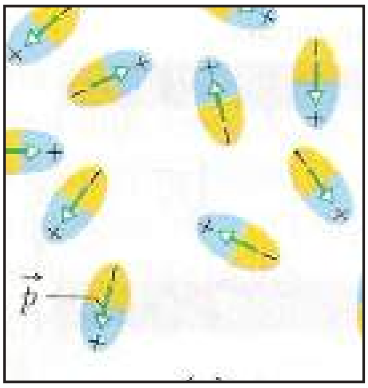

Figure (6)

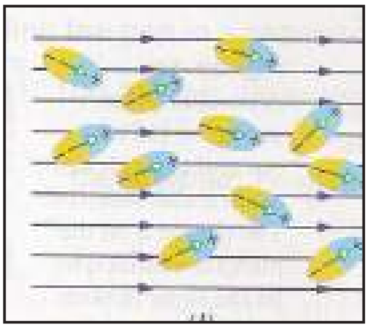

Figure (7)

Consequently, an electric field is generated inside the dielectric. This field has opposite direction to the external field and it has less amount.

As a result, the amount of net electric field between the plates of the capacitor decreases.

**Second type: Non-polar dielectrics:** (like glass and polyethylene), the distance between the centers of their positive and negative charges is not constant. See figure (8-a) when this type of dielectric is inserted between the plates of a charged capacitor, the electric field between the plates of the capacitor will minimally displace centers of the negative and positive charges in the molecule. This means it will temporarily gain dipole electic moment by electric induction method.

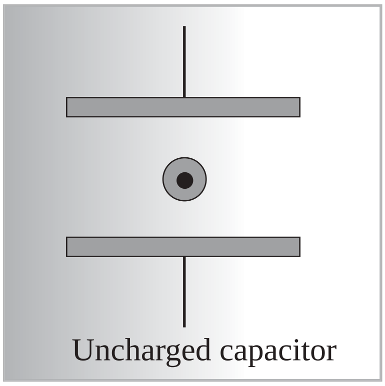


Figure (8-a)

As a result, the molecule turns into electric dipole that align in the opposite direction of effective electric field, see figure (8-b).

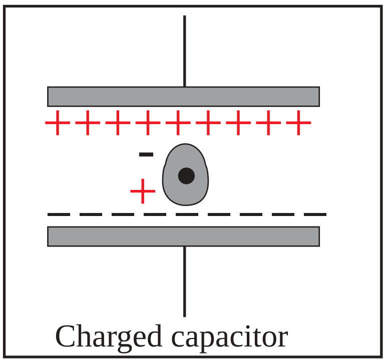


Figure (8-b)

A positive charge appears on the surface of the dielectric facing the negative plate of the capacitor, while a negative charge appears on the surface of the dielectric facing the positive plate (but the dielectric remains electrically neutral), See figure (8-c).

At this point, the dielectric becomes polarized, the two surface charges on the dielectric would generate an electric field inside the dielectric ($E_d$) .This electric field has opposite direction to that of the effective field between the two plates (E), see figure (9).

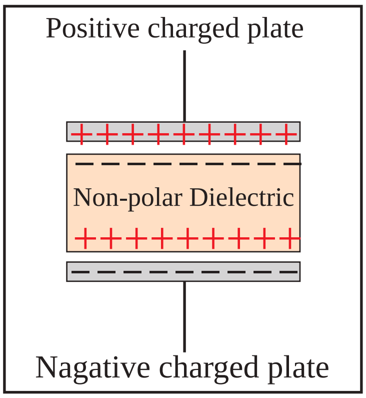

Figure (8-c)

Therefore, it weakens the effective electric field.

In both types of dielectrics, vector of resultant electric field ($E_k$) is expressed in the following relation:

$$\vec{E}_k = \vec{E} + \vec{E}_d$$

and its amount will be $$E_k = E - E_d$$

The amount of electric field between the plates of the capacitor decreases by k and becomes $E_k = E/k$.

Since the electric field is ($E=\Delta V/d$), i.e. the potential difference between the plates of the capacitor is directly proportional to the amount of electric field. So, it reduces potential difference between the plates by (k) too:

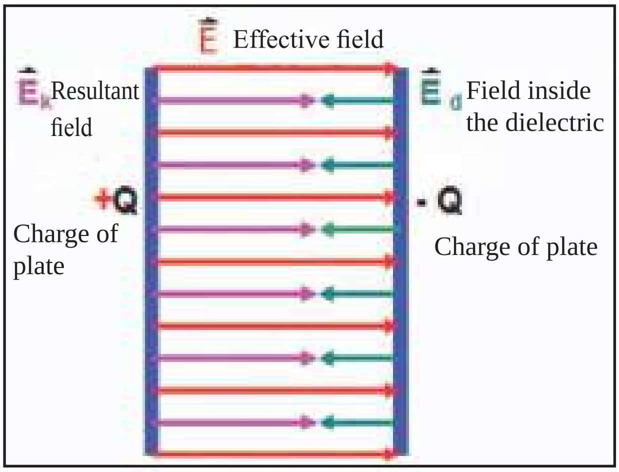

Figure (9)

$$\Delta V_k = \frac{\Delta V}{k}$$

Therefore, ($\Delta V$) is the potential difference between the plates in case of vacuum or air while ($\Delta V_k$) is the potential difference between them when the dielectric is in it.

Capacitance of the capacitor is symbolized by ($C_k$), so it becomes: $C_k = kC$

Dielectric constant (k) of dielectric material is defined as:

**The ratio between capacitance of the capacitor after inserting the dielectric is ($C_K$), and its capacitance in vacuum or air is (C), so;**

$$k = \frac{C_k}{C}$$

$$C_k = kC$$

## Activity

Explain the effect of inserting a dielectric between the plates of a charged capacitor; which is disconnected from the battery in electric potential difference between them (Faradays experiment), what effect would it make in capacitance of capacitor?

### Tools of activity:

Parallel-plate capacitor (air as dielectric) not charged, a battery with proper voltage, a voltmeter, wires and a dielectric plate (dielectric constant k).

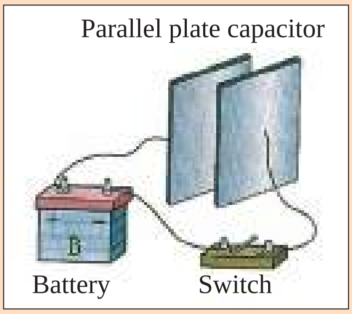

Figure (10 - a)

### Activity steps:

- One terminal of the battery is connected to one plate, and then the other terminal is connected to the second plate.One plate will be positively charged (+Q) and the other is negatively charged (-Q), see figure (10 - a).
- Disconnect battery from the plates.
- Connect the positive terminal of the voltmeter to the positive plate and the negative terminal of voltmeter to the negative plate. Observe the deviate of a pointer of the voltmeter, at specific reading see figure (10 – b). What does that mean? An electric potential difference (ΔV) is generated between the plates of the charged capacitor when air is the dielectric.
- The dielectric plate is inserted between the plates of the charged capacitor; there is a decrease in the reading of the voltmeter (ΔV) see figure (10 - c).

Figure (10 - b)

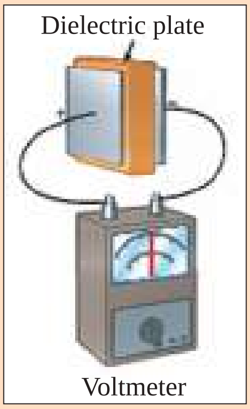

Figure (10 - c)

### Conclusion:

Inserting a dielectric with constant (k) between the plates of the charged capacitor would decrease electric potential difference by the rate of dielectric constant (k), then, $\Delta V_k = \frac{\Delta V}{k}$.

Due to decrease in electric potential difference between the plates, the capacitance of the capacitor increases according to the equation:

$C = \frac{Q}{\Delta V}$ When the amount of charge is constant Q, i.e.:

Capacitance of the capacitor increases by the factor (k) when the dielectric exists:

$$C_k = kC$$

- Notice that writing on each capaciter spicify the maximum value of the electric potintial difference which can used for it, do you see that is necessary?

**Answer:**

Yes, it's necessary because in case the potential difference on the plates kept increasing, this will greatly increase the electric field between plates, which will lead to an electric breakdown of the dielectric, as a result of the electric spark passing through it. This will discharge the capacitor (i.e. damage of the capacitor).

The following chart illustrates amounts of dielectric constant and dielectric strength for different types of materials which are used as insulators between the capacitor plates. The dielectric strength is defined as:

**Maximum amount of electric field that a material can hold before electrical breakdown.**

**Dielectric strength is defined as a measurement of a material's ability to withstand electric field applied on it.**

A table showing the dielectric constant and dielectric strength of materials in practice.

| Material | Dielectric Constant K | Dielectric Strength (Volt/meter) |
|---|---|---|
| Vacuum | 1.00000 | ----------- |
| Air (1 atm) | 1.00059 | $3 \times 10^6$ |
| Rubber | 6.7 | $12 \times 10^6$ |
| Nylon | 3.4 | $14 \times 10^6$ |
| Paper | 3.7 | $16 \times 10^6$ |
| Polystyrene plastic | 2.56 | $24 \times 10^6$ |
| Pyrex glass | 5.6 | $14 \times 10^6$ |
| Silicon oil | 2.5 | $15 \times 10^6$ |
| Teflon | 2.1 | $60 \times 10^6$ |
| Pure water 20°C | 80 | ----------- |
| Strontium | 300 | $8 \times 10^6$ |
| Mica | 3---6 | $(150\text{-}220) \times 10^6$ |

## 1-5 Factors affecting capacitance of parallel plate capacitor

One might wonder, what are the factors affects to capacitance of a capacitor? The factors, which affect capacitance of a parallel plate capacitor (C), are:

1. Surface area (A) of parallel plates, it is directly proportional with it ($C \propto A$)
2. Distance (d) between the plates, it is inversely proportional with it ($C \propto \frac{1}{d}$).
3. Type of dielectric medium between the plates: if vacuum or air was the dielectric between the plates, the capacitance of the capacitor is expressed as follows:

$$C = \frac{\varepsilon_0 A}{d}$$

($\varepsilon_0$) represents constant of proportionality called permittivity of vacuum. In case there is a dielectric material between the plates instead of vacuum or air whose dielectric constant (k) which is the relative permittivity of material and it is called the dielectric constant. It is only a number without units, then, the capacitance of the parallel –plate capacitor (with dielectric between the plates instead of air or vacuum) is expressed by the following:

$$C_k = k\frac{\varepsilon_0 A}{d} \quad \text{Then it will be:} \quad C_k = kC$$

Now we will explain practically how amount of capacitance of parallel-plate capacitor will change when the following factors change:

### a Surface area (A) of the facing plates

Figure (11-a) shows a charged capacitor (Q) of a certain amount which is disconnected from the voltage source and connected to a voltmeter to measure the potential difference between the plates. Since the facing surface area of the capacitor is (A), the reading of the voltmeter will be at a certain degree, the potential difference between the plates will be ($\Delta V$) .

Reducing the facing surface area of the plates to the half

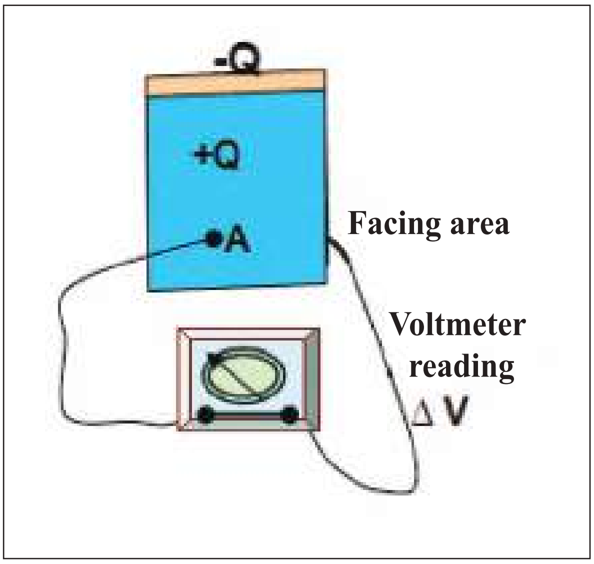

Figure (11-a)

i.e. ($\frac{1}{2}$ A) by removing one of the plates aside (keeping the amount of charge constant). A double increase in the reading of the voltmeter is observed (i.e. 2ΔV). See figure (11-b):

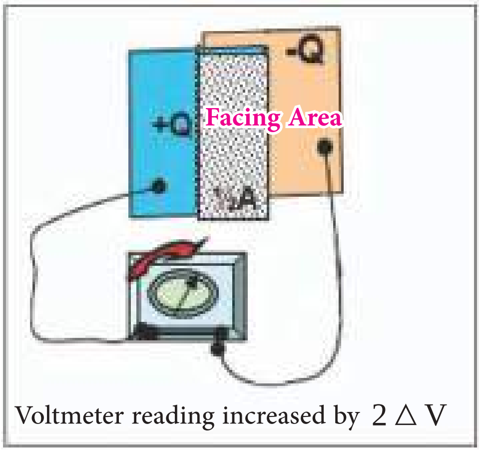


Figure (11-b)

According to the relation ($C = \frac{Q}{\Delta V}$), Capacitance of capacitor decreases when there is increase in potential difference between the plates as the charge (Q) is kept constant. We can conclude that capacitance of capacitor decreases when the facing area of the plates decreases and vice versa: ($C \propto A$)

i.e. **Capacitance (C ) of parallel-plate capacitor is directly proportional with facing area (A) of the plates.**

## b Distance between parallel plates (d)

Figure (12-a) illustrates plates of a charged capacitor with acertain amount of charge, disconnected from voltage source, and connected to ends of a voltmeter. The initial distance between them is (d). Note that the reading of the voltmeter points to a certain amount of potential difference (ΔV) between the charged plates (Q).

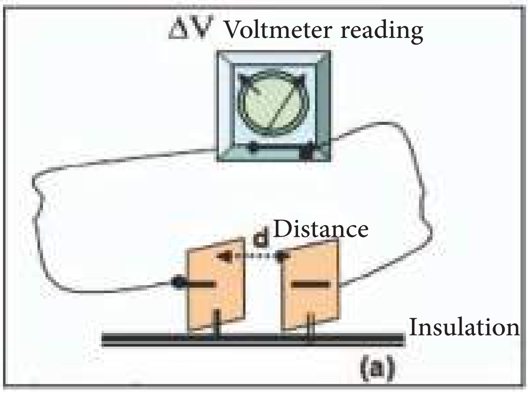


Figure (12-a)

When the plates are brought closer to each other ($\frac{1}{2}$d) (while keeping the charge constant) the reading of the voltmeter drops to the half ($\frac{1}{2}\Delta V$). See figure (12-b).

According to the relation, $C = \frac{Q}{\Delta V}$ decrease in potential difference between plates of capacitor means increase capacitance of capacitor (when the charge is constant).

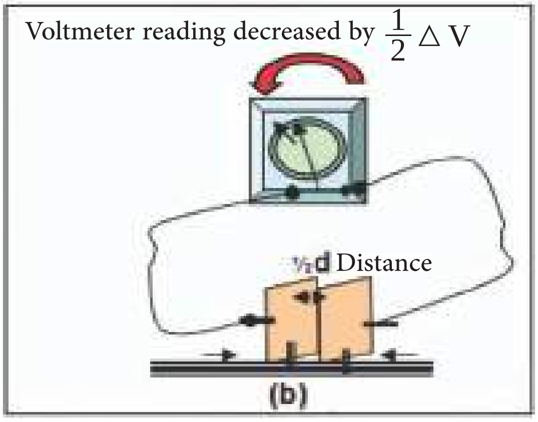


Figure (12-b)

**We can conclude that capacitance of capacitor increases when there is a decrease in distance (d) between the plates and vice versa.**

$$\left(C \propto \frac{1}{d}\right)$$

## Do you know?

Some factories use several ways to increase capacitance of parallel-plate capacitor by controlling the three factors (surface area of the two plates, distance between plates and dielectric). The plates are made very thin and wide, and an insulator (with huge dielectric constant) is placed between them as thin ribbons wrapped in a cylinderical shape. See figure (13).

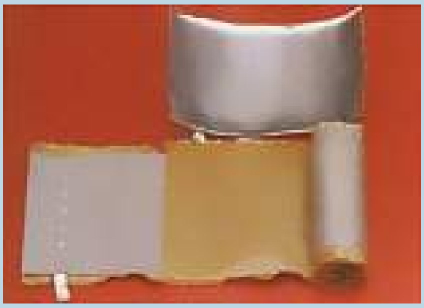

Figure (13)

## Example (1)

A (10 pF) parallel-plate capacitor is charged by a (12V) potential difference battery, then disconnected from the battery, then a material which dielectric constant (6) is inserted fills the space between them, see figure (14):

**Calculate the amount of :**

1. Stored charge in each of the plates?
2. Capacitance of capacitor with inserting the dielectric?
3. Potential difference between the plates after inserting the dielectric?

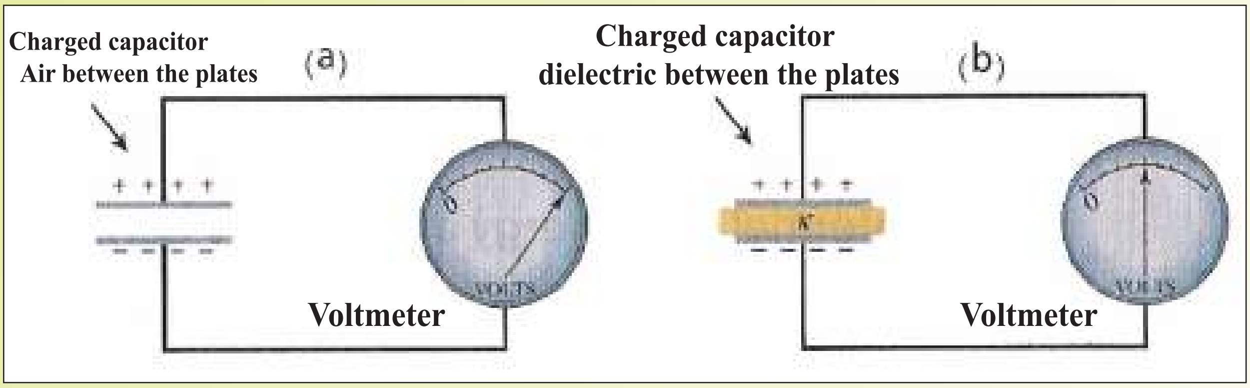


Figure (14)

**The solution:**

1. To calculate the amount of stored charge in each of the plates of the capacitor, we use the following relation: $Q = C \times \triangle V$

   $Q = 10 \times 10^{-12} \times 12 = 120 \times 10^{-12}$ coulomb

2. To calculate capacitance of capacitor with the dielectric: $C_k = kC$

So: $C_k = 6 \times 10 \times 10^{-12} F = 60 \times 10^{-12} F$

3. To calculate potential difference between plates of capacitor after inserting the dielectric: $\triangle V_k = \frac{Q}{C_k} = \frac{120 \times 10^{-12}}{60 \times 10^{-12}} = 2V$

   or calculated from: $\triangle V_k = \frac{\triangle V}{k} = \frac{12}{6} = 2V$

It is worth noting that potential difference between plates of the capacitor after inserting the dielectric decreases by (k) when the capacitor is disconnected from battery, see figure (14-a, b).

Since the capacitor is disconnected from battery, then the dielectric is inserted, the stored charge will be constant: $Q_k = Q = 120 \times 10^{-12}$ coulomb

**Think?**

Your friend says that the charged capacitor store a specific value of charge, and you say that the charged capacitor has a net charge is zero.

Your teacher says both are correct….explain how?

**Example (2)**

Parallel-plate capacitor, distance between plates (0.5cm), both plates are square and each side is (10 cm), There is a vacuum between them (vacuum permittivity is $\epsilon_0 = 8.85 \times 10^{-12} C^2/N.m^2$). What is the amount of:

1. Capacitance of the capacitor.

2. Stored charge in each of the plates after applying (10Volt) potential difference.

**The solution:**

1. We have the relation: $C = \frac{\epsilon_0 A}{d}$

Since both plates are squared, the area will be: $A = (0.1)^2 = 1 \times 10^{-2} m^2$

Distance between plates: $d = 0.5cm = 5 \times 10^{-3} m$

Then we substitute that in the following relation: $C = 8.85 \times 10^{-12} \times \frac{1 \times 10^{-2}}{5 \times 10^{-3}}$

i.e. amount of capacitance of capacitor is: $C = 1.77 \times 10^{-11} F = 17.7 \times 10^{-12} F = 17.7 pF$

2. To calculate amount of stored charge in each of the plates, the following relation applies: $Q = C \Delta V$

$$Q = 17.7 \times 10^{-12} \times 10 = 177 \times 10^{-12} \text{ coulomb}$$

## 1-6 Combination of capacitors (Parallel and Series)

One might wonder what is the purpose of connecting capacitors in parallel is and series combination?

There are two ways to connect capacitors, one is used to increase equivalent capacitance of the group, for this purpose, capacitors are connected in parallel combination with each other, therefore, the facing surface area of the parallel plates (the equivalent parallel group) increases.

The second method decrease equivalent capacitance is the ability to place a larger potential difference on the sides of the group such high potential difference may not be undergone by any capacitor if connected individually, for this the capacitors are connected in series combination.

## a Parallel combination of capacitors

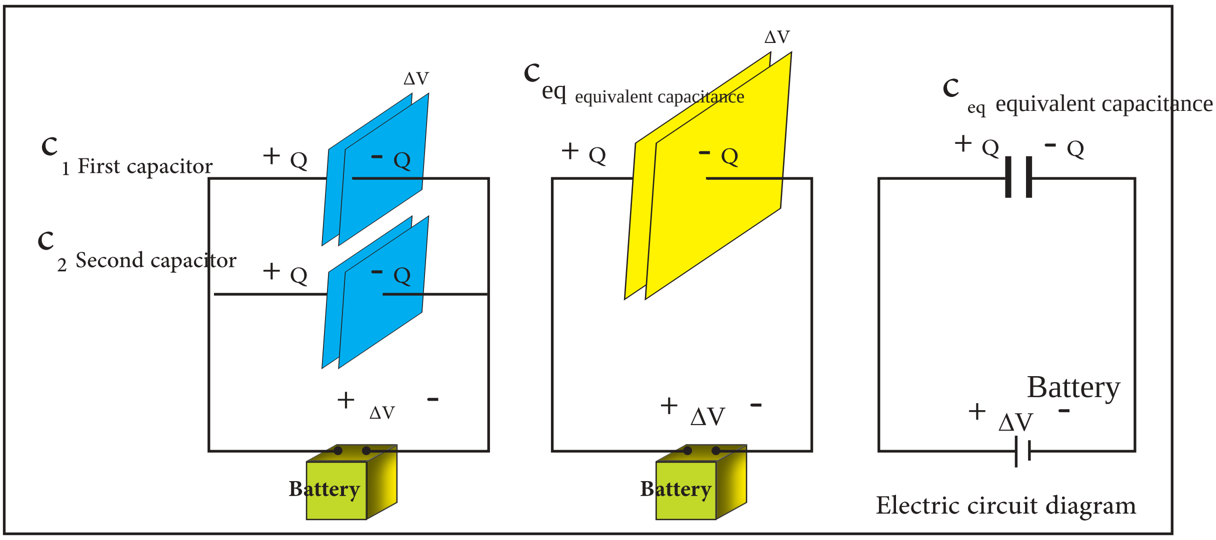


Figure (15) Surface area increase for the equivalent parallel-plate capacitor (with constant distance between the plates and type of dielectric) so the equivalent capacitance is increased.

Figure (15) illustrates a practical way to connect two capacitors ($C_1$, $C_2$) in parallel combination and connect their ends to a battery, therefore, both create equal potential difference:

$$\Delta V_1 = \Delta V_2 = \Delta V_{battery} = \Delta V$$

Since ( $Q = C \Delta V$ ) then:

$$Q_1 = C_1 \Delta V \text{ and } Q_2 = C_2 \Delta V$$

$$Q_{total} = C_{eq} \times \Delta V$$

($Q_{total}$) represents the total charge of the group.

($C_{eq}$) represents the equivalent capacitance, which includes the parallel group.

Then we can derive the equivalent capacitance ($C_{eq}$) for the group of capacitors connected in parallel combination:

Since the total charge of the two capacitors in parallel combination ($Q_{total}$) equals the algebraic summation of the charges on any of their plates, so:

$$Q_{total} = Q_1 + Q_2$$

$$C_{eq} \Delta V = C_1 \Delta V + C_2 \Delta V$$

$$C_{eq} \Delta V = (C_1 + C_2) \Delta V$$

By dividing both sides of the equation by ($\Delta V$) we get:

$$C_{eq} = C_1 + C_2$$

This result can be generalized on any number of capacitors (like n of capacitors) connected in parallel combination, therefore, the equivalent capacitance of the group is:

$$C_{eq} = C_1 + C_2 + C_3 + ................C_n$$

We conclude from this relation: the equivalent capacitance, of a group of capacitors in parallel combination, increase. The reason for this is:

Connecting capacitors in parallel combination means increasing surface area of opposite plates of the equivalent capacitor, which will increase capacitance of equivalent capacitor to be larger than the largest capacitance of any capacitor in the group, assuming that both distance and type of dielectric are constant.

## Example (3)

Four capacitors with the following capacitance (4μF, 8μF, 12μF, 6μF) respectively connected in parallel combination and connected to terminals of a (12V) potential difference battery, **calculate**:

1. Equivalent capacitance of the group.
2. Stored charge in any of the plates of each capacitor.
3. Total stored charge in the group.

## The solution:

A diagram for connecting the capacitors is drawn as in figure (16):

1. Equivalent capacitance of the group is calculated according to the following relation:

$$C_{eq} = C_1 + C_2 + C_3 + C_4$$

$$C_{eq} = 4 + 8 + 12 + 6 = 30\mu F$$

2. Since all capacitors are connected in parallel combination, the potential difference between the plates of each is equal, and it also equals the potential difference between terminal of the battery (12V).

$$\Delta V_{total} = \Delta V_1 = \Delta V_2 = \Delta V_3 = \Delta V_4 = \Delta V$$

The stored charge in the first capacitor will be:

$$Q_1 = C_1 \times \Delta V = 4 \times 12 = 48\mu \text{ coulomb}$$

The stored charge in the second capacitor will be:

$$Q_2 = C_2 \times \Delta V = 8 \times 12 = 96\mu \text{ coulomb}$$

The stored charge in the third capacitor will be:

$$Q_3 = C_3 \times \Delta V = 12 \times 12 = 144\mu \text{ coulomb}$$

The stored charge in the Fourth capacitor will be:

$$Q_4 = C_4 \times \Delta V = 6 \times 12 = 72\mu \text{ coulomb}$$

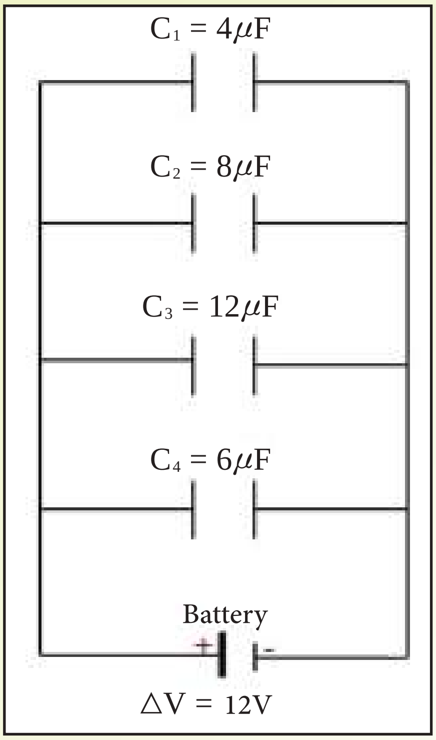

Figure (16)

3. The total stored charge is calculated as follows:

$Q_{total} = C_{eq} \times \Delta V$

$Q_{total} = 30 \times 12 = 360\mu$ coulomb

Or calculated by sum of the stored charges in each capacitor: (Algebraic summation)

$Q_{total} = Q_1 + Q_2 + Q_3 + Q_4$

Total stored charge in the group.

$Q_{total} = 48 + 96 + 144 + 72 = 360\mu$ coulomb

## b Series combination of capacitors:

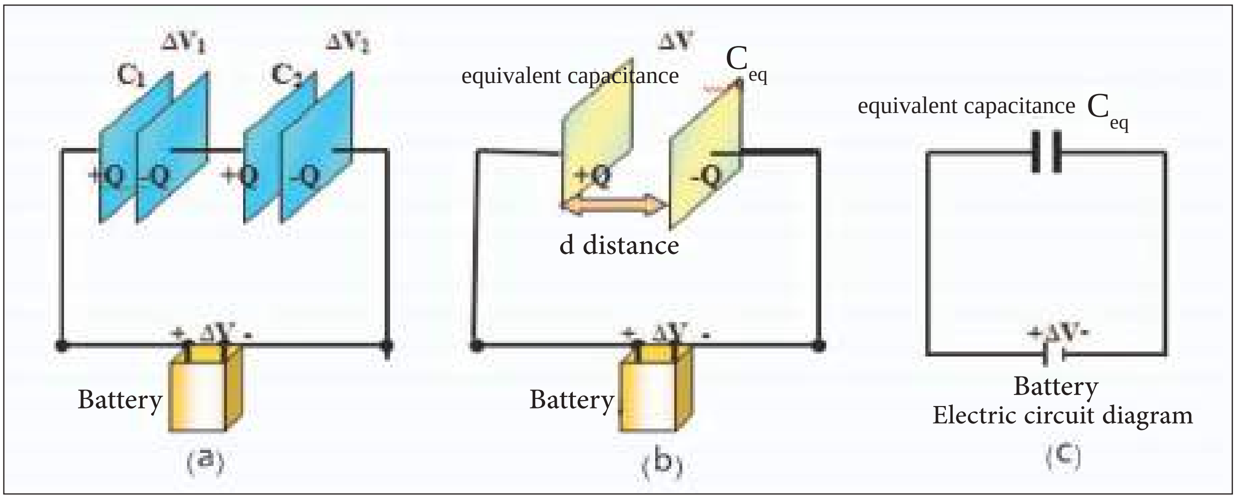


Figure (17) the distance increase between the plates of equivalent capacitor in the series combinantion (with constant area of the plate and the dielectric type) so the equivalent capacitance is decreases .

Figure (17) illustrates a practical way to connect two capacitors ($C_1$, $C_2$) in series combination and connect the ends of the capacitors to a battery. The total charge ($Q_{total}$) equals the amount of stored charge in any of the plates of the capacitors, i.e:

$$Q_{total} = Q_1 = Q_2$$

The explanation for this is: the potential of the two middle plates are equal, they are two plates connected together by a wire, therefore, they can be considered as one conductor and its surface will be an equipotential surface.

They will have equal charges yet different in type of charge (by means of induction), see figure (17 –a).

Assume that; substituted the two capacitors by one capacitor work like a group.

The capacitance of this capacitor is called the equivalent capacitance ($C_{eq}$) for the group of capacitors connected in series combination:

Since: $C = \frac{Q}{\Delta V}$ then:

$$C_1 = \frac{Q}{\Delta V_1}$$

$$C_2 = \frac{Q}{\Delta V_2}$$

$$C_{eq} = \frac{Q}{\Delta V_{total}}$$

($Q_{total}$): represents the total charge of the group (Q), ($C_{eq}$): represents the equivalent capacitance of the group. Then we can derive ($C_{eq}$) for the group of capacitors in series combination. Since the groups of capacitors are connected to a battery, the total potential difference of the group equals sum of potential differences between plates of each capacitor, i.e:

$$\Delta V_{total} = \Delta V_1 + \Delta V_2$$

$$\frac{Q}{C_{eq}} = \frac{Q}{C_1} + \frac{Q}{C_2}$$

$$\frac{Q}{C_{eq}} = Q\left[\frac{1}{C_1} + \frac{1}{C_2}\right]$$

Dividing by Q, we get the following relation: $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}$

or $C_{eq} = \frac{C_1 . C_2}{C_1 + C_2}$ this relation is applied when two capacitors are connected in series combination not more.

This result can be applied to any number (n number of capacitors) connected in series combination. The inverse of equivalent capacitance of the group equals total inverse capacitance of combining capacitors: $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots\ldots\ldots \frac{1}{C_n}$

We conclude that: amount of equivalent capacitance decreases for a group of capacitors in series combination. It is smaller than the smallest capacitance of any capacitor in the group. This can be explained by the fact that connecting capacitors in series combination means increasing distance between plates of the equivalent capacitor, assuming constant area and type of dielectric.

**Think?**

What is the way to connect a group of capacitors?

a. To obtain huge equivalent capacitance to store a huge electric charge and low potential difference, this can not be done by using only one capacitor.

b. In order to impose huge potential difference on the ends of the group that one capacitor cannot hold.

## Example (4)

Three parallel-plate capacitors with capacitances are (6μF, 9μF, 18μF) respectively connected in series combination, the group of capacitors are charged with, (300μ coulomb), see figure (18).

Figure (18)

**Calculate:**

1. Equivalent capacitance of the group.
2. Stored charge in any of the plates of each capacitor.
3. Total potential difference between the ends of the group.
4. Potential difference between plates of each capacitor

## The solution:

1. Since the group of capacitors is connected in series combination, then the equivalent capacitance is calculated from the following relation:

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$\frac{1}{C_{eq}} = \frac{1}{6} + \frac{1}{9} + \frac{1}{18} = \frac{6}{18} = \frac{1}{3}$$

$C_{eq} = 3\mu F$ Amount of equivalent capacitance.

2. Since the capacitors are connected in series combination, the amount of charge stored in any of the plates of each capacitor is equal and it equals the total charge of the group.

$Q_{total} = Q_1 = Q_2 = Q_3 = Q = 300\mu$ coulomb

3. Total potential difference between the ends of the group is calculated:

$$\Delta V_{total} = \frac{Q_{total}}{C_{eq}}$$

$$\Delta V_{total} = \frac{300}{3} = 100V$$

4. Potential difference between plates of each capacitor:

$$\Delta V_1 = \frac{Q}{C_1} = \frac{300}{6} = 50V$$

$$\Delta V_2 = \frac{Q}{C_2} = \frac{300}{9} = (\frac{100}{3})V$$

$$\Delta V_3 = \frac{Q}{C_3} = \frac{300}{18} = (\frac{50}{3})V$$

## Example (5)

From information on figure (19-a), calculate:

1. Equivalent capacitance of the group.
2. Total stored charge in the group.
3. Stored charge in any of the plates of each capacitor.

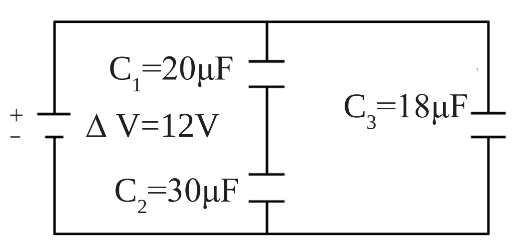


Figure.(19-a)

## The solution:

1. Equivalent capacitance $(C')$ of the capacitors $(C_1, C_2)$ connected in series combination with each other are is calculated as follows:

$$\frac{1}{C'} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$\frac{1}{C'} = \frac{1}{20} + \frac{1}{30} = \frac{5}{60} = \frac{1}{12}$$

The amount of equivalent capacitance in series combination $(C'=12\mu F)$, then the total equivalent capacitance $(C_{eq})$ for the parallel combination $(C', C_3)$ is calculated as in figure (19-b).

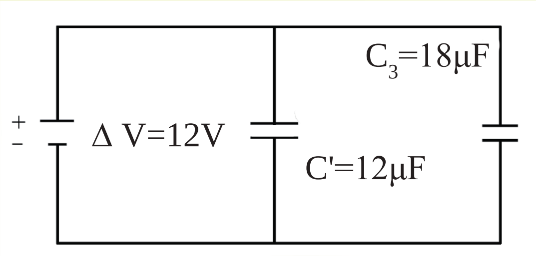


Figure (19-b)

This is the total capacitance for the group: $(C_{eq})$, see figure (19-c).

$C_{eq} = C' + C_3$

$C_{eq} = 12 + 18 = 30\mu F$

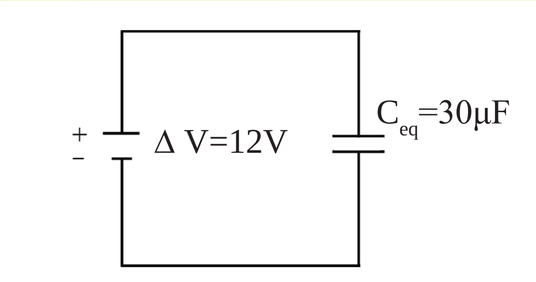


Figure (19-c)

2. To calculate the total charge of the group, the following relation applies:

$Q_{total} = C_{eq} \times \Delta V_{total}$

$Q_{total} = 30 \times 12 = 360\mu$ coulomb

3. In figure (19-b), the potential difference of the parallel combination group $(C', C_3)$ is calculated:

$\Delta V_{total} = \Delta V' = \Delta V_3 = 12V$ then we calculate the charge of each:

$Q' = C' \times \Delta V = 12 \times 12 = 144\mu$ coulomb $= Q_1 = Q_2$

$Q_3 = C_3 \times \Delta V = 18 \times 12 = 216\mu$ coulomb

**Think?**

If you are asked to connect nine identical capacitors with the same capacitance (10μF) together to obtaine an equivalent capacitance (10μF). Explain how to connect this group of capacitors, and draw a digram showing that.

## 1-7 Stored energy in electric field of the capacitor

When a specific amount of electric charges is moved from one position to another with a potential difference between them work must be done on these charges. This work is stored in the form of electric potential energy ($PE_{electric}$) in the electric field between the two positions. Assuming there is uncharged parallel –plate capacitor, the amount of charge of both plates is zero (Q = 0 coulomb), this means the potential difference ($\Delta V$) between the plates is zero for the uncharged capacitor.

After charging the capacitor, a potential difference ($\Delta V$) is created between the plates, and with continuous charging, the potential difference between the plates increases. Stored energy in the electric field of the capacitor can be calculated by drawing a chart which illustrates amount of charge (Q) stored in any of the plates and the potential difference ($\Delta V$), see figure (20) by calculating area of triangle (the shaded area under the curve) which equals:

$$PE_{electric} = \frac{1}{2} \Delta V \times Q$$

[The base (represents $\Delta V$), height (represents amount of charge Q)].by substituting electric capacitance of capacitor ($C = \frac{Q}{\Delta V}$) in the relation mentioned earlier, the stored energy in the electric field between the plates of the capacitor ($PE_{electric}$) can be written in the following formula:

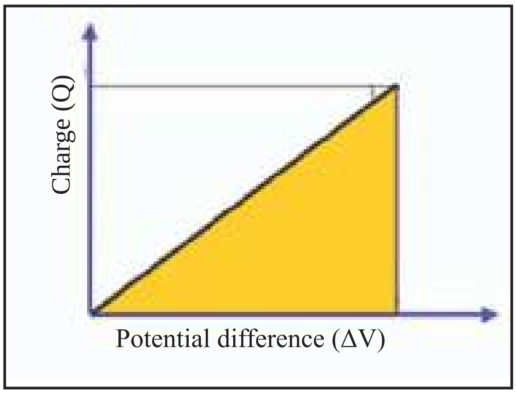

Figure (20)

Either:

$$PE_{electric} = \frac{1}{2} C.(\Delta V)^2$$

or:

$$PE_{electric} = \frac{1}{2} \times \frac{Q^2}{C}$$

## Example (6)

What is the amount of stored energy in the electric field of a (2μF) capacitor, if charged by a (5000 V) potential difference, What is the amount of the power we get when discharged by (10μs) time?

### The solution:

The following relation is applied as: $PE_{electric} = \frac{1}{2} C.(\Delta V)^2$

$$PE_{electric} = \frac{1}{2}(2 \times 10^{-6}) \times (5000)^2 = 25J$$

$$\text{Power (P)} = \frac{PE_{electric}}{time(t)} = \frac{25}{10 \times 10^{-6}} = 2.5 \times 10^6 \text{ Watt}$$

### Do you know?

* Stored energy in the electric field between plates of capacitor in the previous example is huge; it is equivalent to stored energy in a (1 kg) object falling from (2.5 m height).

$$(PE = mgh = 1 \times 10 \times 2.5 = 25 \text{ J})$$

*Capacitor like these are used in high power laser generating devices.

## Example (7)

Two parallel-plate capacitors ($C_1$= 3μF, $C_2$= 6μF) connected in series combination. Their ends are connected to terminals of (24 volt) battery; air was the insulator between the plates of each, see figure (21).

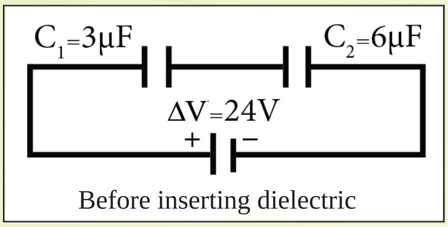

Figure (21)

If an insulating material constant dielectric (2) is placed between the plates of each (the group is still connected to the battery), see figure (22).

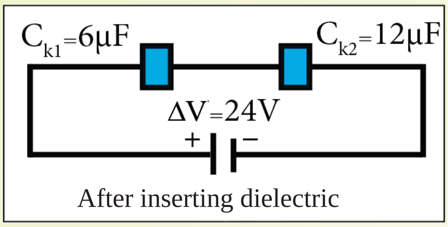

Figure (22)

What is the potential difference between the plates of each capacitor and the stored energy in the electric field between plates of each capacitor in two cases:

1. Before inserting the dielectric.

2. After inserting the dielectric.

## The solution:

1. Before inserting the dielectric, we calculate the equivalent capacitance of the group, see figure (21).

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$\frac{1}{C_{eq}} = \frac{1}{3} + \frac{1}{6} = \frac{3}{6} = \frac{1}{2}$$

The equivalent capacitance of the group will be: $C_{eq} = 2\mu F$

Then the total stored charge in the group is calculated:

$$Q_{total} = C_{eq} \times \Delta V_{total}$$

$$Q_{total} = 2 \times 24 = 48\mu \text{ coulomb}$$

Since the connection is in series combination, the stored charge in any of the plates equals each other;

$Q_{total} = Q_1 = Q_2 = Q = 48\mu$ coulomb

Potential difference between plates of first capacitor: $\Delta V_1 = \frac{Q}{C_1} = \frac{48}{3} = 16V$

Potential difference between plates of second capacitor: $\Delta V_2 = \frac{Q}{C_2} = \frac{48}{6} = 8V$

To calculate the stored energy in the electric field between plates of each capacitor, we apply the following relation:

$$PE_{(1)electric} = \frac{1}{2} C_1 \times (\Delta V_1)^2$$

$$PE_{(1)electric} = \frac{1}{2} \times 3 \times 10^{-6} \times (16)^2 = 384 \times 10^{-6} J$$

$$PE_{(2)electric} = \frac{1}{2} C_2 \times (\Delta V_2)^2$$

$$PE_{(2)electric} = \frac{1}{2} \times 6 \times 10^{-6} \times (8)^2 = 192 \times 10^{-6} J$$

2. After inserting the dielectric, the equivalent capacitance of the group, see figure (22):

**Since :** $C_k = kC$

$C_{k1} = 2 \times 3 = 6\mu$ F, $C_{k2} = 2 \times 6 = 12\mu$ F

Then we calculate the equivalent capacitance of the two capacitors in series combination:

$$\frac{1}{C_{k_{eq}}} = \frac{1}{C_{k1}} + \frac{1}{C_{k2}}$$

$$\frac{1}{C_{k_{eq}}} = \frac{1}{6} + \frac{1}{12} = \frac{3}{12} = \frac{1}{4}$$

Amount of equivalent capacitance of the group : $\boxed{C_{k_{eq}} = 4\mu F}$

Considering that the dielectric material is inserted and the group of capacitors is still connected to the battery, the total potential difference for the group remains constant (24V). Then the total charge of the group is calculated using the following relation:

$$Q_{k\,(total)} = C_{keq} \times \Delta V$$

$$Q_{k\,(total)} = 4 \times 24 = 96\ \mu\ \text{coulomb}$$

In case the connection is in series combination, the amounts of stored charges in any of the plates of each capacitor are equal:

$$Q_{k\,(total)} = Q_{1k} = Q_{2k} = 96\ \mu\ \text{coulomb}$$

**So:**

Potential difference between plates of first capacitor:

$$\Delta V_{k1} = \frac{Q_{k\ total}}{C_{1k}} = \frac{96}{6} = 16V$$

Potential difference between plates of second capacitor:

$$\Delta V_{k2} = \frac{Q_{k\ total}}{C_{2k}} = \frac{96}{12} = 8V$$

Then the electric energy stored in the electric field between the plates of each capacitor is calculated by the following relation:

$$PE_{\,(1)electric} = \frac{1}{2} C_{1k} \times (\Delta V_1)^2$$

$$PE_{\,(1)electric} = \frac{1}{2} \times 6 \times 10^{-6} \times (16)^2 = 768 \times 10^{-6} J$$

$$PE_{\,(2)electric} = \frac{1}{2} C_{2k} \times (\Delta V_2)^2$$

$$PE_{\,(2)electric} = \frac{1}{2} \times 12 \times 10^{-6} \times (8)^2 = 384 \times 10^{-6} J$$

## Do you know?

There is a huge depot for capacitors (called capacitors bank) near Chicago city, see figure (23). It is used to store huge amount of electric energy used in particle accelerator device at Vermy laboratory.

The device requires huge and sudden amount of electric energy.

This energy is provided by discharging the capacitors in that depot in a short time.

This is similar to collecting water in reservoirs on roofs of buildings to be drained and used in a very short time by firefighters.

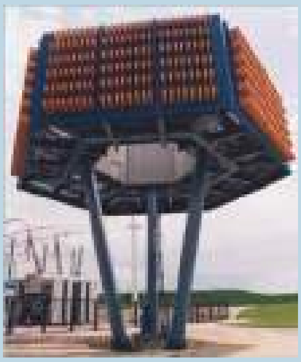

Figure (23)

## 1-8 Some types of capacitors

There are several types of capacitors used in industry. They have various types, sizes, and manufacturing materials to be suitable for all practical applications.

Some have varying capacitance some have constant capacitance. Values of capacitances range between (1pF up to more than 1F), examples:

**a. Wax paper capacitors:** this type is used in many electrical and electronic devices. They are small size, with large plates area notice figure (24).

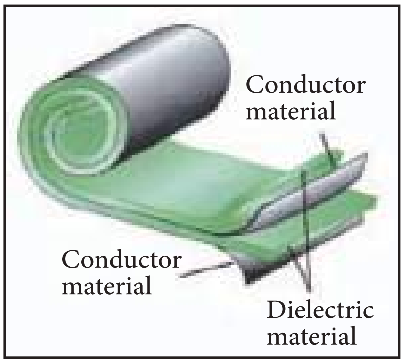


Figure (24)

**b. Rotary –plate with variable capacitance of capacitor:** it consists of two groups of plates as half disks, one group is fixed (unmovable), while the other rotate around a fixed axis.

The two groups are connected between the terminals of battery while charging; therefore, this capacitor is equivalent to a group of capacitors in parallel combination.

The capacitance of this capacitor changes during rotation due to change in surface area of the plates. Air is the dielectric between the plates see figure (25). This type of capacitor is used in radio and wireless devices.

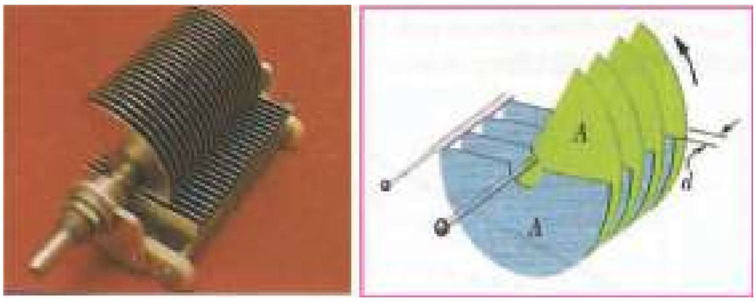

Figure (25)

### c. Electrolyte capacitor:

This capacitor consists of two plates, one of them is aluminum and the other is electrolytic paste, and then a dielectric material is generated as a result of the chemical reaction between aluminum and the electolyte, and the plates are wrapped in a cylindrical shape, see figure (26).

This capacitor has the advantage of tolerating high potential difference; a mark is placed on the sides of the capacitor to indicate polarity, in order to be connected properly in the electric circuit. Below a table shows values of some capacitors used in a practical applications and maximum potential difference between its plates the capacitor before electric crash breakdown of dielectric:

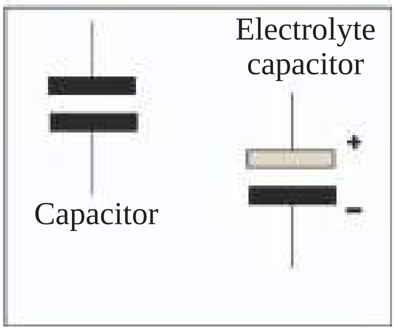


Figure (26)

| Type of capacitor | Range of capacitance | Range of potential difference |
|---|---|---|
| mica | 1pF-10nF | 100V -600V |
| ceramic | 10pF-1 $\mu$ F | 30V -50KV |
| polystyrene | 10pF-2.7 $\mu$F | 100V -600V |
| polycarbonate | 100pF-30 $\mu$F | 50V-800V |
| tantalum | 100nF-500 $\mu$F | 6V-100V |
| electrolyte | 100nF-2F | 3V-600V |

*** Note: this table for refrence only (not required).**

## 1-9 Direct current circuits consist of resistor and capacitor (RC-circuit)

You have already studied electrical circuits of the direct current, which are provided by voltage (like battery) and a resistor. In these circuits, the current is constant at a period of time (doesn't change over time).

Let us Assume a direct current circuit containing a capacitor as well as battery and a resistor, this circuit is called Resistor-Capacitor circuit (RC-circuit),the current in this circuit changes over time. The simplest practical form is charge and discharge circuits of the capacitor. In order to understand how capacitors are charged and discharged, we need to do the following activity:

## Activity

### First - How to charge the capacitor

**Tools of activity:**

a battery with proper voltage, Galvanometer (G), capacitor (C) with parallel plate (A&B), double switch (k), constant resistor (R), identical lamps ($L_1$,$L_2$), conecting wires.

**Activity steps:**

The circuit is connected as in figure (27), where by the switch (k) in position (1), what does this mean? This implies connecting the plates of the capacitor to the terminals of the battery, to be charged, so the pointer of the galvanometer (G) instantly moves to one side zero reading (to the right for example) and back quickly to zero reading, notice in the same time the lamp glows for awhile ($L_1$) then it goes off as if the battery is not connected to the circuit.

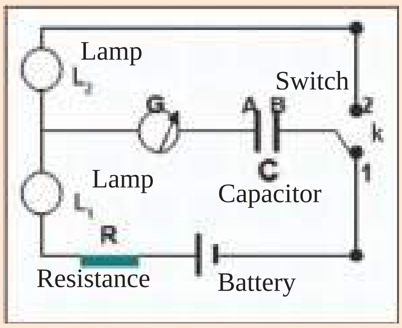

Figure (27)

One might wonder why the pointer of the Galvanometer (G) moves back to zero?

The answer is, when the capacitor is charged completely, the potential of each plate is equal with battery terminals, so, the capacitor is fully charged, which means:

Potential difference between plates of capacitor, equals potential difference between terminals of the battery. In this case, therefore, there is no potential difference between the sides of the resistor in the circuit, this makes the current in the circuit zero.

Therefore, existence of charged capacitor in the direct current circuit is considered as open switch.

Since both plates of capacitor are isolated from each other, electrons accumulate on plate (B) which is connected to the negative terminal of the battery, so it is charged with negative charge (–Q), while plate (A) which is connected to the positive terminal of the battery, is positively charged (+Q) similarly by means of induction. Figure (28) illustrates the relation between capacitor charge current and time spent to charge it.

**Think?**

The capacitor which placed in a direct current circuit act as an open switch (open circuit)?

It has been practically proven that charge current (I) starts with huge amount at the moment of closing the charge circuit, and it equals: $I = \dfrac{\Delta V_{battery}}{R}$ Then it decreses to zero as soon as possible when complete its charging, figure (28).

**I:** Charge Current, **R:** resistance, ($\Delta V_{battery}$) = Potential difference of battery.

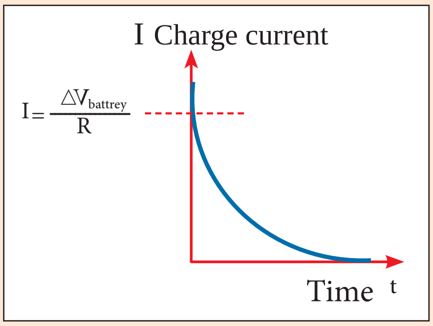

Figure (28)

## Second- How to Discharge the capacitor

### Steps of the activity:

We use the electric circuit connected in the previous activity, see figure (29), but the switch (K) is in position (2). What does that mean?

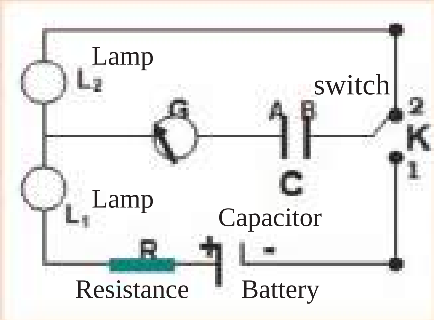


Figure (29)

This means connecting the plates of the capacitor by a wire, in this way, the capacitor will be discharged, i.e neutralized charge of plates. So, the Galvanometer (G) instantly moves from zero (to the left) then back to zero quickly and the lamp glows ($L_2$) at the same time, then goes off.

**We conclude that:** An instantaneous current flows in the electric circuit, it is called discharge current, this discharge current fading **(equals zero)** when there is no potential difference between the plates of the capacitor ($\Delta V_{AB} = 0V$).

Figure (30) illustrates the relation between capacitor discharge current and time spent to discharge it.

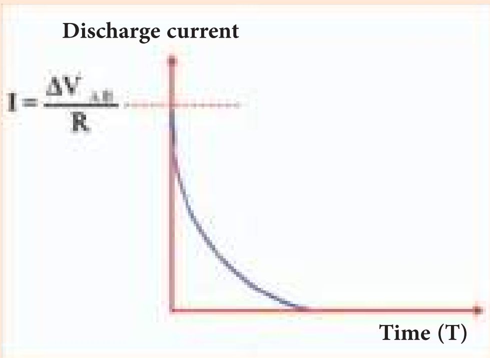


Figure (30)

It has been practically proven that discharge current starts with a huge $I = \frac{\Delta V_{AB}}{R}$ amount the moment the circuit is closed (once the plates of the capacitor are connected to each other by a wire), it drops quickly to zero after completing discharge.

**Remember:**

Plates of a capacitor remain charged for some time unless connected to each other by a wire. This will discharge the capacitor instantly. This process is called Discharge (opposite to capacitor charge).

## Example (8)

An electric circuit in series combination consiste of a lamp resistance ($r = 10\ \Omega$), a resistor ($R = 20\ \Omega$) and a potential difference of battery ($\Delta V = 6V$). A parallel-plate capacitor ($5\mu F$) is connected to the circuit.

What is the amount of charge stored in each of the plates and the electric stored energy in the electric field, if the capacitor is connected:

1. In parallel combination with the lamp, see figure (31-a).
2. In series combination with the lamp, resistor and the battery in the same circuit. (after disconnecting the capacitor from the first circuit and completely discharged from all its charge), see figure (31-b).

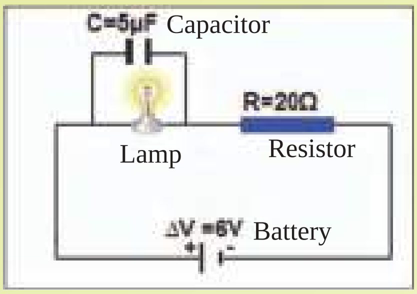

Figure (31-a)

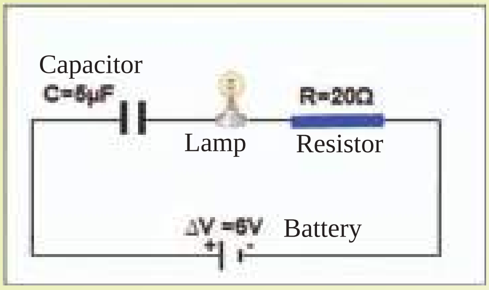

Figure (31-b)

## The solution:

**The first circuit:** figure (31-a) calculate the amount of current in the circuit:

$$I = \frac{\Delta V}{r + R} = \frac{6}{10 + 20} = \frac{6}{30}$$

$$I = 0.2A$$

**Then calculate the potential difference between the terminals of the lamp:**

$$\Delta V = I \times r = 0.2 \times 10 = 2V$$

**Since the capacitor is connected to the lamp in parallel combination, so:**

The potential difference of the terminals of the lamp equal to the potential difference between plates of the capacitor.

The potential difference between the plates of the capacitor is ($\Delta V = 2V$). The stored charge on any of the plates of the capacitor is calculated from the following relation:

$$Q = C \times \Delta V$$

$$Q = 5 \times 10^{-6} \times 2 = 10 \times 10^{-6} = 10\mu \text{ coulomb}$$

**Then the stored energy in the electric field of the capacitor is calculated as follows:**

$$PE = \frac{1}{2} C \times (\Delta V)^2$$

$$PE = \frac{1}{2} \times 5 \times 10^{-6} \times (2)^2 = 10 \times 10^{-6}\ J$$

**The second circuit** figure (31-b)**:** Since capacitor is connected in series combination in a direct current circuit, it disconnects the current in the circuit (I = 0) after it is fully charged (capacitor works as an open switch in the direct current circuit).

So, the potential difference between the two plates of the capacitor equals the potential difference between the terminals of the battery, hence, this circuit is considered open-circuit, the potential difference of the capacitor: ($\Delta V = 6V$) and hence, the stored charge in each of the plates is:

$$Q = C \times \Delta V$$

$$Q = 5 \times 10^{-6} \times 6 = 30\mu \text{ coulomb}$$

To calculate the stored energy in the electric field between the plates of the capacitor, the following relation applies:

$$PE = \frac{1}{2} C \times (\Delta V)^2$$

$$PE = \frac{1}{2} \times 5 \times 10^{-6} \times (6)^2 = 90 \times 10^{-6} \text{ J}$$

## 1-10 Some practical applications of the capacitor

1. The capacitor placed in the flash lamp system in the camera, figure (32) (After charging it with a battery in the system), it supplies the lamp with enough energy to glow suddenly with a bright light while the capacitor is being discharge.

Figure (32)

2. The capacitor placed in microphones, see figure (33), where one of its plates is solid fixed and the other is flexible and free movement, and the two plates are at constant potential difference.

Sound waves cause vibration of the flexible moving plate it back and forth, so the amount of capacitance of the capacitor changes according to the change of distance between its two plates, and with same sound waves frequency, which means transformation of mechanical vibrations into electrical vibrations.

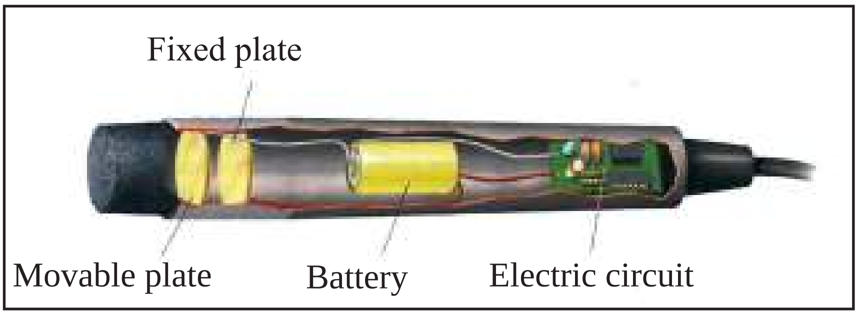


Figure (33)

3. The capacitor placed in the device for stimulating and regulating the movment of heart muscles (the defibrillator), see figure (34-a), is one of the important applications use in medicine. This device is used to transfer different and specific amounts of electric energy to the patient who suffers disturbances in the movement of his heart muscles, when his heart not able to pump blood, so the doctor uses a strong electric shock, figure (34-b) which stimulate the heart and reorganizes its work. the charged capacitor in the defibrillator device discharges its stored energy, which range between (10J - 360J) in the pntients' body for avey short period of time.

Figure (34-a)

Figure (34-b)

4. Capacitor used in computer keyboard a capacitor is placed under each letter in the keyboard, see figure (35). Each key is connected to a movable plate, which represents one plate of the capacitor, while the other plate is connected to the base of the key. When the key is pressed, the sepration distance between the plates of the capacitor decreases, which in turn, increase the capacitance. This makes the external electronic circuits recognize the pressed keys.

**Remember:**

The benefit of using capacitor in practical applications lies in the fact that these capacitors can hold huge amounts of electric energy, and the possibility to of discharging this huge energy instantly, like the capacitor used camera flash lamp system in the camera and the capacitor placed in the device for stimulating and regulating the movment of heart muscles (the defibrillator).

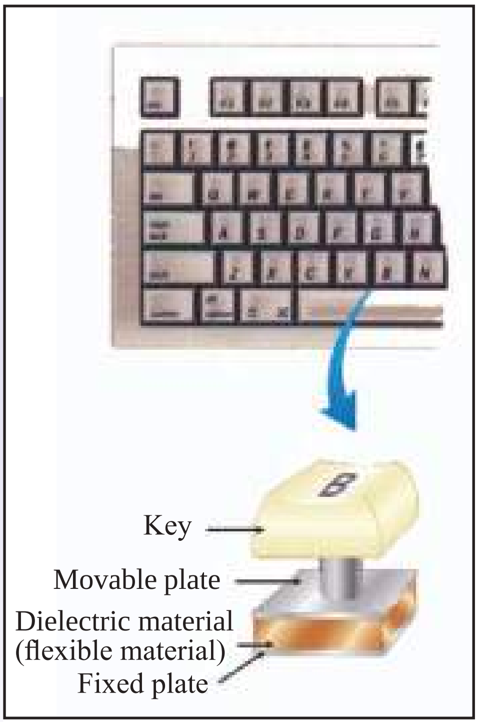


Figure (35)

## Do you know?

Modern applications of capacitors is touch screens in mobile smart phones (iPhone and iPad), computers, ballot machines which are common nowadays. See figure (36) illustrates the use of capacitors in touch screen of iPhone. When the finger touches the screen, capacitance of the capacitor in that spot changes and identifies the order.

Figure (36)

**Q1 Choose the correct statement for each of the following:**

1. Parallel-plate capacitor charged and disconnected from battery, air fills the space between its two plates, then a dielectric with constant is (k =2) inserted between plates. The amount of electric field ($E_k$) between the plates with the dielectric compared with the amount of (E) in the case of air will be:

   a. $\frac{E}{4}$ b. 2E c. E d. $\frac{E}{2}$

2. (Farad) unit is used to measure capacitance of capacitor, it is not equal to one of the following units:

   a. $Coulomb^2/J$ b. Colulomb/V c. Coulomb $\times V^2$ d. $\frac{J}{V^2}$

3. Parallel-plate capacitor its capacitance (C), brought its two plate closer together until the distance between them became (1/3) what it was, so the amount of its new capacitance equals:

   a. $\frac{1}{3}C$ b. $\frac{1}{9}C$ c. 3C d. 9C

4. (20μF) capacitor, in order to store (2.5 J) energy in its electric field, it needs to be connected to a direct potential difference that equals:

   a. 150V b. 350V b. 500V d. 250kV

5. The capacitance of parallel-plate capacitor (50μF), air is the dielectric between plates, if a dielectric is inserted between plates to increase the capacitance by (60μF); dielectric constant of that material is:

   a. 0.45 b. 0.55 c. 1.1 d. 2.2

6. While you are in the laboratory, you needed (10μF) capacitor, you have a set of identical capacitors, with a capacitance (15μF) then the number of capacitors are used and combination method is:

   a. (4 capacitors), all connected in series combination.
   b. (6 capacitors), all connected to parallel combination.
   c. (3 capacitors), 2 connected in series combination, the group is connected to the third in parallel combination.
   d. (3 capacitors), two connected in parallel combination, the group is connected to the third in series combination.

7. Parallel-plate capacitor, its two plates are connected between terminals of a battery with constant potential difference, if the plates are separated from each other a little while the battery is still connected to them, the electric field between the two plates:

a. Increases, stored charge in either of its plates increase.
b. Decreases, stored energy in either of its plates decrease.
c. Remains constant, the stored charge in any of the plates remain constant.
d. Remains constant, stored charge in either its plates increases.

8. To obtain maximum equivalent capacitance of group of capacitors in figure (37), we choose one of the circuits below:

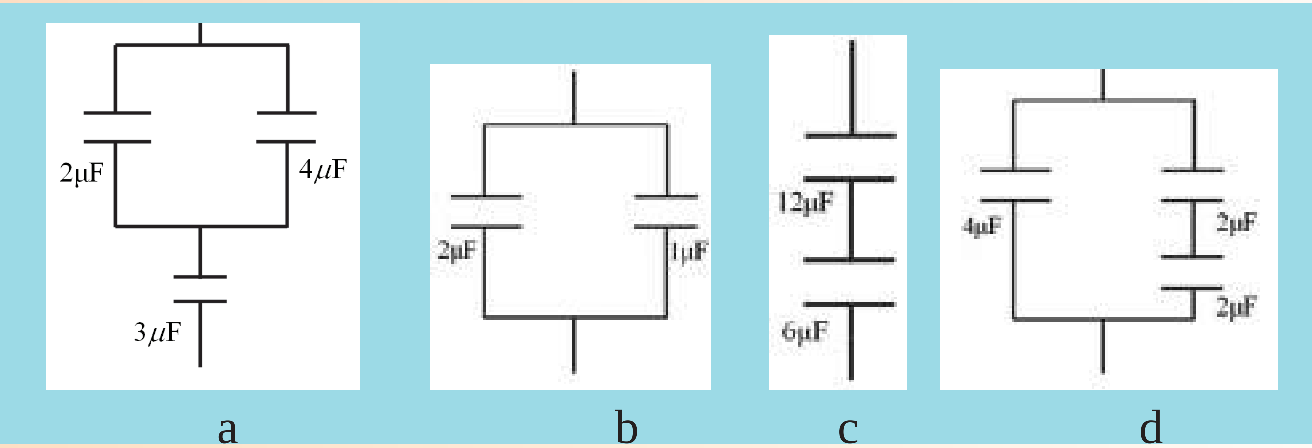


Figure (37)

9. Two capacitors ($C_1$, $C_2$) connected in series combination, the group is connected to the terminals of the battery, capacitance of the first was larger than the second, when comparing potential difference between the plates of capacitor one ($\Delta V_1$) with that of capacitor two ($\Delta V_2$), we find that:

a. ($\Delta V_1$) greater than ($\Delta V_2$).
b.($\Delta V_1$) less than ($\Delta V_2$).
c. ($\Delta V_1$) equals ($\Delta V_2$).
d. All above, it depends on charge of each.

10. Three capacitors, ($C_1.C_2.\ C_3$) connected in parallel combination, this group is connected to a battery, if the capacitances are ($C_1 > C_2 > C_3$), compare charges ($Q_1.Q_2.\ Q_3$) stored in any of the plates of each capacitor, we find that:

a. ($Q_3 > Q_2 > Q_1$)
b. ($Q_1 > Q_3 > Q_2$)
c. ($Q_1 > Q_2 > Q_3$)
d. ($Q_3 = Q_2 = Q_1$)

**Q2** When doubling the electric potential difference between the two plates of the capacitor with a constant capacitance, what happens to the amount of each of the following:

a. Stored charge (Q) in each of the plates.

b. Stored energy in the electric field between the plates.

**Q3** A charged capacitor, potential difference between the two plates is very high (disconnected from voltage source), such capacitor is dangerous for along time if plates are touched by hand directly. What is your explanation for that?

**Q4** Parallel-plate capacitor (air is the insulator between plates) explain how the amount of its capacitance changes when the following factors change (mention mathematical relation in your answer):

a. Surface area of the two plates.

b. Distance between the two plates.

c. Type of dielectric between the two plates.

**Q5** Draw a diagram of an electric circuit (with marking its parts) and illustrate the following:

a. The charging process of the capacitor.

b. The process of discharging the capacitor from its charge .

**Q6** You have three identical capacitors, each with a capacitance (C) and a continuous voltage source with constant potential difference between the terminals.

Draw a diagram of an electric circuit, illustrate proper way to connect the three capacitors in the circuit to obtain maximum amount of elecetrical energy that can be stored in the group. Then prove that the arrangement you chose is the best.

**Q7** Are the capacitors (variable) capacitance of rotating plates in figure (38), connected in series combination or in parallel combination? Explain this?

Figure (38)

**Q8** The capacitor ($C_1$) is connected to a battery terminals. Explain what happens? to the potential difference between the plates of ($C_1$) and the stored charge in it, if another capacitor ($C_2$) not charged is connected to ($C_1$) (while the battery is still connected to the circuit), the connection method was:

1. In parallel combination with ($C_1$)
2. In series combination with ($C_1$)

**Q9** In figure (39); three identical capacitors each have capacitance (C). Arrange the four figures in descending from the largest amount of the equivalent capacitance of the group to the smallest amount:

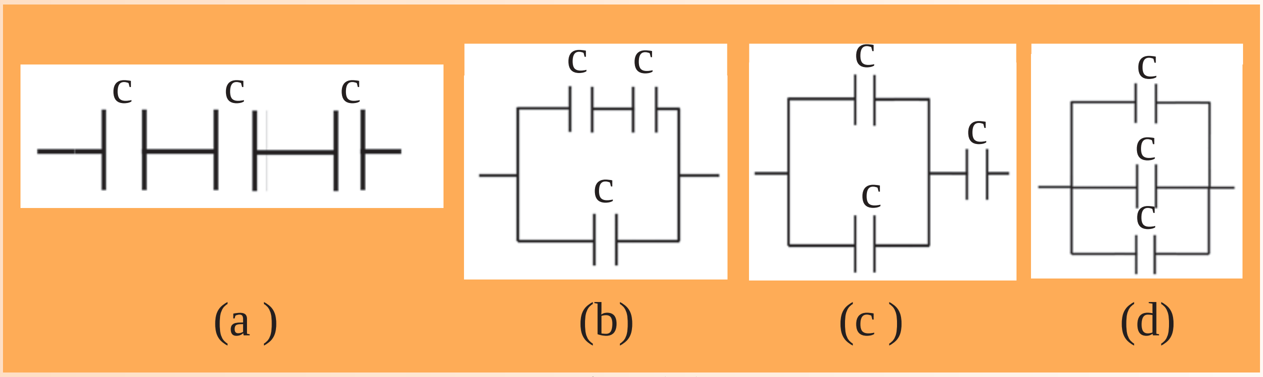


Figure (39)

**Q10** a. Mention three practical applications of the capacitors and explain practical benefit of using this capacitor in each application.

b. A parallel plate capacitor is charged and disconnected from battery. When pure water is inserted instead of air between plates of capacitor, the amount of potential difference between plates is decrease. Explain how?

c. What are the two practical benefits of inserting dielectric that fills the space between the two parallel plate capacitor instead of air.

d. What is the factor which changes capacitance of capacitor placed in a keyboard of computer which is being used?

e. What is the source of applied electrical energy of medical instrument (defibrillator) which is used to produce electric shock for purpose of stimulating and restoring regularity of the work of patient's heart.

f. What is the physical explaination of the followings?

1. Increase of equivalent capacitance of group when they are connected in parallel?
2. Decrease of equivalent capacitance of group when they are connected in series?

**Q11** **State the reason of the followings:**

a. A charged capacitor insert in (DC) circuit behaves like an open switch?

b. The amount of electric field between the plates of the capacitor decreases when its disconected and insert a dielectric material between the plates.

c. The maximum amount of electric potential difference can be determined, is specified and written on the capacitor.

**Q12** A capacitor with two parallel plates the air is insulator between plates is charged by a battery then disconnected from it, when a dielectric plate which dielectric constant (k = 2) is placed between plates of the capacitor.

What happens for the following quantities of the capacitor (mention the reason):

a. Stored charge in any of its plates.

b. Its capacitance.

c. Potential difference between plates of the capacitor.

d. The electric filed between its plate.

e. Stored energy in electric field between its plates.

**Q13** A parallel plates capacitor, the air is an insulator between the plates and the capacitor is connected to the battery. When a dielectric material which dielectric constant (k = 6) is inserted in capacitor, the battery is still connected.

**What happens for the followings quantities of the capacitor mention the reason:**

a. Potential difference between its plates

b. Its capacitance.

c. Stored charge in any of the plates.

d. Electric field between its plates.

e. Stored energy in the electric field between its plates.

## Problems of chapter one

**P.1** From the information shown in the electrical circuit figure (40):

a. Maximum amount of the charging current at the moment of closing the switch.

b. Potential difference between plates of capacitor after a priod of closing the switch (after complete charging process).

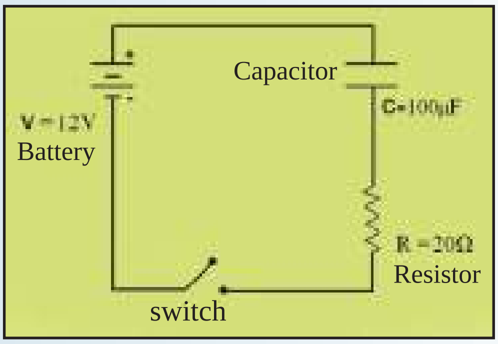


Figure (40)

c. Stored charge in any plates of the capacitor.

d. Stored energy in the electric field between its two plates

**P.2** A parallel plate capacitor with a capacitance of (4μF) is connected to the terminals of (20V) battery.

a. Find the amount of stored charge in any plates of the capacitor.

b. If the capacitor is disconnected from the battery and a dielectric is inserted between its plates, the potential difference reduces to (10V), what is the dielectric constant of the dielectric and find the capacitance of capacitor after inserting dielectric between its plates.

**P.3** Two capacitance ($C_1$= 9 μF, $C_2$= 18 μF) of parallel plates capacitor are connected in series combination and then connected to the battery which potential difference is (12V).

a. Calculate the potential difference between plates of each capacitor and electric energy stored in it.

b. A dielectric which dielectric constant (4) is insert between plates of first capacitor ($C_1$) (the battery is still connected to the circuit). What is the amount of potential difference between plates of each capacitor and the stored energy in the electric field between its plates after inserting dielectric?

**P.4** Two parallel plate capacitors ($C_1$= 16 μF, $C_2$= 24μF) are connected in parallel combination and their group connected to (48V) battery. When a dielectric material with dielectric constant (k) is placed between plates of first capacitor ($C_1$) and the group is still connected to the battery, total amount of charge of the group is (3456μC).

**Calculate:**

a. Dielectric constant (k).

b. Stored charge in any plates of each capacitor before and after inserting dielectric.

**P.5** Two parallel plate capacitors ($C_1 = 4\mu F$, $C_2 = 8\mu F$) are connected in parallel combination. If the total stored charge of the group is ($600\mu C$) when they are charged by a continuous voltage source then they are disconnected.

a. Calculate the amount of stored charge and stored energy in the electric field between its plates for each capacitors.

b. If a dielectric material which dielectric constant (2) is placed between plates of second capacitor ($C_2$), find the stored charge in each of the plates, potential difference and the stored energy in the electric field between its plates after inserting the dielectric.

**P.6** You have three capacitors in which their capacitances ($C_1 = 6\mu F$, $C_2 = 9\ \mu F$, $C_3 = 18\mu F$) and an (6V) battery is connected to them. Draw circuit diagram and explain how to connect these three capacitors in order to get:

a. Maximum amount of equivalent capacitance, then find stored charge in the each of the plates and stored charge in the group.

b. The smallest amount of equivalent capacitance, then find stored charge in the each of the plates and stored charge in the group.

**P.7** Four capacitors are connected to each other as shown in the figure (41).

**Calculate:**

a. Equivalent capacitance of the group.

b. Stored charge in any of the plates of each capacitor.

c. Stored energy in the electric field between plates of capacitor ($C_4$).

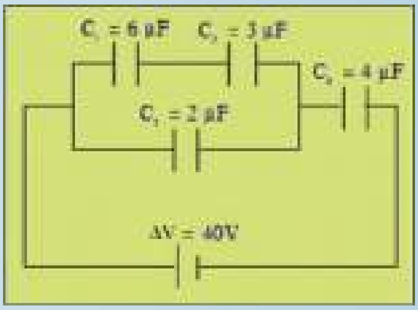

Figure (41)

**P.8** Two capacitors ($C_1 = 3\mu F$, $C_2 = 6\mu F$) connected in series combination with each other, then their group is connected between two terminals of the battery, potential difference is (90V), see figure (42-a). If the capacitors are disconnected from each other and from the battery without losing energy, then they are reconnected with each other

First: as in figure (42-b) after connecting the identical charge plates of the two capacitors with each other.

Second: as in figure (42-c) after connecting the different charge plates of the two capacitors with each other. Find the amount of stored charge in any plates of each capacitor in figures (42-b, 42-c) .

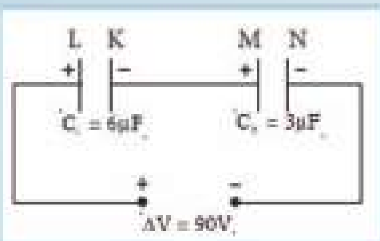

Figure (42-a)

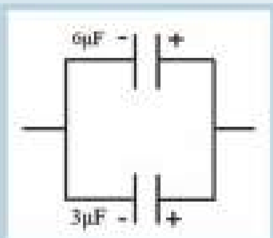

Figure (42-b)

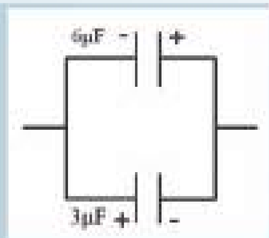

Figure (42-c)

**P.9** In the figure (43):

a. Calculate equivalent capacitance of the group.

b. If an electric potintial diffrence (20V) is applied between the points (a) and (b), what is the amount of the total stored charge of the group.

c. Calculate the amount of stored charge in each capacitors.

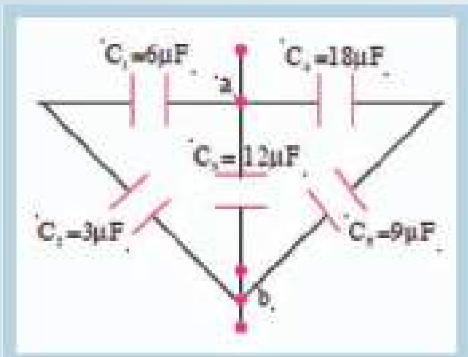

Figure (43)

# CHAPTER 2

# Electromagnetic induction

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2-2 Effect of electric and magnetic fields on charged particles moving through it

2-3 Electromagnetic induction

2-4 Faraday's discovery

2-5 Motional electromotive force ($\varepsilon_{motional}$)

2-6 Induced current

2-7 Electromagnetic induction & principle of conservation of energy

2-8 Magnetic flux

2-9 Faraday's law

2-10 Lenz's law

2-11 Eddy currents

2-12 Electric generators

2-13 (DC) Electric motors

2-14 Inductance

2-15 Self inductance

2-16 Potential energe in inductance

2-17 Mutual induction.

2-18 Induced electric fields

2-19 Some practical application of electromagnetic induction


## Behavioural targets

**After studying this chapter, the student should be able to:**

- Define the concept of magnetism.
- Show the effect of both electric and magnetic fields on charged particles moving through it.
- Explain the phenomenon of electromagnetic induction.
- Mention Faraday's discovery.
- Learn about motional electromotive force.
- Define magnetic flux.
- Know Lenz's law and what is the practical benefit of its application.
- Understand the operation of the electric generator.
- Compare between the operation of an alternating current generator and a direct current generator.
- Explain an experiment about how to generate an induced electromotive force on the ends of a coil.
- Recognize the phenomenon of mutual induction.

## Scientific Terms

| | |
|---|---|
| Electromagnetic Induction | الحث الكهرومغناطيسي |
| Electromotive Force | القوة الدافعة الكهربائية |
| Induced Currents | التيارات المحتثة |
| Magnetic Flux | الفيض المغناطيسي |
| Motional emf | القوة الدافعة الكهربائية الحركية |
| Eddy Currents | التيارات الدوامة |
| Faraday' s Law | قانون فراداي |
| Lenz' s Law | قانون لنز |
| Electric Generator | المولد الكهربائي |
| Electric Motor | المحرك الكهربائي |
| Induced Electromotive Force | القوة الدافعة الكهربائية المحتثة |
| Induced Electric Fieldes | المجالات الكهربائية المحتثة |
| Self - Inductance | الحث الذاتي |
| Mutual Induction | الحث المتبادل |
| Inductors | المحاثات |
| Metal Detectors | كاشفات المعادن |
| Magnetic Field | المجال المغناطيسي |
| Moving Charges | الشحنات المتحركة |
| Magnetic Force | القوة المغناطيسية |
| Lorentz Force | قوة لورنتز |
| Induction Stove | الطباخ الحثي |
| Faraday' s Discovery | اكتشاف فراداي |

## 2-1 Introduction to magnetism

You have previously studied that magnetism is one of the most important topics in physics. Electromagnet is used in lifting heavy iron pieces and many other electrical devices such as (generator, motor, sound generator, audio-visual recorder, electric guitar, computer, magnetic resonance and high-speed express trains), see figure (1).

You have also studied that magnetic field are generated a round moving electric charges and also around permanent magnets.

Figure (1)

## 2-2 Effect of electric and magnetic fields on charged particles moving through it

If a charged particle moves in a uniform electric field and moves in a uniform magnetic field, do you think that both fields have the same effect on that particle?

What happens if this particle moves in both fields at the same time?

* If a positively charged particle (+q) moves in a perpendicular direction to the lines of a uniform electric field ($\vec{E}$) , this particle will be affected by electric force ($\vec{F}_E$) parallel to lines of electric field, see figure (2), which illustrates electric force which given by the following relation:

$$\vec{F}_E = q\vec{E}$$

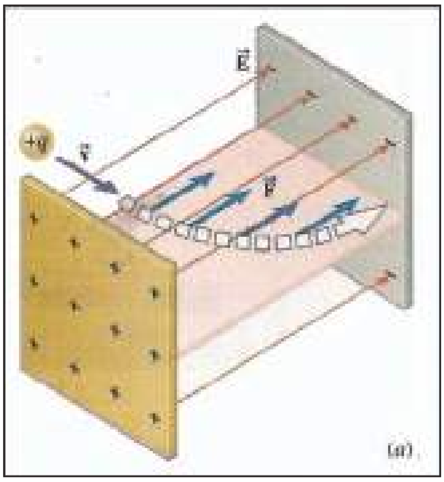



Figure (2) Illustrates the effect of electric force on positively charged particle.

* If the same particle moves with a velocity ($\vec{v}$) perpendicularly on the lines of a uniform magnetic field, with a flux density ($\vec{B}$). It will be affected by a magnetic force ($\vec{F}_B$) is perpendicular on that flux, the particle will deviate from its original path, it will follow a circular path because the magnetic force affects perpendicularly on the velocity vector ($\vec{v}$). see figure (3) The vector formula for magnetic force is given by the following relation:

$$\vec{F}_B = q(\vec{v} \times \vec{B})$$

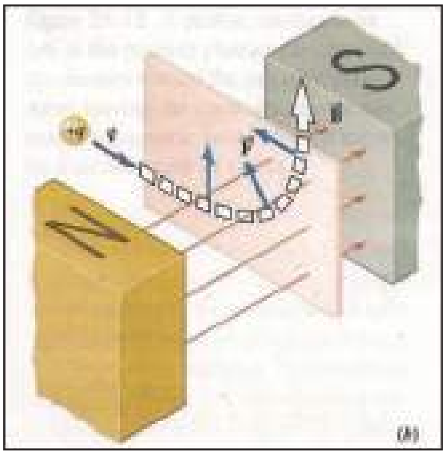



Figure (3) Illustrates the effect of magnetic force on a positively charged particle.

To identify direction of magnetic force ($\vec{F}_B$), right –hand rule is applied, see figure (4):

(Right-hand fingers rotate in the direction of velocity ($\vec{\nu}$) towards the magnetic field ($\vec{B}$), so, the thumb points to force direction ($\vec{F}_B$)).

Magnetic force ($\vec{F}_B$) always affects in a perpendicular direction on the plane, which contains both ($\vec{B}$, $\vec{\nu}$).

The effect of the magnetic force on the moving negative charge is opposite to magnetic force which affects the positive charge. see figure (5). To calculate the magnetic force ($\vec{F}_B$), this relation is applied:

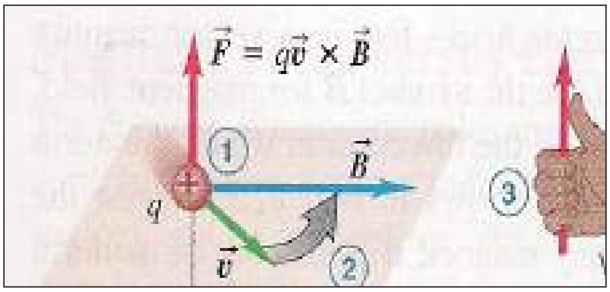



Figure (4)

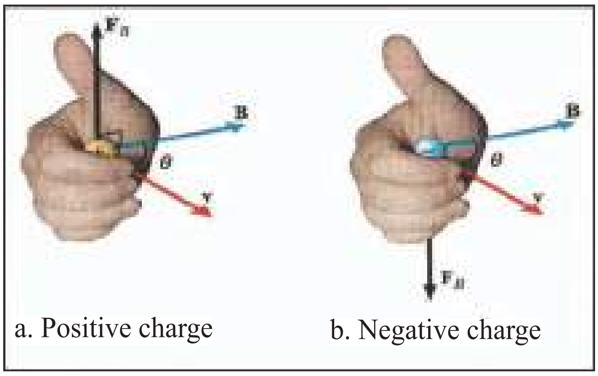



Figure (5)

$$F_B = q\,\nu\, B \sin\theta$$

(θ) is the angle between the velocity vector ($\vec{\nu}$) and the magnetic flux density vector ($\vec{B}$).

From the relation above, magnetic flux density ($\vec{B}$) units in the international system of units (SI) are:

($\frac{N}{A.m}$), called Tesla symbolize by (T). If the velocity vector ($\vec{\nu}$) is parallel to ($\vec{B}$) vector, the angle will be ($\theta = 0°$) Therefore ($\sin 0° = 0$), Then no magnetic force is created, ($F_B = 0$).

if ($\theta = 90°$) then the maximum magnetic force will be: $F_B = q\,\nu\, B$.

- Assuming there is region affected by both a uniform electric field ($\vec{E}$) and a magnetic field with a uniform flux density ($\vec{B}$), at the same time, and suppose both fields are perpendicular with each other, the electric field effects in this page while the magnetic field affects perpendicularly in to the page (far from the reader represented by X), see figure (6).

When a positively charged particle (+q) is thrown with velocity ($\vec{\nu}$) in the plane of the page perpendicularly on both electric and magnetic fields. This particle will be affected by two forces, one is electric force ($\vec{F}_E$) that affecting in the electrical field ($\vec{E}$), expressed as follows:

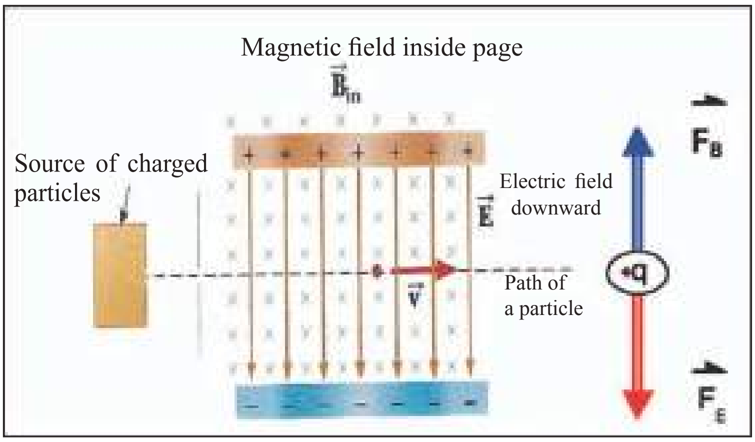



Figure (6)

$$(\vec{F}_E = q\vec{E})$$

The other is magnetic force ( $\vec{F}_B$ ), that affecting in the magnetic field ( $\vec{B}$ ), expressed as follows:

$$\vec{F}_B = q(\vec{\nu} \times \vec{B})$$

Since the magnetic force ( $\vec{F}_B$ ) is perpendicular on both ( $\vec{B}$ , $\vec{\nu}$ ), it moves either in the direction of the electric force ( $\vec{F}_E$ ) or the opposite direction, see figure (6).

The resultant of both forces is called (Lorentz force) Lorentz force is expressed as follows:

$$\vec{F}_{Lorentz} = \vec{F}_E + \vec{F}_B$$

Lorentz force is used in practical applications, like Cathode –ray tube that controls the path electronic band on the monitor, see figure (7), which illustrates path of electronic band. This band is affected by both uniform electric and magnetic fields through the cathode plotter.

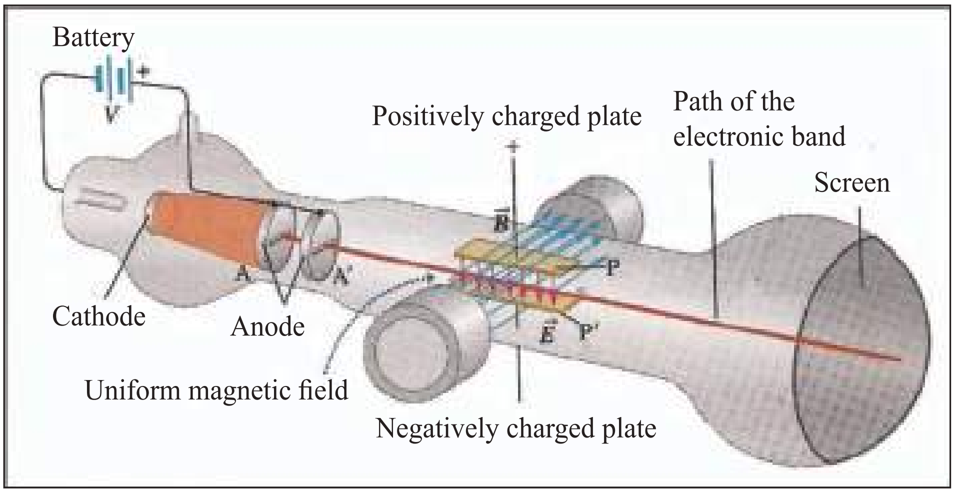



Figure (7) For reference only (Not required)

**Remember**

If a positively charged particle moves perpendicularly on:

- Uniform electric flux, the particle will be affected by electric force ( $\vec{F}_E = q\ \vec{E}$ ) with a parallel plane to the electric flux.
- Uniform magnetic flux, the partical will be affected by a magnetic force $\vec{F}_B = q\ (\vec{\nu} \times \vec{B})$ with a perpendicular plane to the magnetic flux.
- Uniform both magnetic and electric flux at the same time and perpendicular on each other, the particle will be affected by resultant of both forces ( $\vec{F}_B$ , $\vec{F}_E$ ) which called Lorentz force.

The direction of the magnetic force ( $\vec{F}_B$ ) will be opposite to the electrical force ( $\vec{F}_E$ ) or in the same direction and same line of the action, therefore;

$$\vec{F}_{Lorentz} = \vec{F}_E + \vec{F}_B$$

## 2-3 Electromagnetic induction

As you have previously studied, Orsted 1819 discovered that (the electric current generates a magnetic field). Therefore, Orsted was the first to discover the relation between electricity and magnetism. This discovery made scientists search and survey access to the opposite concept, i.e. Is it possible for the magnetic field to generate an electric current in an electric circuit? This question remained unknown for a long time until 1831, Faraday in England and Henry in US, after many experiments, (Individually) discovered that: it is possible to generate electric current in a closed conductor ring (or a coil from a conductor wire) by an alternating magnetic field facing this ring or coil.There are many ways in which, the magnetic field is used to generate electric current, see figure (8) which illustrates Orsted and Faraday concept, they complement each other.

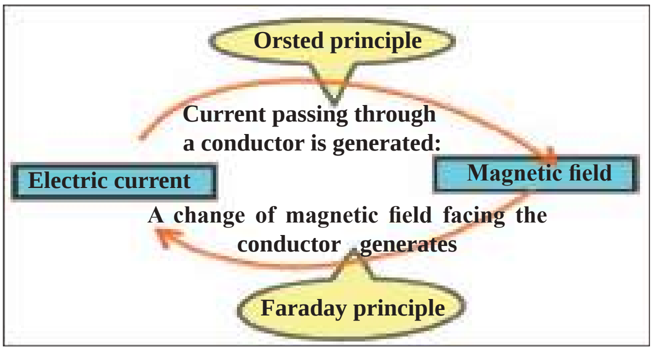


Figure (8)

Figure (9-a) shows one of those ways, it shows magnetic rod and a coil form a conductor wire connected to a digital ammeter.

When the magnetic rod is at rest relative to the coil, the reading of the ammeter is zero. Why?

Figure (9-a)

The answer is: the magnetic flux ( $\Phi_B$ ), which penetrates the coil, does not change through time. Moreover, there is no relative motion between the magnet and the coil. Therefore, no current pass through the circuit. See figure (9-a) However, when we hold the magnetic rod by hand and direct its north pole to one sides of the coil, push it towards the coil and a parallel to coil axis, what happens?

Looking closely at figure (9-b), we find the answer, the ammeter indicates deflection of current in the circuit in a certain direction. The reason for this is increase in magnetic flux ( $\Phi_B$ ), which penetrates the coil when the magnet approaches to the coil.

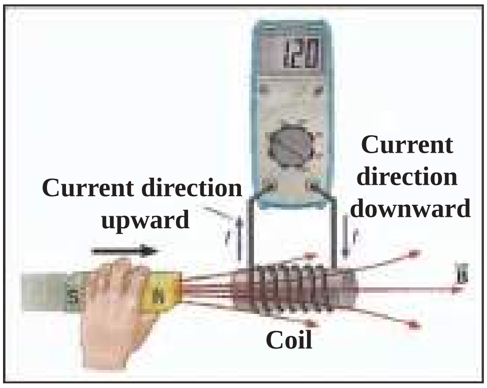


Figure (9-b)

If the magnetic rod is moved away with a same velocity and its north pole facing the coil and which is parallel to its axis, Will the ammeter point to current flow? Will this current have the same direction when the north pole of the rod comes closer to the coil?

See figure (9-c) and answer this query?

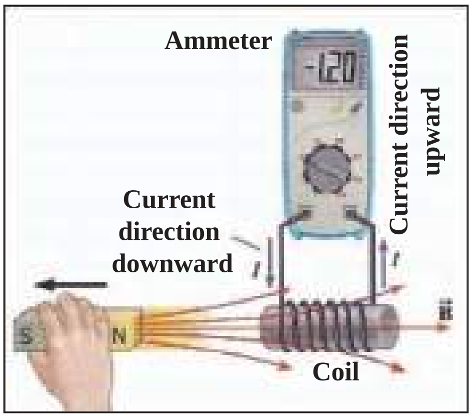


Figure ( 9-c)

The flowing current in the circuit in both cases is called induced current symbolized by ($I_{ind}$), it is generated due to change in the magnetic flux ($\Delta\Phi_B$) which penetrates the coil to the unit time.

It has been practically proven that induced current increases when:

- Velocity of relative motion between the magnet pole and the coil.
- Number of turns for the coil.
- The amount of magnetic flux penetrates the coil.
- Magnetic permeabilty of core coil material (inserting a core of wrought iron inside the coil instead of air will increase density of magnetic flux).

**Think?**

If the magnetic rod is fixed (with its south pole facing one side of the coil), then the coil is push towards the rod which is parallel to its axis. Will the induced current in the coil be reversed? or, it will flow in same direction when the magnetic rod is moved towards the coil? What is your answer?

## 2-4 Faraday's discovery

There are so many experiments that can be conducted in laboratory to explain Faraday's experiment on electromagnetic induction, like using two coils of two wires wrapped around a closed ring of wrought-iron. One of the coils is connected in series combination to a battery and a switch the circuit on the left side as figure (10-a), which is called the primary coil circuit, while the other coil is connected to a device that detects small currents.

It has zero point in the middle (circuit on the right side) this one is called the secondary coil circuit.

Faraday observed deflection of the pointer, connected to the secondary coil, to one of the sides at the switch connected to the primary coil is turned off, then it goes back to zero, see figure (10-a).

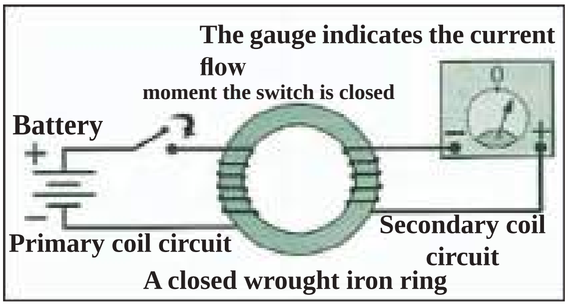


Figure (10-a)

You might ask, what happened? The deflection of the gauge pointer is the proof of electric current flow in the secondary coil circuit, this current is called "induced current", although there is no battery or voltage source in this circuit. As for the pointer goes back to zero after closing the switch, it was because the current flow in the primary coil circuit was constant. Hence, there was no change in the magnetic flux, which penetrated the secondary coil per unit time ($\frac{\Delta\Phi_B}{\Delta t}$), see figure (10-b).

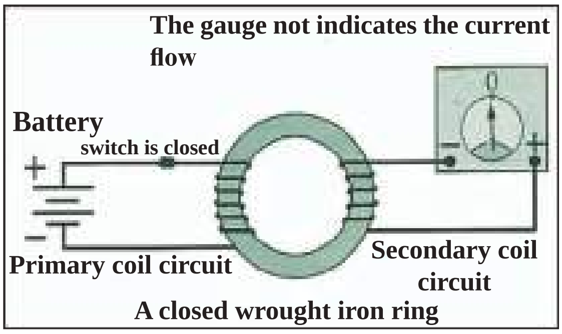


Figure (10-b)

Faraday also noticed that another deflection in the pointer of the gauge again, at the moment when the switch is opened, but this time the deflection was opposite to zero, see figure (10-c), then it went back to zero.

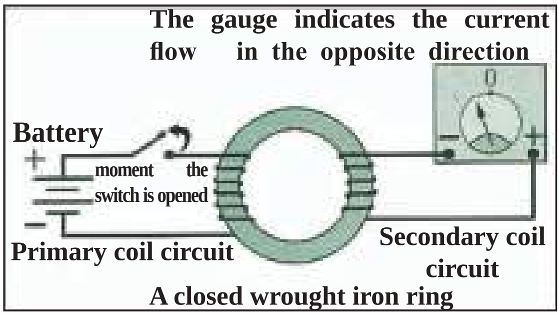


Figure (10-c)

Faraday's observation was: this effect (current flow in the secondary circuit) accrued only during the two stages of growth and decay of current in the primary coil circuit.

Since both growth and decay of current in the primary coil circuit would cause increase and decrease in the magnetic flux, that penetrates the core of iron that wrapped in the two coils.

Therefore, Faraday pay attention to the necessity of the availability of the basic factor to generate induced current in a closed circuit, the change in the magnetic flux that penetrates the coil to the unit time. According to this, Faraday concluded:

An induced current is generated in a closed circuit (like a wire coil or conductive ring) only when there is change in the magnetic flux which penetrates that circuit per unit time ($\frac{\Delta\Phi_B}{\Delta t}$).

After successful observations, Faraday finally gave a physical explanation why previous attempts failed to generate electric current by using magnetic field, all of the previous attempts relied on constant (fixed) magnetic fields only.

To illustrate the concept of the phenomenon of electromagnetic induction after Faraday's dramatic discovery, many experiments were conducted to generate induced current in a closed electrical circuit dose not contain battery or voltage source.

## Activity (1):

## Explaining electromagnetic induction phenomenon:

**Tools of activity:**

Two hollow wire coils of different diameters (one can be inserted in the other), Galvanometer with zero reading in the middle, magnetic rod, wires, battery and electric switch.

**Activity steps:**

**First:**

- One end of the coils is connected to the galvanometer.
- Put north end of the magnetic rod faces the coil during in activity for the coil. Do you notice deflection in the pointer reading of the galvanometer?

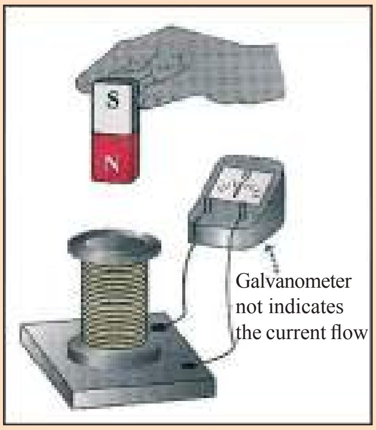


Figure (11-a)

We will find that galvanometer pointer will remain fixed at zero scale. There is no flow of current in the coil circuit. See figure (11-a).

- The magnetic rod is pushed towards the coil, then moved away, what do you notice?

Figure (11-b)

We find that the galvanometer pointer deflects to one side of zero scale (when the rod is close) and the pointer moves to the opposite direction (when is moved away). This indicates induced current flow in the coil, in both cases. See figure (11-b).

**Second:**

- Connect the two ends of other coil (primary coil) are connected to a battery terminals by wires to create electromagnet.
- The primary coil connected to the battery is moved in front of the secondary coil which connected to the galvanometer, brought it closer and then moved away from it which is parallel to its axis. What do you notice?

Figure (11-c)

We note that the pointer of galvanometer is deflected on one side about zero scale and in opposite direction again. This indicates an induced current flow in the secondary coil circuit and then it goes back to zero when there is no relative motion between the two coils. See figure (11-c).

**Third:**

- Connect an electrical switch to the primary coil circuit and make it open.
- Insert the primary coil is in the secondary coil; the ratio of both is maintained. Will the galvanometer pointer deflected?
- Close and open the switch in the primary coil circuit. What do you notice? We find the galvanometer pointer deflects by moving on both sides of the zero reading in opposite directions only once the switch is turned on and off in the primary coil circuit respectively. It indicates flow of induced current in the secondary coil circuit in those two ways. See figure. (11- d).

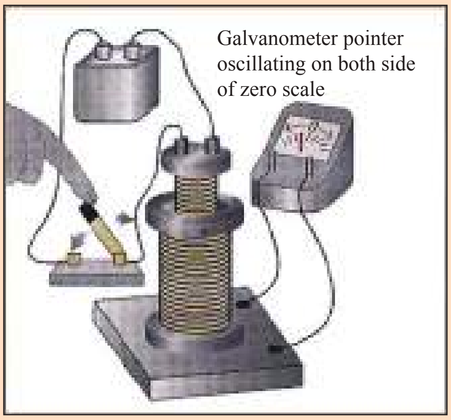



Figure (11-d)

**From the above three activities, we conclude the following:**

- An electromotive force is induced ($\varepsilon_{ind}$) and an induced current ($I_{ind}$) flows in a closed circuit (conductive ring or a coil) only when there is change in the magnetic flux that penetrates that circuit per unit time, (although there is no battery in that circuit).
- The polarity of the induced emf ($\varepsilon_{ind}$) and direction of the induced current ($I_{ind}$) in the electric circuit, have a certain direction when there is increase in the magnetic flux that penetrates it, and they have opposite direction when the flux decreases.

## 2-5 Motional electromotive force ($\varepsilon_{motional}$)

Inducing emf by moving a conductor rod inside a uniform magnetic field is called motional electromotive force. It is considered as a special case of electromagnetic induction:

As a result of, the movement of the conductor rod inside the magnetic field, the positive charges of the rod are affected by a magnetic force ($F_{B1} = q\nu B \sin\theta$).

When the rod is moved perpendicularly against the magnetic flux, this force is expressed as follows:

$$(F_{B1} = q\nu B)$$

It affects parallel to the axis of the rod; therefore, this force detaches the positive charges from the negative charges. Positive charges gather on one end and the negative charges gather on the other end.

Figure (12-a) shows how positive charges gather at the upper end and the negative charges at the lower end, according to the right-hand rule, when the density of the magnetic flux ($\vec{B}$) is in a perpendicular direction to the page, and the rod is moved at certain velocity ($\vec{\nu}$) towards the right and in a plane of the paper.

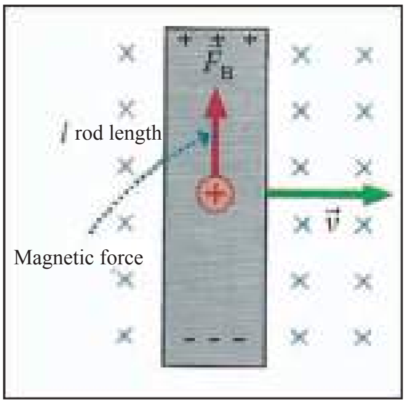



Figure (12-a)

The charges keep gathering along the ends of the rod and they move inside the magnetic field. An electric potential difference is generated between ends of the rod, it is called motional electromotive force ($\mathcal{E}_{motional}$).

Consequently, an electric field is created ($\vec{E}$) witch is directed downward, see figure (12-b). The generated electric force will affect these charges ($F_E = qE$).

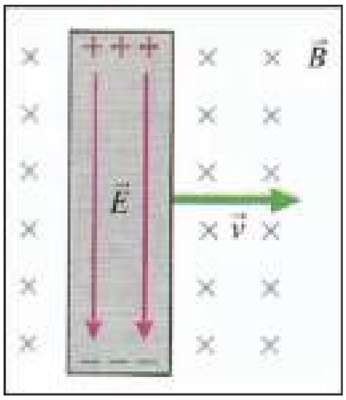



Figure (12-b)

It is noted here that direction of the force of the electric field ($\vec{F}_E$) is downward and parallel to the axis of the rod, it is opposite to the direction of the force that affects the magnetic field ($\vec{F}_{B1}$) in that charge which affects upward. Both forces are at same plane and same line of action. See figure (12-c). When these forces are equal, equilibrium (balance) happens: $\vec{F}_E = \vec{F}_{B1}$

Which becomes: $qE = q\nu B$ Then, we have the following relation:

$E = \nu B$

Since electric potential gradient equals the amount of the electric field, i.e:

$$\frac{\Delta V}{\ell} = E$$

($\ell$) represents length of the rod inside the magnetic field, so:

$$\frac{\Delta V}{\ell} = \nu B$$

Thus, the potential difference between ends of the rod is: $\Delta V = \nu B \ell$

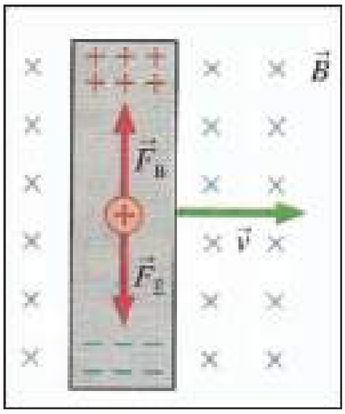



Figure (12-c)

Electric potential difference between the two ends of the rod depends on density of magnetic flux ($\vec{B}$), velocity ($\nu$) in which the rod moves inside the magnetic field.

Motional electromotive force which is created on the both ends of conductor the length ($\ell$) moving at velocity ($\nu$) perpendicular to the direction of the density of the magnetic flux ($\vec{B}$), and expressed as follows: $\mathcal{E}_{motional} = \nu B \ell$

**Think?**

If the direction of the moving rod is reversed or the magnetic field is reversed, will the polarity of the motional electromotive force ($\mathcal{E}_{motional}$) reverse?

## Do you know?

In 1996 space scientists did experiments to make use of Earth's magnetic field to generate motional electromotive force ( $\varepsilon_{motional}$ ) on the ends of a long metal wire while the wire is moving along the magnetic field of earth. One of the ends of the wire is connected to the spaceship Columbia and pulled up to space.

## 2-6 Induced current

Now you are entitled to wonder, what is the practical procedure taken to flow an induced current in the moving rod inside a magnetic field?

To answer this question: this rod is placed in a closed electric circuit, this process is made by sliding the rod at certain velocity ( $\nu$ ) to the right along a conducting track U-shaped and connected to a lamp in series combination, this track is placed on a table, see figure (13). In this order, the rod, the track and the lamp becomes a closed electric circuit.

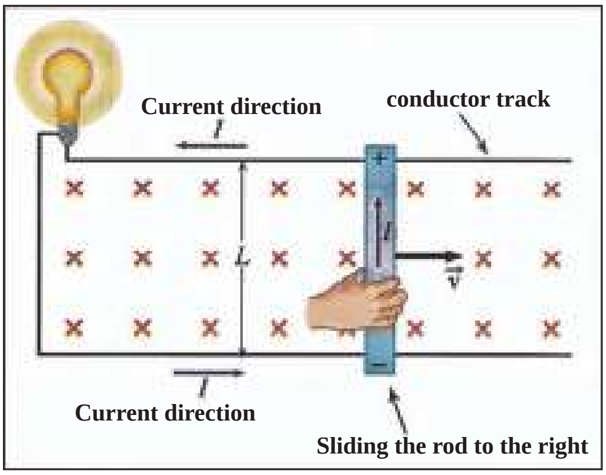



Figure (13)

If a uniform magnetic field with a magnetic flux density ( $\vec{B}$ ) is exerts in a perpendicular direction to the plane of that circuit (for example: its direction is inside the paper, as shown in figure (13). These positive charges in the rod will be affected by a magnetic force pushing it towards one end of the rod, while the negative charges are pushed to the other end. In this case, it will be ($F_{B1} = q\nu B$).

Since this circuit is closed, charges will keep moving and don't gather at the ends of the rod, therefore, a current flows in the circuit, it is called Induced current. Current flow in the circuit indicates the glow of lamp, which is connected to the track in series combination. If the right-hand rule is applied to a positive charge, the direction of the induced current in the circuit is counter clockwise. If the total resistance (R) in the circuit, then the induced current in this circuit is expressed as follows:

$$\boxed{I = \frac{\varepsilon_{motional}}{R}} \longrightarrow \boxed{I = \frac{\nu B\ell}{R}}$$

As a result of the flow of induced current in the rod in perpendicular direction to the magnetic flux, a magnetic force appears ($F_{B2}$) affecting on its rod, given by the following relation ( $F_{B2} = I\ell B$ ) which was previously studied.

Applying right-hand rule, we find that the force ($\vec{F}_{B2}$) affects perpendicularly on the rod and towards the left, i.e opposite to the direction of velocity ($\nu$) of the rod, therefore, this force obstruct the movement of the rod, it causes deceleration of the rod. See figure (14). in order to keep this rod's velocity constant under these conditions, an external force ($\vec{F}_{pull}$) pull must be imposed toward the right, as follows:

$$F_{pull} = F_{B2} = I\ell B = \left(\frac{\nu B\ell}{R}\right)B\ell = \frac{\nu B^2\ell^2}{R}$$

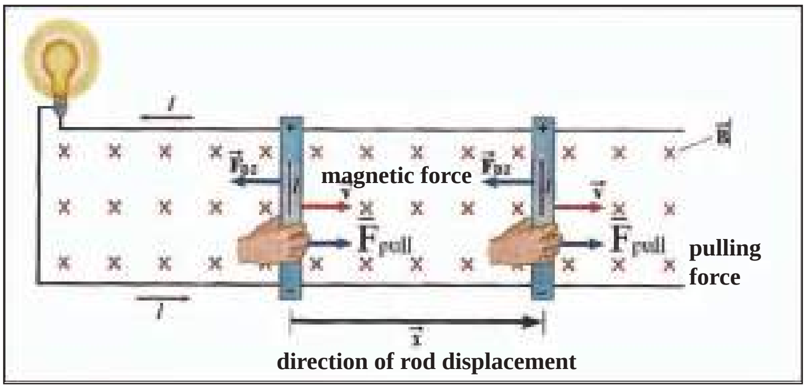


Figure (14)

**Think?**

Is there an induced current flow in the circuit figure (15)?

If yes, determine the direction of induced current in it.

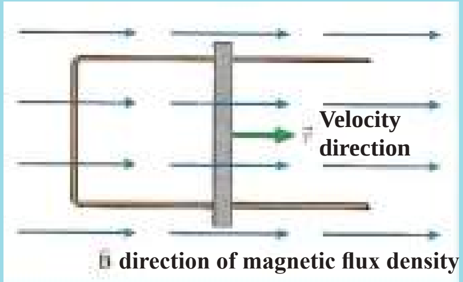


Figure (15)

## 2-7 Electromagnetic induction & principle of conservation of energy

Pulling the conductor rod at a certain displacement inside a magnetic field means that work has been done in moving the rod, what about the stored energy in that rod as a result of that work? Does the energy in that rod dissipated or conserved while moving the rod in the magnetic field? The answer to this, you have to remember information about power which is defined as time rate of work done ($P = \frac{work}{time}$), and since the pulling force caused the movement at the velocity ($\nu$), the power gained in the circuit is given by the following relation:

$$P = F_{pull}.\nu = \frac{\nu^2 B^2\ell^2}{R}$$

We find here that the electric circuit dissipates the power in the form of thermal power in the total resistance (R) in the circuit (items of the circuit and connecting wires), the dissipated power ($P_{dissipated}$) in the resistance by induced current flows ($I_{ind}$) is expressed as follows:

$$P_{dissipated} = I^2R = \frac{\nu^2 B^2\ell^2}{R}$$

Notice that the two aforementioned relation are equal. What dose that means?

**Answer:** The time rate of work done in moving the conductor rod through a magnetic field equals exactly the dissipated power in the total resistance of this circuit in the as a heat or any kind of power in load. This is an application of conservation law of energy.

## Example (1)

Suppose a (1.6) m conductor rod slid on a conductor track with (5m/s) speed perpendicular to a uniform magnetic field with magnetic flux density (0.8T), and the resistance of the lamp (128 Ω) is connected to the track in series combination. See figure (16).

(Neglect the electric resistance of the track and rod) then calculate:

1. Motional emf.
2. Induced current in the circuit.
3. Electric power provided to the lamp.

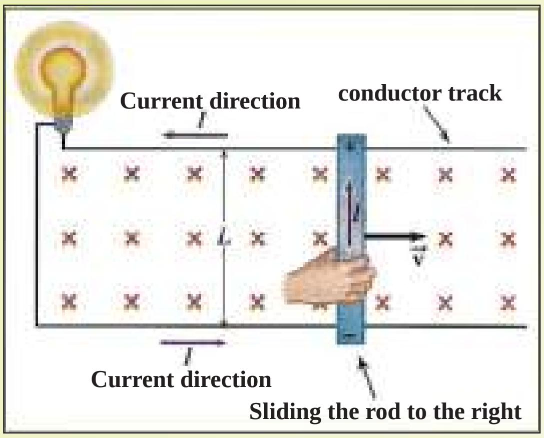



Figure (16)

## The solution:

1. The following relation is applied to calculate the motional emf:

$$\varepsilon_{motional} = \nu B \ell$$

$$\varepsilon_{motional} = 5m/s \times 0.8T \times 1.6m = 6.4V$$

2. The following relation is applied to calculate the current:

$$I_{ind} = \frac{\varepsilon_{motional}}{R} = \frac{6.4V}{128\Omega} = 0.05A$$

3. The following relation is applied to calculate dissipated power in circuit resistance:

$$P_{dissipated} = I^2R = (0.05A)^2 \times 128\ \Omega = 0.32W$$

## 2-8 Magnetic flux

The basic element in generating the induced emf ($\varepsilon_{ind}$). is change in magnetic flux ($\Phi_B$) which penetrates a conductor ring or wire coil, this can be done by several ways: (other than presence of relative movement between the magnetic rod and the conductor ring or wire coil):

**First:**

Change in angle measurement (θ) between area vector ($\vec{A}$) and magnetic flux density vector ($\vec{\mathbf{B}}$). The simplest example is rotation of the generator core coil inside a uniform magnetic field, see figure (17).

(Area vector ($\vec{A}$) represented by the column on area (**A)**).

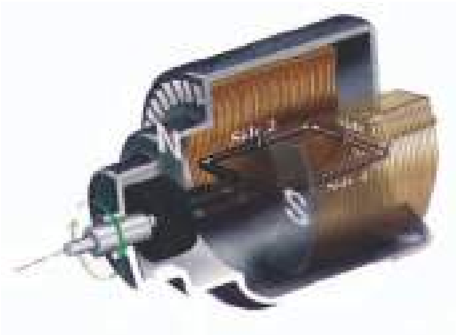


Figure (17)

Let's assume a magnetic field with a uniform flux density ($\vec{\mathbf{B}}$) that penetrates a conductor ring and surface area vector ($\vec{A}$), both forming an acute angle (θ) with ($\vec{\mathbf{B}}$) vector. See figure (18).

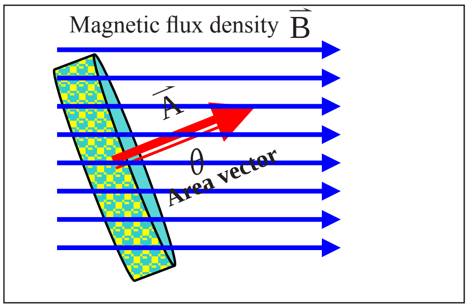



Figure (18)

In this case, the magnetic flux ($\Phi_B$) which penetrates that area, by the following rule:

$$\Phi_B = \vec{B}.\vec{A} \text{ ,with value } \Phi_B = BA\cos\theta$$

The magnetic flux density component (B cosθ) which is perpendicular to the ring plane that specifies amount of magnetic flux which penetrates the ring.

But if the magnetic flux density ($\vec{\mathbf{B}}$) is perpendicular to the ring plane, see figure (19), the magnetic flux that penetrates the area of the ring will be at maximum amount. In this case, the angle (θ) between area vector ($\vec{\mathbf{A}}$) and uniform magnetic flux density vector ($\vec{\mathbf{B}}$) equals zero ($\theta = 0^\circ$).

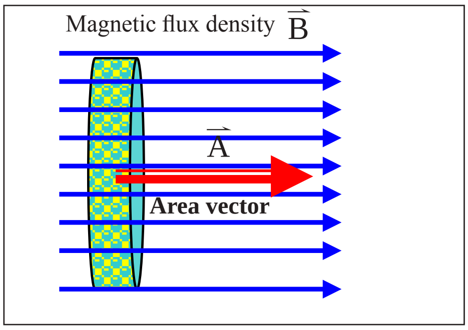



Figure (19)

$$\Phi_B = BA\cos\theta = BA\cos 0^\circ$$

$$\Phi_B = BA$$

If the magnetic flux density ($\vec{\mathbf{B}}$) is parallel to the ring plane, see figure (20). In this case, no magnetic flux penetrates the ring.

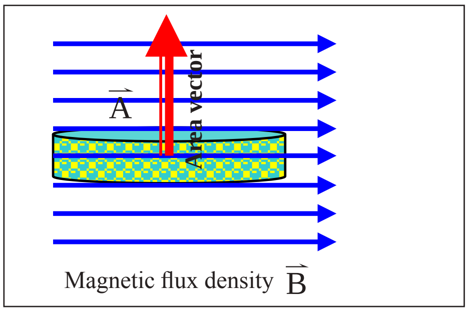



Figure (20)

i.e: the angle (θ) between area vector ( $\vec{A}$ ) and uniform magnetic flux density ( $\vec{B}$ ) is ( $\theta$ = 90° ),

so: $\Phi_B = BA\cos\theta = BA\cos 90° = 0$

$\Phi_B$ = zero

### Second:

Changing area of the ring facing the uniform magnetic flux ($\Phi_B$) . This is done by pressing the ring or pulling it from opposite sides, thus area (A) reduces, see figure (21-a).

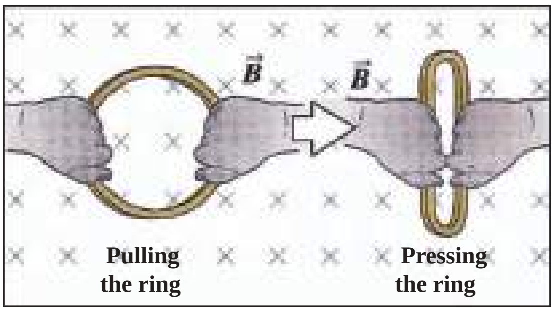



Figure (21-a)

Area can be increased by shifting the rod, see figure (21-b) to the right, and thus changing the area from ($A_0=X_0L$) to (A=XL), and hence find that ($\Delta A=A-A_0$), so the change in magnetic flux is expressed as follows: $\Delta\Phi_B = B.\,\Delta A$

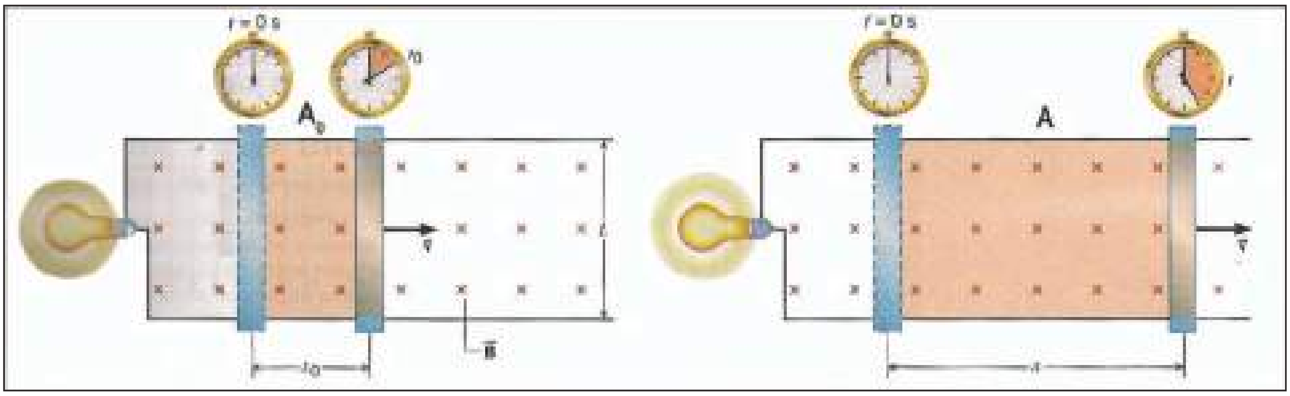



Figure (21-b)

### Third:

Moving the conductive ring in a plane perpendicular to a uniform magnetic flux:

(Pushing the ring to be inserted into a uniform magnetic field or pulling it out of the field). See figure (22). There will be a change in the magnetic flux which penetrates the ring of unit time when the ring enters the magnetic field or during its exit form the field.

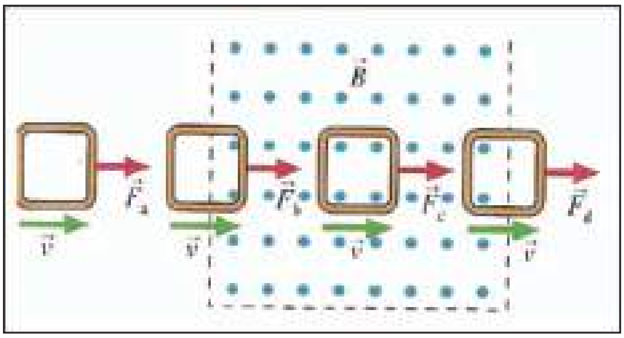


Figure (22)

The magnetic flux unit ($\Phi_B$) in the international system of units is Weber and it is symbolized by (Wb).

Time rate of change in magnetic flux ($\frac{\Delta\Phi_B}{\Delta t}$) is measured in the international system of units by (Weber/second). Then the induced emf ($\varepsilon_{ind}$). is measured by Volt.

## Example (2)

A conductive circular ring with a diameter (0.4m) is inserted in a uniform magnetic field with flux density (B = 0.5T) and parallel to ring area vector ( $\vec{A}$ ).

a. Calculate the magnetic flux that penetrates the ring, see figure (23-a).

b. What is the amount of magnetic flux, assuming that the ring rotates counter-clockwise direction till area vector ( $\vec{A}$ ) created an angle ($\theta=45^0$) with the magnetic flux density direction ( $\vec{B}$ ), see figure (23-b).

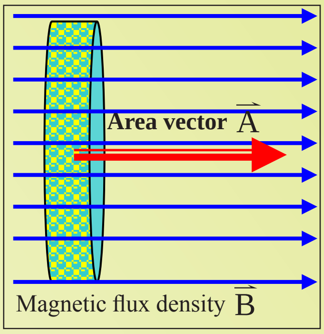


Figure (23-a)

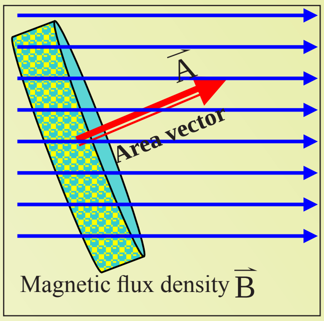


Figure (23-b)

## The solution:

First, the area of the ring is calculated

$A = \pi r^2 = 3.14 \times (0.2)^2 = 12.56 \times 10^{-2}\ m^2$

a. To calculate the magnetic flux when ($\theta = 0^0$), the following relation applies: $\boxed{\Phi_B = BA}$

$\Phi_B = 0.5 \times 12.56 \times 10^{-2} = 6.28 \times 10^{-2}$ Weber

b. After rotating the ring $45^0$ angle, this relation applies:

$\Phi_B = BA \cos\theta = BA \cos 45^0$

$\Phi_B = 0.5 \times 12.56 \times 10^{-2} \cos 45^0$

$\Phi_B = 6.28 \times 10^{-2} \times 0.707 = 4.44 \times 10^{-2}$ Weber

## 2-9 Faraday's law

From all aforementioned observations; it is known that induced emf ($\varepsilon_{ind}$) is generated and an induced current flows in a closed conductive ring if there is change in the magnetic flux that penetrates the ring in unit time (for whatever reason).

Faraday's law in electromagnetic induction is an experiment law and state that:

"Amount of induced emf ($\varepsilon_{ind}$) in a conductive ring is directly proportional to the time rate of change in the magnetic flux that penetrates the ring". The mathematical formula of Faraday's Law is:

$$\varepsilon_{ind} = -\frac{\Delta\Phi_B}{\Delta t}$$

* The negative sign in Faraday's law is set according to Lenz's law (will be studied later) to indicate polarity of the induced emf. This polarity determines the direction of the induced current in the ring or coil. Since the magnitude of the change in magnetic flux is expressed by: $\Delta\Phi_B = \Delta (BA \cos\theta)$.

Any change that takes place in one of the three factors (magnetic flux density (B), area (A), angle ($\theta$)) with time or all of them, will cause induced emf ($\varepsilon_{ind}$), if we have wire coil instead of a ring with a number of winds (N), Faraday's law is expressed as follows:

$$\varepsilon_{ind} = -N\frac{\Delta\Phi_B}{\Delta t}$$

It is clear from Faraday's Law that, an induced electromotion force ($\varepsilon_{ind}$) is generated in a greater amount whenever the time rate of change in magnetic flux $\frac{\Delta\Phi_B}{\Delta t}$ that penetrates the ring or coil is large. The polarity of the induced emf depends on the magnetic flux $\frac{\Delta\Phi_B}{\Delta t}$ whether increasing or decreasing.

**Example (3)**

Figure (24) shows a coil of (50) identical turns, area of one wind (one turns) is ($20cm^2$). If the density of the magnetic flux which penetrates the coil is changed from (0T to 0.8T) in (0.4s), calculate:

1. Average of induced emf ($\varepsilon_{ind}$) in the coil.
2. Amount of flowing current in the circuit if the coil was connected to a galvanometer, and the total resistance in the circuit is (80Ω).

**The solution:**

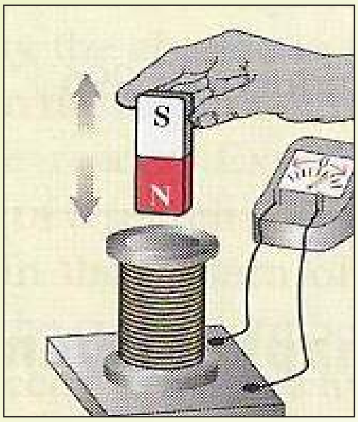


Figure (24)

1. The following rule is applied to calculate the amount of emf:

$$\varepsilon_{ind} = -N\frac{\Delta\Phi_B}{\Delta t}$$

$$\varepsilon_{ind} = -N\frac{A.\Delta B}{\Delta t}$$

$$(\varepsilon_{ind}) = -50 \times \frac{(20\times10^{-4})(0.8T - 0.0T)}{0.4} = -0.2V$$

(negative sign indicates that the emf opposite the cause that generated it.Which is the time rate of change in the magnetic flux according to Lenz's law).

2. To calculate the current, we apply the following relation:

$$I = \frac{\varepsilon_{ind}}{R} = \frac{0.2}{80} = 2.5\times10^{-3}A$$

**Remember**

To have a flowing electric current in a closed circuit, there must be a source for electromotive force ( like a battery or a generator in that circuit).

- To have an induced current in a closed circuit, like a closed conductor ring or a coil (does not have a battery or a generator), there must be an induced electromotive force, which is generated by change of magnetic flux which penetrates that ring in unit time.

## 2-10 Lenz's law

After studying Faraday's law, we have clearly understood how we can practically generate an induced current in a closed circuit. The question is: does the direction of the induced current in the electric circuit really matters? And what is the effect of the magnetic field generated by the induced current (induced magnetic field) on the main factor which generates this current?

The scientist Lenz' answered these two questions through his famous law (Lenz's Law), which states that:

"The induced current in a closed electric circuit has an opposite direction (in its magnetic field) to the change in magnetic flux that causes it".

Lenz's law is the proper way to determines the direction of the induced current in a closed conductive ring. To understand Lenz's law more practically,

we need to answer the question: How can an induced current generate in an induced magnetic field that is opposite by its effect to the cause? The answer is, a magnetic rod is moved near the front of a closed conductive ring and parallel to its perpendicular axis on both sides and passes from its center. If the north pole of the rod is facing the ring.

a. When the north pole approaches from the face of the ring, it causes increase in the magnetic flux penetrates the ring $(\frac{\Delta\Phi_B}{\Delta t} > 0)$.The direction of the effective magnetic flux $(\vec{B})$ downward and it increases by $(\frac{\Delta B}{\Delta t} > 0)$. See figure (25).

Therefore, the direction of the induced current is counter clockwise (according to right-hand rule).It generates an induced magnetic field with density $(\vec{B}_{ind})$ its direction upward, so it opposite the affecting magnetic flux itself, in order to resist the increase in the magnetic flux that generated the induced current. Simply, a north pole (N) is created at the front of the ring facing the north pole of the rod, so that it repulses the appraching north pole (N) (according to Lenz law).

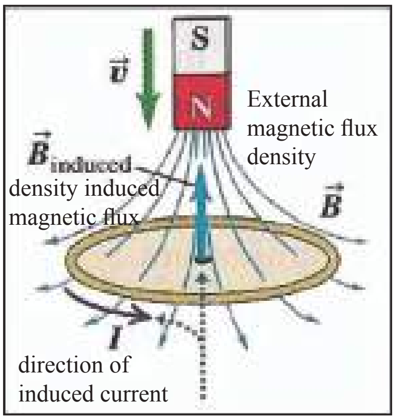


Figure (25)

b. When the North Pole is moved away from the face of the ring there will be decrease in the magnetic flux that penetrate the ring. Direction of the affecting magnetic flux density ($\vec{B}$) is downward and decreasing by ($\frac{\Delta\Phi_B}{\Delta t} < 0$). See figure (26)

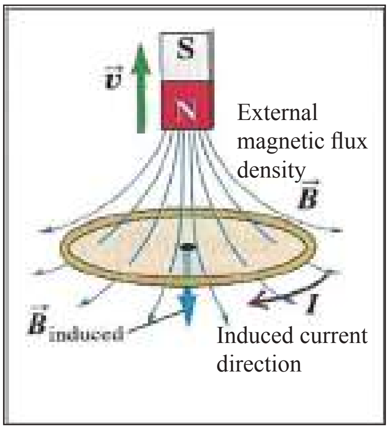


Figure (26)

The direction of the induced current is clockwise (according to right- hand rule). It generates an induced magnetic field with density ($\vec{B}_{ind}$) downward, so it will be in the direction of the affecting magnetic flux itself ($\vec{B}$), in order to resist decrease in magnetic flux which generated the induced current. This means, a south pole (S) is created at the face of the ring to attract the north pole (N) which moves away from it.(according to Lenz law) You might wonder, what is the practical advantage of Lenz Law?

Lenz's law is useful for determining the direction of the induced current in a closed electric circuit.

It is also an application of conservation law of energy. Because in both cases (approaching the magnet or moving it away from the ring) it takes a mechanical work , this work is transformed into another kind of energy in load (when the ring is connected to a load), this is an application conservation law of energy.

## Remember

You need to distinguish between external magnetic flux density ($\vec{B}$) whose flux change generates an induced current in a closed circuit according to Faraday's law of electromagnetic induction.

And between the induced magnetic flux density ($\vec{B}_{ind}$) (generated by the induced current), which opposite the change in external magnetic flux (the causative factor of the induced current), According to Lenz's law.

## Think?

Assume a magnetic rod falls freely downward vertically in to a wide copper close and fixed ring horizontally (Neglect air resistance), see figure (27).

1. Does this rod fall in acceleration equal to that of the earth gravity? Is it larger than or smaller?
2. Determine the direction of the magnetic force that the ring will affect as the rod approaches the ring.

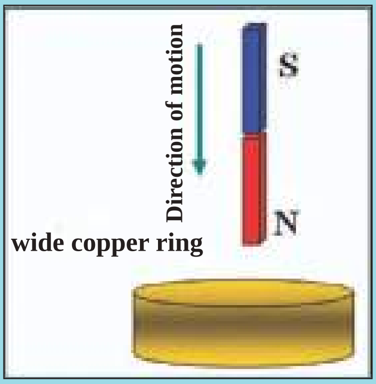


Figure (27)

## 2-11 Eddy currents

In many electrical devices [motors, electrical measurements, like the scale shown in figure (28), metal detectors, brakes of some trains or cars] there are fixed metal plates installed against a variable magnetic flux with time. These plates are sometimes removable against a uniform magnetic field, therefore, these plates will be exposed to a variable magnetic flux with time and according to Faraday's electromagnetic induction law, whereby, an induced electromotive force is created ($\varepsilon_{ind}$) and an induced current flows in these plates. These currents are closed and circular. They are at the center of each plate perpendicularly aligned to the causing magnetic flux ($\Phi_B$). See figure (29). These currents are called **Eddy Currents**. (they are similar to eddy currents in water or air).

Figure (28)

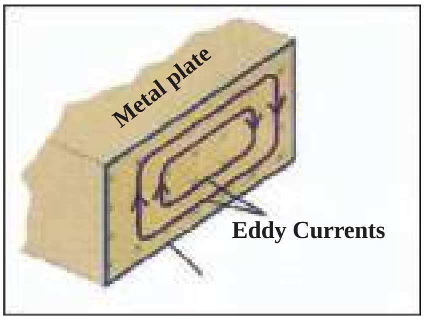
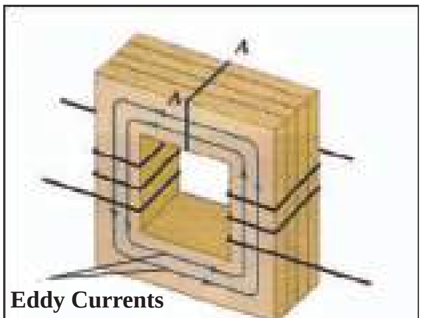



Figure (29)

These eddy currents have the disadvantage of wasting the energy in the form of heat in the devices or at the core of the iron of the coils according to joule's law. In order to reduce the amount of dissipated energy in the form of heat, as in transformers (for example), the core is made in form of plates of wrought iron, arranged parallel to the changing magnetic flux ($\Phi_B$) that penetrates them, these plates are isolated from each other and tightly compressed, see figure (30) Therefore, the electrical resistance increases largely inside the plates, the amount of eddy currents decreases.




The core is made in form of plates of wrought iron, arranged parallel isolated and compressed.

Figure (30)

One might ask, why are eddy currents created in conductors? What is the effect of the magnetic fields generated by them? How can these currents be invested in modern technology?

To explain this, see figure (31), which illustrates a copper plate horizontally pulled by the poles of an electromagnet with a uniform flux density ($\vec{B}$) heading downward.

As a result of the relative movement between the metal plate and magnetic flux, eddy current are created on the surface of the plate according to faraday's law of electromagnetic induction.

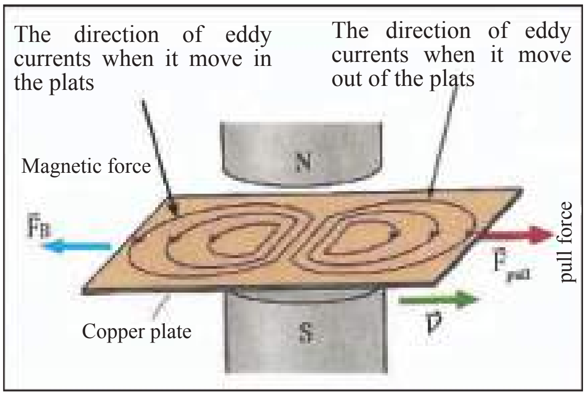



Figure (31)

When the right side of the plate moves out of the magnetic field, the magnetic flux within decreases, so, the direction of the eddy currents is a clockwise direction, to generate an induced magnetic flux (its density $\vec{B}_{ind}$) opposite to the cause of the these currents according to Lenz's law. The direction of the induced magnetic flux is downward (in order to support the decreasing affected magnetic field). As for the left side of the plate, the direction of the eddy currents is counter clockwise for the same reason. Consequently, a magnetic force ($\vec{F}_B$) arises to the left and opposite the pulling force, it is an obstructive force to the direction of movement. (i.e. opposite the pulling force of the rod ($\vec{F}_{pull}$)).

To illustrate how eddy currents are reduced in conductors, the following activity is done:

## Activity (2):

### How to reduce effect of eddy currents in conductors:

**Tools of activity:**

Two identical pendulums each in the form of plate made of aconductive material with weak magnetization (not ferromagnetic for example aluminum), connected to the end of light rod made of the same material. One of the plates is sliced and the slices are isolated like the teeth of a comb, the other plate (is not sliced), strong magnet (high flux density), a holder.

**Activity steps:**

- Diplace the two plates with equal displacement to one side of their stabilization site.
- Both plates are left simultaneously to swing freely between the poles of the magnet, What do you expect? Do the pendulums swing with the same amplitude? or do they differ? why is that?

The answer is revealed by looking at the pendulums: the (unsliced) plate pendulum stops when the gap comes between the magnetic poles, while the sliced plate goes between the magnetic poles and crosses to the other side and keeps swinging back and forth but with slow deceleration, see figure (32).

Figure (32)

## The conclusion from this activity:

Huge eddy currents are generated in the unsliced plate when goes into the magnetic field between the poles, in a specific direction, due to an increase in magnetic flux that penetrates to the unit of time ( $\frac{\Delta\Phi_B}{\Delta t}$ ) (according to Faraday's law).

Yet, they have an opposite direction when they go out of the field, due to decrease in the magnetic flux ( $\frac{\Delta\Phi_B}{\Delta t}$ ).In both cases, a magnetic force is generated ( $\vec{F}_B$ ) which hinders the movement of the plate (according to Lenz's Law). In conclusion, the swinging amplitude of the plate and finally stops, see figure (33). While the eddy currents in the sliced plate are very small, therefore, they have little effect on the plate.

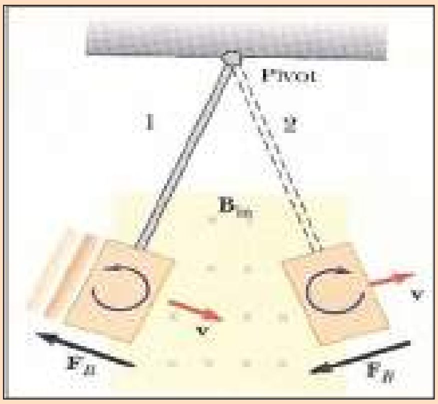


Figure (33)

## Think?

What about the vibration energy in the unsliced plate inside a magnetic field, when it stops vibrating?

Eddy currents are utilized in modern trains' brakes. Wire coils (acting as an electric magnets) are applied facing the railway rods, see figure (34) In the uniform movement, no electric current flows in these coils, to stop from moving the train, the electrical circuit of these coils is closed, electric current flows in these coils; this current generates a strong magnetic field that pass through the railway rods. Because of the relative movement between the magnetic field and the railway rods, eddy currents are generated in them.

According to Lenz law, these currents generate a magnetic field that hinders that movement, so the train stops.

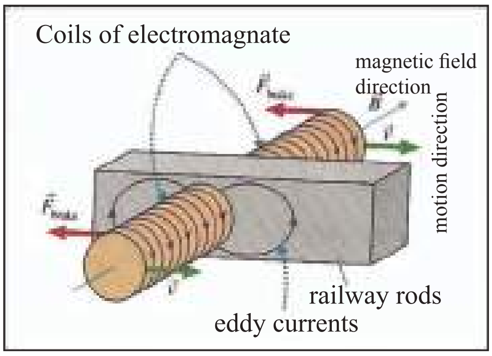


Figure (34)

Eddy currents are also utilized in metal detectors (currently used in checkpoints and airports). The concept of metal detectors depend on electromagnetic induction, which is sometimes called pulse induction.

A metal detector has two wire coils, one is a transmitter, and the other is a receiver, see figure (35). An alternating potential difference is forced on the transmitter coil,

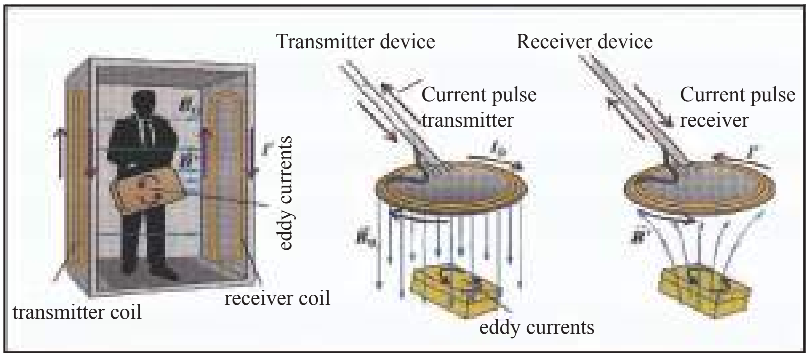


Figure (35) For refrence only (not required) an alternating current flows in the coil, which, in turn generates an alternating magnetic flux, this time-variable flux induces a current the receiver coil. This current is measured initially in the case where there is no material between the two coils except air. When a conductor material comes in between the emitter and receiver coils (not required to be a plate), eddy currents will generated in that metal object.

Induced eddy currents in that object will hinder change in the magnetic flux in the emitter coil, this causes decrease in the initial current measured in the receiver when there is air between them, hence, metal objects can be detected in bags, purses and clothes. Metal detectors are also used to control traffic lights on some roads.

## 2-12 Electric generators

In some electric power production stations, see figure (36) Electric generators convert mechanical energy into electric energy by effect of a magnetic field. Electric generators are of two types:

Figure (36)

1. Alternating Current generator (AC) (single or three phase).
2. Direct Current generator (DC).

### 1. Single – Phase (AC) generator:

Along the core coil terminals, two metal rings (sliding rings) are connected and attached to the outer circuit by means of two carbon-brushes.

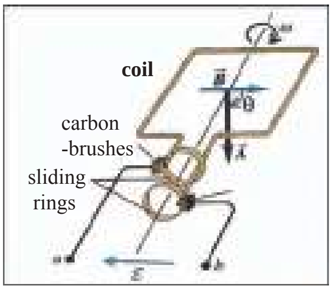



Figure (37-a)

figure (37-a) show a wire coil of an alternating single-phase electric generator rotating inside a uniform magnetic field.

When the coil rotating at a uniform angle velocity ($\omega$) inside a magnetic field with a uniform flux density (B), area of one wind (A), figure (37-b) (as learned earlier). The magnetic flux which penetrates the wind of the coil at any instant of time is expressed as follows:

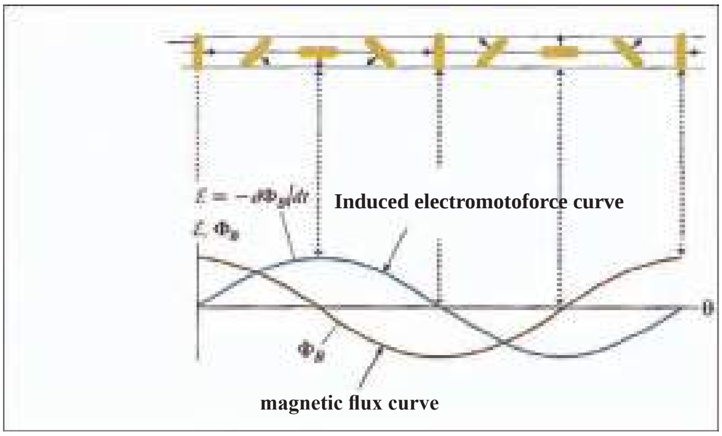



Figure (37-b)

$$\Phi_B = BA\cos\theta$$

Angular velocity (ω) is measured by (rad/s) unit, frequency (f) is measured by Hertz (Hz) unit. Since time rate of change in angular displacement represents angular velocity: ($\omega = \frac{\Delta\theta}{\Delta t}$), when angular velocity is uniform, then ($\theta = \omega t$), the magnetic flux which penetrates the single wind is expressed as follows:

$$\Phi_B = BA\cos(\omega t)$$

It is a cosine function cos (ωt) that changes with time.

The time rate of change in magnetic flux, which penetrates the single wind, it is expressed as follows:

$$\frac{\Delta\Phi_B}{\Delta t} = -BA\,\omega\sin(\omega t)$$

since; $\left[\frac{\Delta[\cos(\omega t)]}{\Delta t} = -\omega\sin(\omega t)\right]$

According to Faraday's law for electromagnetic induction, the induced electromotive force ($\varepsilon_{ind}$) in the coil is:

$$\varepsilon_{ind} = -N\frac{\Delta\Phi_B}{\Delta t} = -N\{-BA\omega\sin(\omega t)\}$$

Then, the induced electromotive force on both ends of a coil is:

$$\varepsilon_{ind} = N\,B\,A\,\omega\sin(\omega t)$$

since: $\omega = 2\pi f$

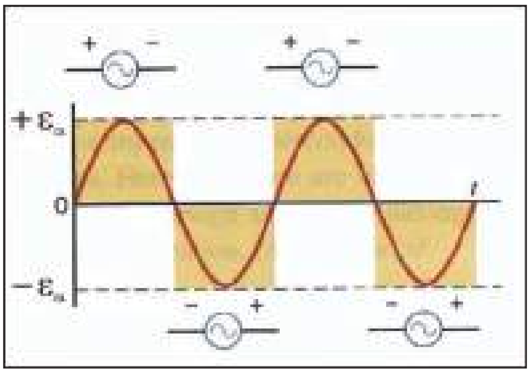


Figure (38)

The above stated equation shows that the induced electromotive force changes sinusoidally with time, it is a sinus function, see figure (38). Instantaneous voltage ( $\varepsilon$ ), is expressed as follows:

$$\varepsilon = \varepsilon_{max}\sin(\omega t)$$

It increases gradually from zero at (t = 0), until it reaches maximum amount of ($\varepsilon_{max}$) after quarter of a round (revolution), so ($\omega t = \frac{\pi}{2}$), then ($\sin(\omega t) = \sin\frac{\pi}{2} = 1$).

Then, $\varepsilon_{instantinus} = \varepsilon_{(max)}$ i.e: $\varepsilon_{(max)} = N\,B\,A\,\omega$

The maximum amount of the induced electromotive force ($\varepsilon_{max}$) is called **climax of induced voltage.**

Then it decreases gradually until it reaches zero again at the moment when ($\omega t = \pi$). Then the induced electromotive force ($\varepsilon_{ind}$) gradually increases towards the negative direction till it reaches maximum amount at the moment when ($\omega t = 3\pi/2$), then it declines gradually to zero when the coil completes one round (revolution), i.e at the moment when ($\omega t = 2\pi$). figure (38): Polarity of the electromotive force is inversed twice in the single round (revolution), when the ends of the coil are connected to an external circuit, of the total resistance (R).

The current in this circuit is expressed as follows:

$$I = \frac{\varepsilon_{ind}}{R} = \frac{N B A \omega \sin(\omega t)}{R}$$

The maximum amount of induced current is as follows:

$$I_{(max)} = NBA\,\omega / R$$

The output current of this generator is an alternating sinusidual current, expressed as follows:

$$I = I_{max} \sin(\omega t)$$

(I): Instantaneous current.

($I_{max}$): Represents maximum current amount.

### Three – Phase (AC) generator :

It consists of three coils around the core, connected in "star-connection", see figure (39), separated by equal angles each of which is ($120^0$), their other terminals are connected to a wire called neutral wire or (zero line), the output current is transmitted via three lines.

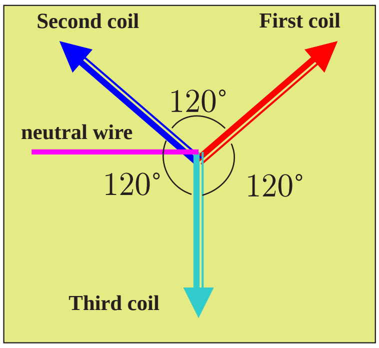


Figure (39)

A generator like this supplies an alternating current with a larger amount than that of single-phase alternator.

### 2. Direct Current generator (DC- generator):

In order to make the flowing current in the external circuit of the coil in one direction (to make its direction constant), it required to raise the two metal rings (the two slippery rings) and put in the two ends of the coil a single metal ring consisting of two halves isolated from each other by electric isolation, called the commutator. See figure (40). They are in contact with the carbon brushes in order to connecting the coil with the external circuit, the number of commutator pieces is twice of the generator coils.

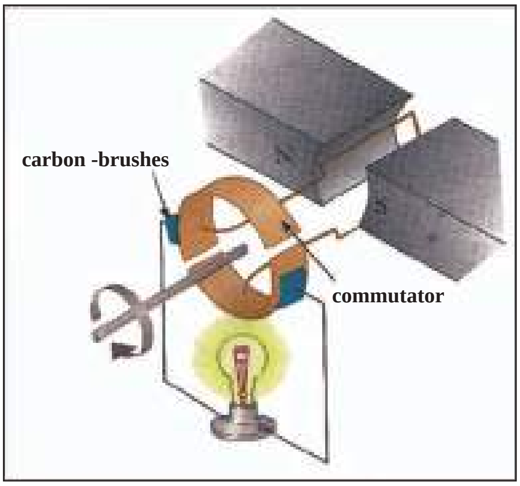


Figure (40)

The output current from this generator is a pulsed current, see figure (41).

The average amount ($I_{average}$) of this current is as follows:

$$I_{average} = 0.636\ I_{max}$$

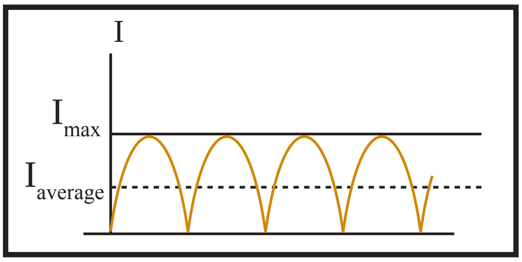



Figure (41)

To make the output current of the single coil direct current generator closer to the battery current (the amount is approximatly constant), the number of coils around the core is increased, with equal angles between them.

## Example (4)

Figure (42) shows a wire coil of (500) circular winds of (4 cm) diameter placed between two magnet poles with uniform magnetic flux. When the magnetic flux make a ($30^\circ$) angle with the coil plane and the density of the magnetic flux decreased throught one wind by (0.2T/s), calculate the induced electromotive force at both sides of the coil.

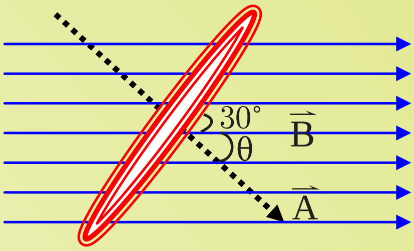



Figure (42)

## The solution:

In the following relation of the magnetic flux: $\Phi_B = B\,A\cos\theta$

The angle θ is formed between area vector ($\vec{A}$) and magnetic flux density vector ($\vec{B}$) and the angle stated in the question lies between the coil plane and the magnetic flux density ($\vec{B}$).

Therefore: $\theta = 90^\circ - 30^\circ = 60^\circ$

$$\varepsilon_{ind} = -N\frac{\Delta\Phi_B}{\Delta t} = -N\,A\cos\theta \times (\Delta B/\Delta t)$$

The coil area is calculated: $A = \pi r^2 = 3.14 \times (4 \times 10^{-4}) = 12.56 \times 10^{-4} m^2$

$$\varepsilon_{ind} = -N\,A\cos\theta \times (\Delta B/\Delta t)$$

$$= -500 \times 12.56 \times 10^{-4} m^2 \times \cos 60^\circ \times (-0.2T/s)$$

$$\varepsilon_{ind} = +628 \times 10^{-4} = +0.0628\ V$$

## 2-13 (DC) Electric motors

Electric motors usually convert electric energy into a mechanical energy, instead of the current generated by a closed conductive ring rotating in a magnetic field, this ring is supplied with an electric current through a voltage source (a battery for example).

Figure (43) magnetic forces which affect the ring rotates it by the effect of a torque called a coupled torque inside a magnetic field.

The (DC) motor consists of the same parts of the (DC) generator, but, it works the opposite to the work of the generator, as it converts electric energy into mechanical energy using the magnetic field.

### Back electromotive force ($\varepsilon_{back}$) :

Do not surprised if you knew that the electric motor operate as the electric generator when its core rotates (when operating), when the core coil rotates inside a magnetic field, change happens in the magnetic flux which penetrates the coil. According to Faraday's law of electromagnetic induction, an induced electromotive force is genarated on both sides of core coil of the motor, it is called back electromotive force ($\varepsilon_{back}$).

It is called back because it is opposite to the which generated it according to Lenz law, as follows:

$$\varepsilon_{back} = -N\frac{\Delta\Phi_B}{\Delta t}$$

The electric circuit on the left, figure (43-a), shows electric current flow in a motor coil due to applied continuous voltage ($V_{applied}$) between two ends of the motor core coil, which in turn generate coupled tourqe which rotate the coil.

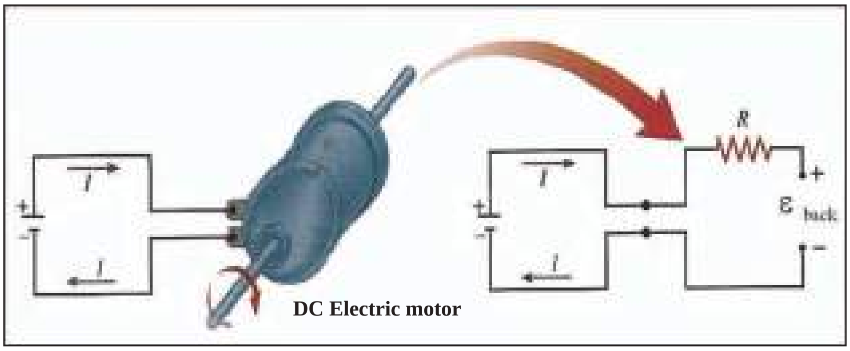



Figure (43-a) Figure (43-b)

As for the circuit on the right, figure (43-b), it shows generation of back induced electromotive force ($\varepsilon_{back}$) on both sides of the core coil while rotating inside a magnetic field according to Faraday's law of electromagnetic induction.

Amount of back induced electromotive force ($\varepsilon_{back}$) depends on:

Velocity of core rotation, (i.e. the average time for change in magnetic flux of one winding), number of winds of the coil, the winding area and the magnetic flux density.

You might ask, what determines the amount of flowing current in the motor circuit?

**Answer:** Difference in applied voltage ($V_{applied}$) and back induced electromotive force ($\varepsilon_{back}$) in the motor circuit determine the amount of flowing current in that circuit, as follows:

$$I = \frac{V_{applied} - \varepsilon_{back}}{R}$$

## 2-14 Inductance

You have learned so far that, in order to generate an induced electromotive force in a coil, there must be a change in the magnetic flux, which penetrates that coil. In addition, you have understood that, relative movement between the magnetic rod and the coil make this change, now you may ask: Can the change in magnetic flux (resulting from flowing current in the coil) generate electromotive force in that coil?

To explain this, see the electric circuit in figure (44) Two identical lamps are connected in parallel combination to a battery. The alternating resistance R has an equal amount to that of the coil resistance L, and connected in series combination to one of the lamps, while the coil is connected to the other lamp in series combination (the coil core is wrought iron to increase magnetic flux density to have clear effect). The question is

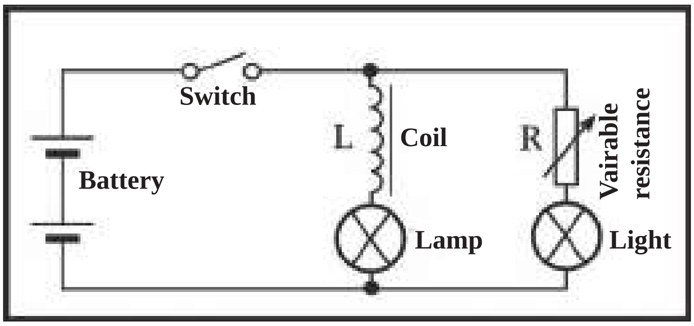



Figure (44)

“would you expect the two lamps glow at the same amount when the switch of the circuit was closed?. Did the two lamps reach an equal glow at the same time?” To explain this: after closing the switch, for a while both lamps glow equally when the current becomes constant, but, they don’t reach that moment at the same time, there is a considerable delay in time for the lamp which is connected in series combination with the coil compared to the other lamp connected in series combination to the resistance, you might ask why?

The answer is: There is delay in glow of the lamp connected to the coil is because **inductance effect of the coil** (or self-inductance of the coil), such a coil is called inductor.

## 2-15 Self inductance

If an electric circuit (consisting of a coil, battery and a switch is connected in series), like the one in figure (45). We find that, when the switch is closed, there is increasing in current from zero to a constant amount, see figure (46). Change in flowing current in the coil would cause change in the magnetic flux within it. In turn, change in magnetic flux generates an induced electromotive force in the coil, which opposite that change. This change is called self electromotive force (ε) that resists the change which caused it according to Lenz's law, (change in flowing current of the coil itself).

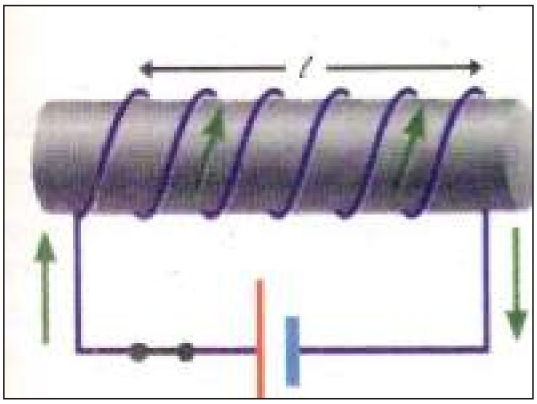


Figure (45)

This Phenomenon is called self-inductance, and it is defined as:

A process that generates an induced electromotive force in a coil, due to change in flowing current to the time unit in the coil itself.

### Calculating amount of self-induced electromotive force ($\varepsilon_{ind}$):

Suppose a direct electric current (I) flows in a coil, this would cause a magnetic flux of ($\Phi_B$) through each wind of the coil, and this flux is directly proportional to the current, i.e.: $N\Phi_B \alpha I$

So: $N\Phi_B = LI$

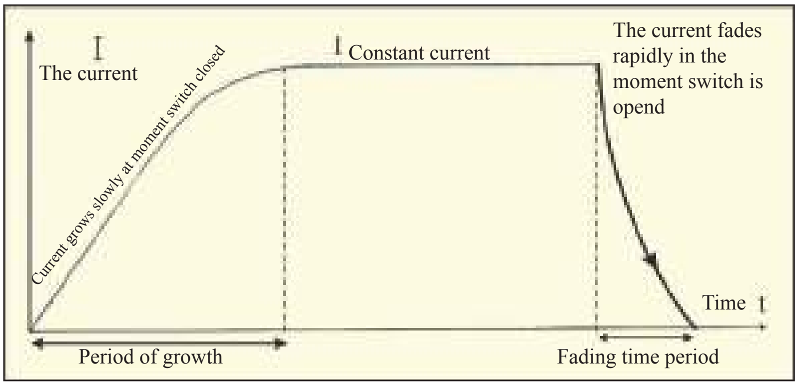



Figure (46) shows that current fade time (from constant reading to zero) is smaller than the time needed to current growth (from zero to a constant reading)

L = is proportionality constant, it represents self-inductance coefficient of the coil, if the current changed in time ($\frac{\Delta I}{\Delta t}$), the generated magnetic flux changes in time ($\frac{\Delta \Phi_B}{\Delta t}$).

Therefore: $N \times (\frac{\Delta \Phi_B}{\Delta t}) = L \times (\frac{\Delta I}{\Delta t})$

Since the induced electromotive force ($\varepsilon_{ind}$) in the coil is directly proportional to time rate of change in magnetic flux ($\frac{\Delta \Phi}{\Delta t}$), according to Faraday's law of electromagnetic induction $\varepsilon_{ind} = -N\frac{\Delta \Phi_B}{\Delta t}$:

So: $\varepsilon_{ind} = -L\frac{\Delta I}{\Delta t}$

coefficient of self-inductance for a coil **"Ratio of induced electromotive force to the time rate of change of flowing current in the coil itself"** is expressed by the following:

$$L = \frac{\varepsilon_{ind}}{-(\frac{\Delta I}{\Delta t})}$$

self-inductance L, is measured in the system international unit by (Volt. Second/Ampere), it is called Henry, according to the scientist Henry, who discovered self-inductance (H), it is often measured by (microHenry or miliHenry).

Henry is the unit for self-inductance coefficient of a coil. If the current changes by $(\frac{Ampere}{second})$, one volt of induced electromotive force ($\varepsilon_{ind}$), is generated on its both sides.

Self-inductance coefficient (L) of a coil depends on:

Number of turns, size of the coil, geometric shape of the coil, and the magnetic permeability of the medium inside the coil.(self-inductance coefficient of a coil increases when a core of wrought iron is inserted inside the coil).

To illustrate self-inductance more clearly, look at the following figures:

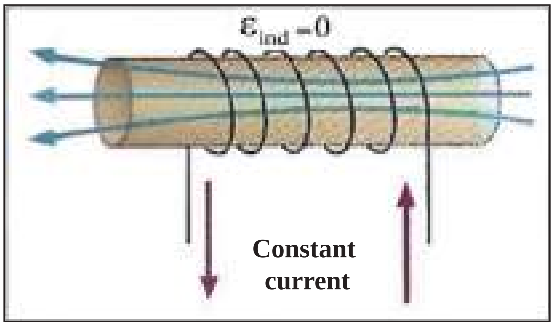


Figure (47-a)

figure (47-a) show a flow of a constant current amount in the coil, this current generates a constant magnetic flux in the coil, so it does not generate induced electromotive force ($\varepsilon_{ind}$) of both sides of the coil. i.e. $\varepsilon_{ind} = -L\frac{\Delta I}{\Delta t} = 0$

Net voltage is expressed as: $V_{applied} = I_{const}. R$

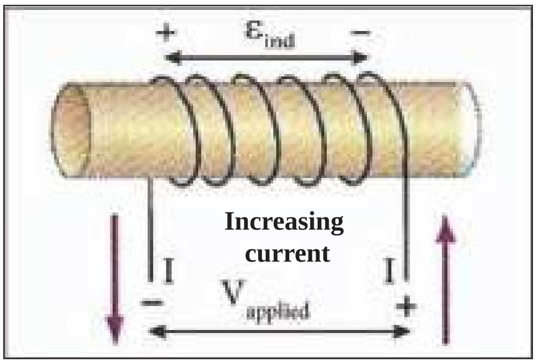


Figure (47-b)

figure (47-b): shows flow of an increasing current in the coil ($\frac{\Delta I}{\Delta t}$)>0. This increasing current generates an increasing magnetic flux in the coil too, as a result, an induced electromotive force ($\varepsilon_{ind}$) is generated on both sides of the coil with an opposing polarity to the voltage on both sides of the coil, so it hinders increase in current.

So the growth of current from zero to a constant amount will be huge, net voltage in that circuit is expressed as: $V_{net} = V_{applied} - \varepsilon_{ind}$

If: ($V_{applied}$) represents voltage applied on the coil, and the resistance is (R), so the rule will be:

$$V_{applied} - \varepsilon_{ind} = I_{inst}.R$$

Figure (47-c): shows a decreasing flowing current ( $\frac{\Delta I}{\Delta t}$ )<0 in the coil, this decreasing current generates a decreasing magnetic flux too, so an induced electromotive force ($\varepsilon_{ind}$) is created on both sides of the coil. It has the same polarity of the voltage applied on the coil, then, net voltage in the circuit is expressed as follows:

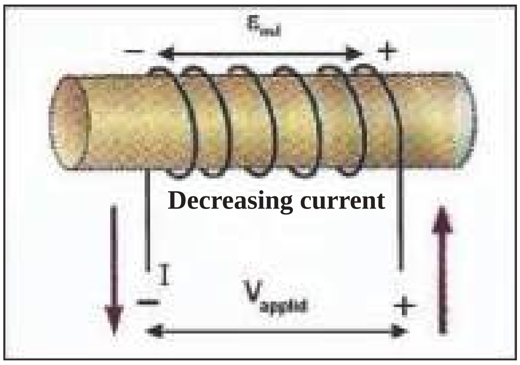


Figure (47-c)

$$V_{applied} + \varepsilon_{ind} = I_{inst}.R$$

So the fading current time from constant amount to zero is small compared to growth time; this is due to air gap between sides of the switch, which makes the circuit resistance so big.

**Do you know?**

Resistor that made of wire are winded as a non-inductive wrapped. they are usually wrapped in layers, the direction of winding the first half of the wire (one of the layers) is opposite to the direction of winding the second half of the wire (the next layer), and as a result, the inductive effects generated in the first half of the wire cancel out the inductive effect of the second half. it is equal in magnitude and opposite in direction, the reson for this is the current flows in the two halves of the wire in opposit direction.

## 2-16 Potential energy in inductance

In the first chapter of this book, you learned that (PE) electric stored energy in the electric field between plates of a capacitor is directly proportional with square stored charged in any of the plates of the capacitor, as follows:

$$PE = \frac{1}{2} \times \frac{q^2}{C}$$

q: amount of stored charge in any of the plates of the capacitor, C: capacitance of capacitor. The stored energy in the magnetic field of the inductor is a magnetic energy, this energy is directly proportional with square constant current (I).

The stored energy in the magnetic field of the inductor is given as:

$$PE = \frac{1}{2} LI^2$$

L: self-inductance coefficient of the inductor.

I: current flowing in the inductor.

It is worth noting that the inductor is considered as a coil neglecting resistance, this means there is no waste in energy.

## Activity (3):

## Generating self-induced electromotive force at both ends of the coil:

### Tools of activity:

(9 V) battery, switch, wire coil with wrought iron at the core and (80 V) neon lamp.

### Activity steps:

- The coil, switch, and battery are connected in series combination.
- The neon lamp is connected in parallel combination with the coil. see figure (48).
- The coil and battery circuit is closed by the switch, no glow in the lamp.

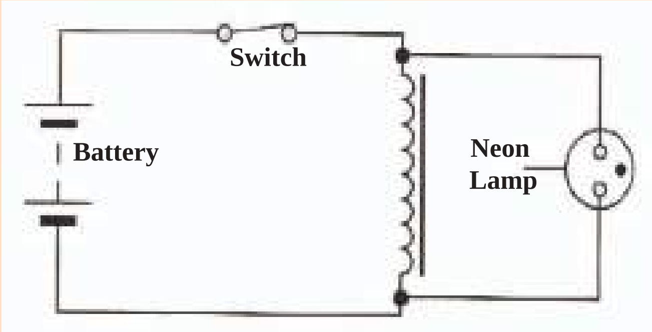


Figure (48)

- The coil and battery circuit is opened by the switch; the neon lamp will glow brightly for a while, although the battery is disconnected from the circuit.

### Conclusion:

**First:** the neon lamp doesn't glow when the switch is closed, because the voltage applied on its ends is not sufficient to glow it. The growth of current from zero to a constant amount is slow because of generate an induced electromotive force in the coil hinders the cause of that force according to Lenz's law.

**Second:** the neon lamp glows when the switch is opened because of generate a huge voltage on its ends was sufficient to glow. This is because the quick fading of the current through the coil generates a huge self-induced electromotive force on the coil. **The coil acts as a source of energy which provides the lamp by an enough voltage to glow.**

**Example (5)**

A coil with (2.5 mH) coefficient of self-induction with (500) turn and (4 A) direct current flows, **calculate:**

1. Amount of magnetic flux, which penetrates one turn of the coil.
2. Stored energy in the magnetic field of the coil.
3. Amount of induced electromotive force in the coil if the direction of the current is reversed during (0.25s).

**The solution:**

1. We have the relation: $N\Phi_B = LI$

$$500 \times \Phi_B = 2.5 \times 10^{-3} \times 4$$

$$\Phi_B = 2 \times 10^{-5} \text{wb}$$

2. We calculate the energy stored in the magnetic field of the coil:

$$PE = \frac{1}{2} L\, I^2$$

$$PE = \frac{1}{2} \times 2.5 \times 10^{-3} \times (4)^2 = 0.02J$$

3. when the current is reversed ($\Delta I$ = - 8A) $\varepsilon_{ind} = -L\frac{\Delta I}{\Delta t}$

$$\varepsilon_{ind} = -2.5 \times 10^{-3} \times \frac{(-8)}{0.25} = 0.08V$$

## 2-17 Mutual induction

Earlier, you have learned that two conductors adjacent straight wires may effect each other when a direct current flows in one of them, the flowing current in one of the wires creates a magnetic field that affects the flowing current in the other conductor wire.

In this chapter, is there a similar effect between two closed and adjacent rings (or two coils) when the flowing current in one of them changes?

The answer is: Change in the flowing current in one of these coils can induce a current in the other coil.

To explain this, assume there are two adjacent wire coils. See figure (49), the flowing current in the primary coil (1) generates a magnetic field ($\vec{B}$), and magnetic flux ($\vec{\Phi}_{(B1)}$) penetrated the secondary coil (2).

if the flowing current in coil (1) changes in time, the magnetic flux ($\vec{\Phi}_{(B2)}$) would change accordingly and penetrated the coil (2) in time. According to Faraday's Law of electromagnetic induction, an induced electromotive force is generated ($\varepsilon_{ind(2)}$) in coil (2) , with the number of turns ($N_2$).

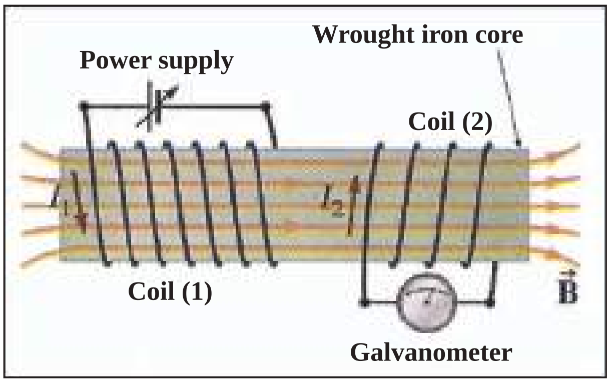


Figure (49)

$$\varepsilon_{ind(2)} = -N_2 \frac{\Delta\Phi_{B(2)}}{\Delta t}$$

It has been practically proven that the magnetic flux which penetrated each turn of the secondary coil is directly proportional with the flowing current in coil ($I_1$), which means: $\Phi_{B(2)} \alpha I_1$

Hence, the magnetic flux which penetrated each turns of the secondary coil with the number of turns ($N_2$) is directly proportional to the flowing current in primary coil ($I_1$) which means: $(N_2\Phi_{B(2)})\,\alpha\, I_1$

Proportionality constant is called mutual inductance coefficient (M) between the adjacent coils, so: $N_2\Phi_{B(2)} = MI_1$

When the current in the primary coil changes in time ($\frac{\Delta I_1}{\Delta t}$), the magnetic flux, which penetrated the secondary coil, also changes in time ($\frac{N_2\Phi_{B(2)}}{\Delta t}$) Since:

$$\varepsilon_{ind(2)} = -N_2 \frac{\Delta\Phi_{B(2)}}{\Delta t}$$

The induced electromotive force in the secondary coil is expressed as:

$$\varepsilon_{ind(2)} = -M\frac{\Delta I_1}{\Delta t}$$

If both coils were in the air, see figure (49), the mutual inductance coefficient (M) between coils depends on: Constants of coils ($L_1$ and $L_2$), i.e (size of each coil, geometric shape of each coil, number of turns of each coil, magnetic permeability of the matter inside each coil. It also depends on situation of each coil, and the separator between the coils and in case, there is a core of iron and closed between the coils. The mutual inductance coefficient (M) between the coils depends only on: Constants of the two coils, ($L_1$ and $L_2$), due to full magnetic coupling between the coils, as in the electric transformer. The mutual inductance coefficient between the coils in this case is expressed as:

$$M = \sqrt{L_1 \times L_2}$$

Mutual inductance phenomenon is used in transcranial magnetic stimulation (TMS) device A time-alternating current is applied on the primary coil which is placed on the patient's brain, the generated alternating magnetic field penetrates the patient's brain, figure (50) which generates an induced electromotive force in it. This, in turn, generates an induced current, which disturbs the electric circuits in the brain, and, using this; mental and psychological diseases are cured.


Figure (50)

**Example (6)**

Two adjacent coils, wound around a closed ring made of wrought iron, ends of the primary coil are connected to a battery with 100 V potential difference and a switch in series combination. If the self-inductance of the primary coil is (0.5H). and (20 Ω) resistance, then calculate:

1.Time rate of change of current of the primary coil at the moment of closing circuit.
2. Mutual inductance coefficient between the coils if a (40V) induced electromotive force on the ends of the secondary coil is created once the switch is off in the primary coil circuit.
3. Constant flowing current in the circuit of the primary coil after closing circuit.
4. Coefficient of self-induction of the secondary coil.

**The solution:**

1. In the primary coil we have the following relation:

Whereby ($I_{inst} = 0$) once the circuit is closed.

$$V_{app} = L\frac{\Delta I_1}{\Delta t} + I_{ins}R$$

$$100 = 0.5\frac{\Delta I_1}{\Delta t} + 0$$

$$\frac{\Delta I_1}{\Delta t} = \frac{100}{0.5} = 200A/s$$

2. To calculate mutual inductance coefficient between the coils, we have this relation:

$$\varepsilon_{ind(2)} = -M\frac{\Delta I_1}{\Delta t}$$

Since the current in the primary coil circuit is increasing $(\frac{\Delta I}{\Delta t}) > 0$, once the switch is off, so $(\varepsilon_{ind})$ will be negative:

$$-40 = -M \times 200$$

$$M = \frac{-40}{-200} = 0.2H$$

3. To calculate the constant current:

$$I_{const} = \frac{V_{app}}{R} = \frac{100}{20} = 5A$$

4. Since the magnetic correlation between the coils is totally when the two coils are around a ring of wrought iron, then:

$$M = \sqrt{L_1 \times L_2}$$

$$0.2 = \sqrt{0.5 \times L_2}$$

$$0.04 = 0.5 \times L_2$$

$$L_2 = \frac{0.04}{0.5} = 0.08H$$

## 2-18 Induced electric fields

In this chapter, we learned how an induced current flows in a closed conductor ring. Yet, the question is what causes this current? What are the forces that stimulate electric charges to move in that ring?

To answer this question, charges move because of electric fields and magnetic fields. The magnetic forces are responsible for generating motional electromotive force in the conductor, which moves inside a constant magnetic field. However, these forces do not give any explanation about induced currents in a closed conductor ring, fixed in position against an alternating magnetic field.

Figure (51) shows a closed conductor ring in rest state inside an increasing magnetic flux, induced current flows according to faraday's law of electromagnetic induction. As for the direction of that current is determined according to Lenz's Law. It will be counter-clockwise, movement of the electric charges inside the ring is due to the electric field, which always affects in tangential directions, this electric filed is called induced electric field.

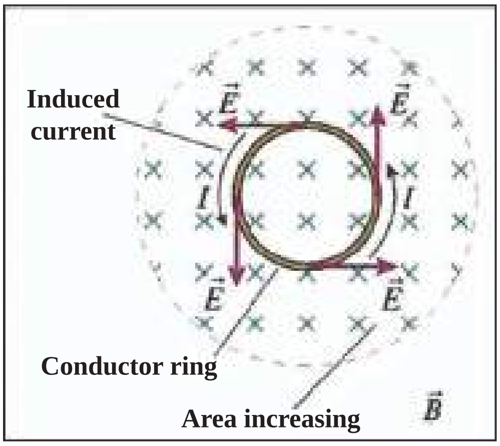


Figure (51)

The induced electric field is generated due to change in magnetic flux in unit time, which penetrates the ring.

We have already learned that the induced electric field is the basic factor in creating the induced current in the static conductor ring compared to alternating magnetic flux. Since all electric fields, we studied generated by the static electric charges. These fields are called (electrostatic fields). The electric fields which are generated by changes in magnetic flux are called (Nonelectrostatic fields).

**Do you know?**

Practical applications of induced electric fields:

a. Hybrid cars, which have both motors (gasoline motor and electric motor). Induced currents in their circuits are utilized in recharging the battery. figure (52).

Figure (52)

b. In some planes, induced currents in their electric circuits keeps the engines running, even when electrical systems malfunction. figure (53).

Figure (53)

## 2-19 Some practical application of electromagnetic induction

### 1. Credit card:

When the magnetic credit card slides in wire coil, it induces an electric current then this current is magnified and converted into volt pulses, which contains information. figure (54).

Figure (54)

## 2. Electric guitar:

Strings of electric guitar (made of ferromagnetic materials) magnetize when shake by wire coils each containing a magnetic rod, these coils are placed in various places under the strings of the electric guitar, when these strings shake, an alternating current with equal frequency to that of the strings is induced. Then this current is passed to an amplifier, see figure (55).

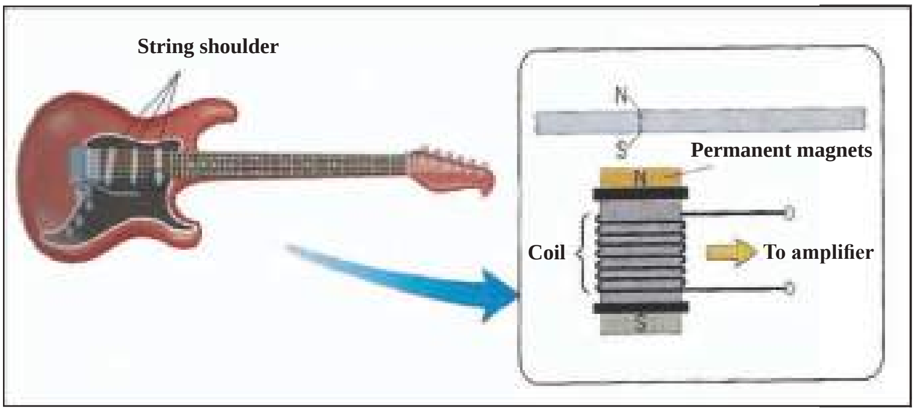


Figure (55) For reference only (not required)

## 3. Induction stove:

Electromagnetic induction is utilized to manufacture this type of stoves. A wire coil is placed under the upper surface of the stove. An alternating current flows, and it induces an alternating magnetic field outward, when the alternating current passes through the base of the pot (if it was metal). Eddy currents are generated at the base of the pot, see figure (56-a), hence the base of the pot is heated, then water boils. If the pot was made of glass, no eddy currents generate at its base because the glass is dialectric and doesn't heat the water inside it, if the surface of the induction stove is touched, no heat is felt, figure (56-b).


Figure (56-a)

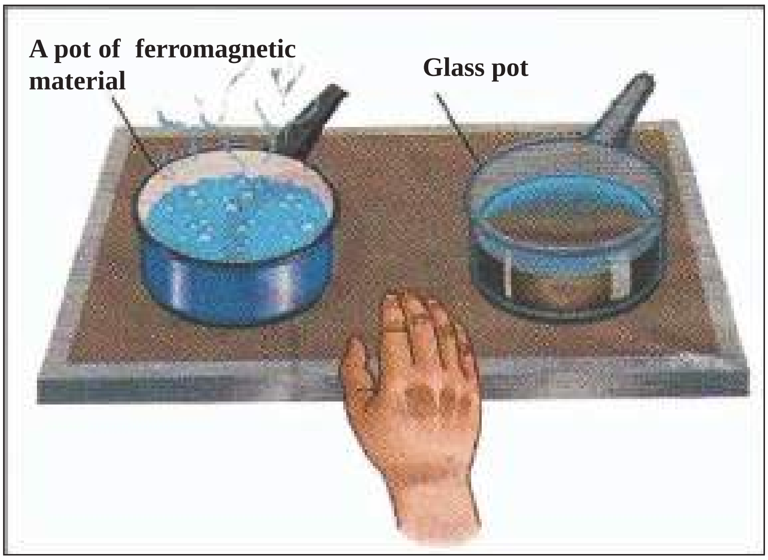


Figure (56-b)

## Q1 Choose the correct statement for each of the following:

1. Which one of the following figure (57) shows the correct direction of induced current in the conductor ring?

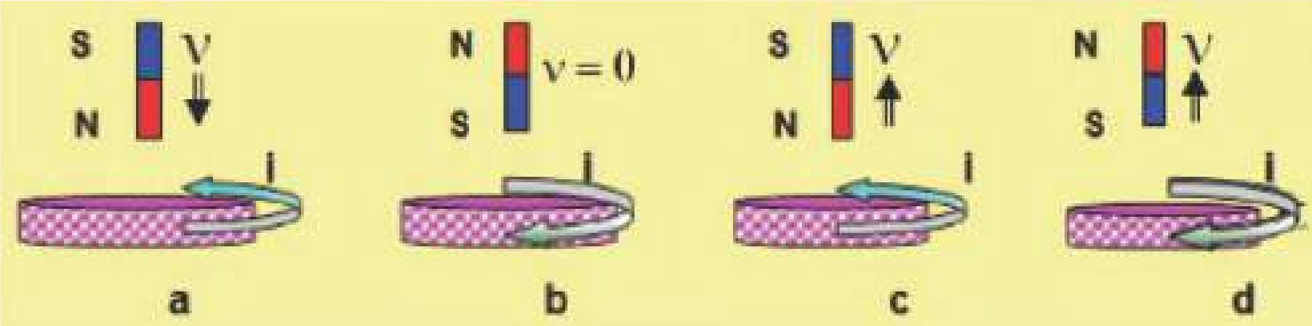


Figure (57)

2. In the figure (58) a ring is made of copper placed in the plane of the paper and connected with resistor (R) an exert  magnetic field which is perpendicular to the plane and the direction out of the page. In which case induced current in the resistor (R) will be directed from left to right.

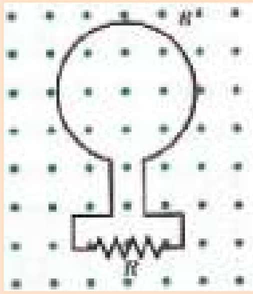


Figure (58)

a. When the magnetic flux that penetrate the ring is increases.

b. When the magnetic flux that penetrate the ring is decreases.

c. When the magnetic flux that penetrate the ring is constant.

d. In all case which is mentioned above.

3. When a magnetic rod falls through a wide ring of aluminum  placed in horizontally by a holder under the rod, notice figure (59). the direction of induced current in the ring is:

a. Always in the direction of clockwise.

b. Always in the direction of counter-clockwise.

c. In the direction of clockwise, then it becomes zero for a moment, then in the direction of counter-clockwise.

d. In the direction of counter-clockwise, then it becomes zero for a moment, then in the direction of clockwise.

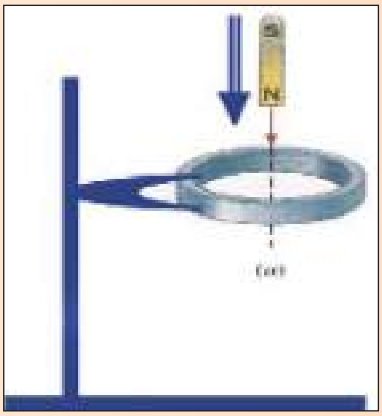


Figure (59)

4. When a magnetic rod falls through unclosed aluminum ring, which is placed horizontally under the rod magnet, notice figure (60).

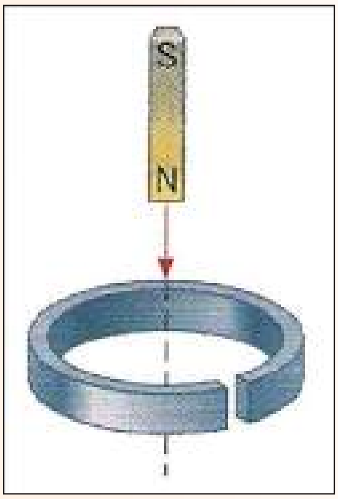


Figure (60)

a. The rod is affected by the repulsive force when approaching to the ring, then it is affected.
   by attractive force when it is moved away from the ring.
b. The rod is affected by the attractive force when approaching to the ring, then it is affected.
   by repulsive force when it is moved away from the ring.
c. The rod is not affected by any force when it is approached to the ring or it's moved away from it.
d. The rod is affected by the repulsive force when it is approached to the ring and affected by the repulsive force moved away from the ring.

5. In figure (61) ahollow core coil is connected in series to a lamp, resistor, battery and switch. When the switch in the circuit is closed the glow of the lamp is constant.
   If we enter an iron core into the gap of the coil, the glow of the lamp:

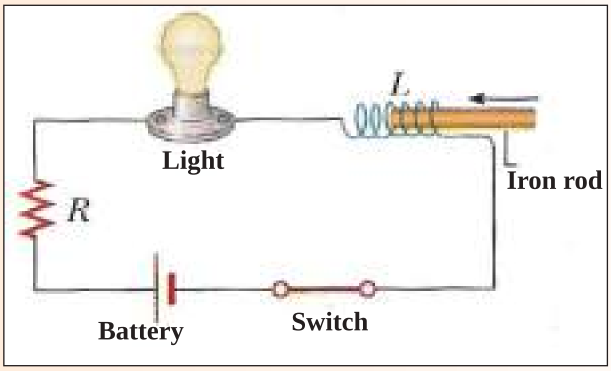


Figure (61)

a. Increase.
b. Decrease.
c. Remain constant.
d. Increase then decrease.

6. When a circular coil rotates around a perpendicular axis which is parallel to the coil face within a magnetic field of uniform horizontal flux density ( $\vec{B}$ ) see figure (62), the maximum amount of induced electromotive force ($\varepsilon_{max}$) is generated. when triple the number of turns of coil, reduce the dimeter of the coil to half what was it, and double rotational frequency. The maximum amount of induce electro motive force will be:

a. $\frac{3}{2}\ \varepsilon_{max}$
b. $\frac{1}{4}\ \varepsilon_{max}$
c. $\frac{1}{2}\ \varepsilon_{max}$
d. $3\ \varepsilon_{max}$

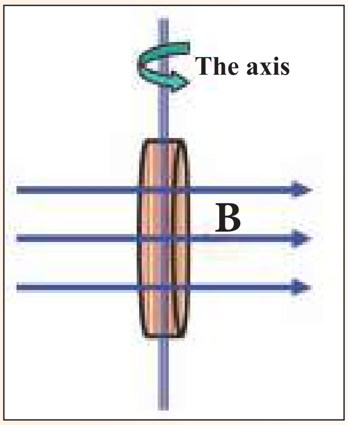


Figure (62)

7. The phenomenon of self-induction rerify in a given coil when:

a. Pulls a rod magnet away from the face of the coil.

b. This coil is placed near another coil in which a variable electric current flows per unit time.

c. An electric current flows in this coil of variable amount per unit time.

d. This coil rotates in the uniform magnetic field.

8. The amount of induced electromotive force between two ends of a conducting rod moving in a uniform magnetic field in static state does not depend on:

a. length of the rod.

b. diameter of the rod.

c. the situation of the rod with respect to the magnetic flux.

d. magnetic flux density.

9. When the angular velocity of rotating the core coil of the electric motor decreases as a result of an increase in connected load with its coil, causes a decreses in the amount of:

a. Back-electromotive force.

b. The voltage between two ends of the core coil.

c. The current passing through the engine.

d. The lost voltage (IR) between ends of the core coil.

10. It is possible to induce the electric current in a closed conductor ring in one of the following cases except one. In which case the current is not induced:

a. A closed conductor ring rotates around its axis that is parallel to its plane and perpendicular to the uniform magnetic flux ($\vec{B}$).

b. Area vector of the closed conductor ring is parallel to the ($\vec{B}$) that changes with the unit time.

c. Area vector of the closed conductor ring is perpendicular to the ($\vec{B}$) that changes with the unit time.

d. The closed conductor ring which area vector parallel to the ($\vec{B}$) is pressed from both opposite sides.

11. The unit of magnetic flux density ($\vec{B}$) is:

a. weber .

b. weber/s .

c. weber/$m^2$ .

d. weber.s.

12. In the figure (63) when the conductor ring rotates around a perpendicular axis parallel to the it's face and the magnetic flux is perpendicular to the its axis and reverses twice through each:

a. one revolution b. quarter revolution

c. half revolution d. Two revolution

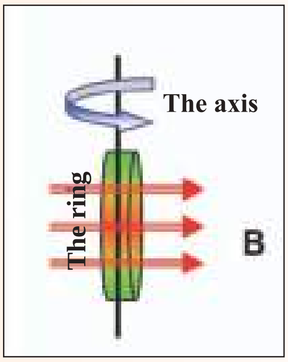


Figure (63)

13. Coefficient of self-induction of the coil does not depends on:

a. Number of turns of the coil. b. Geometry of the coil.

c. The time rate of changing of the current flows in the coil.

d. Magnetic permeability of the medium in the core.

**Q2** Give the reasons of the followings:

1. The neon lamp that is connected in parallel to the coil is brightened strongly for a short time at the moment when the switch is on inspite of that the battery is disconnected from the circuit and does not glow when the switch is off.
2. Water boils inside the metal container which is placed on the induction coil but water does not boil in the glass container which is placed on the same oven.
3. If a change in the electric current flows in one of adjacent coils the induced current is generated in the other coil.

**Q3** Explain by an experiment how do you know existence of magnetic or electric field in definite area.

**Q4** When a coil which area of one turn of coil is (A) rotates with angular velocity of $(\omega)$ inside a uniform constant magnetic flux density $(\vec{B})$. The magnetic flux that penetrate one turn is given by a cosine function $[\Phi_B = BA\cos(\omega t)]$ induced electromotive force is supplied as $[\varepsilon_{ind} = NBA\omega\sin(\omega t)]$. Explain it by mathematically.

**Q5** What the meant of the non-electrostatic field?

**Q6** Define some areas which are eddy currents are used in them and explain each.

**Q7** If a conductor rod (ab) in the figure (64) moves in paper plane horizontally to the left inside uniform magnetic field which directed perpendicular to the page (directed to the viewer), the electric field is generated inside the rod directed to (b). while if the rod is moved to right and inside the same magnetic field, the electric field is reversed to (a). Explain why?

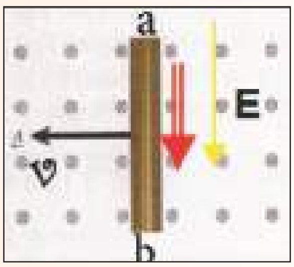


Figure (64)

**Q8** Indicate the direction of induced current face the ring opposite the wire coil, in the figures (65).

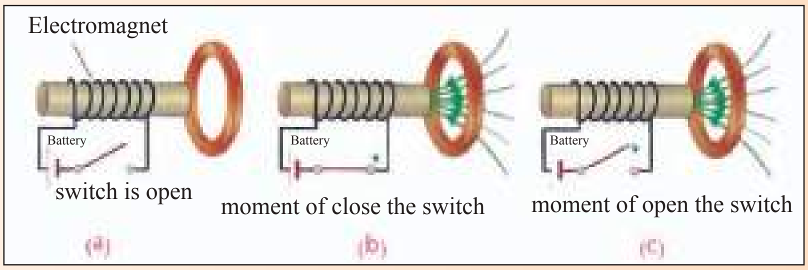


Figure (65)

**Q9** Consider that the coil and the magnet shown in figure (66) each move at the same relative velocity to the earth.
Dose the digital millimeter (or Galvanometer) connected to the coil indicate to current flow in the circuit? Explain that.

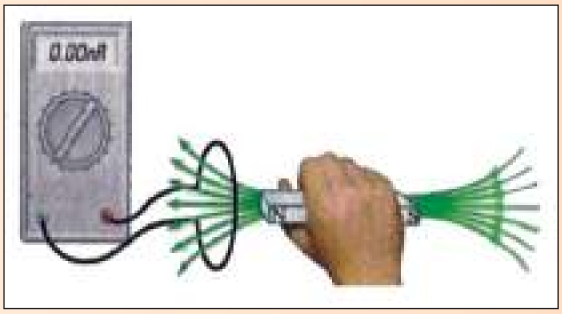


Figure (66)

**Q10** What is the physical quantity which are measured by followings:
a. Weber b. Weber/m² c. Weber/s d. Tesla e. Henry

**Q11** How eddy currents works to stop the vibration of metal plate which vibrates perpendicularly to the uniform constant magnetic field?

**Q12** A copper plate is placed between the poles of uniform electromagnet which has large flux density and perpendicular to the magnetic flux. When the plate is pulled out horizontally from the field by definite velocity this process need to exert a definite force. And the amount of definite force increase by increasing that speed.
What is the correct explanation of the for both condition?

**Q13** A copper wire and copper ring are located as in the figures (67, 68).
In which figure an induced current forms in the ring when the current starts to flow from the wire? Explain.

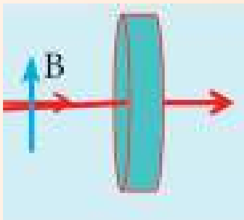


Figure (67)

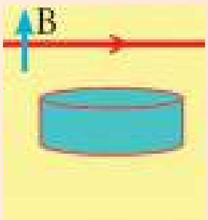


Figure (68)

**Q14** You have a wire with constant length and you want to make simple generator which provides greatest amount of electromotive force. Is it necessary to make coil with one loop or two loops or three loops by the wire, when you rotate the coil which you have get with definite amount angular velocity inside the uniform magnetic field? Explain.

**Q15** In most coils, laminated soft iron core is used instead of one piece of iron. Explain why?

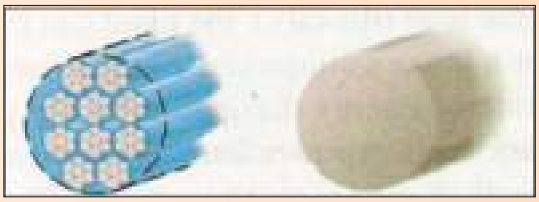


Figure (69)

## Problems of chapter 2

**P.1** A coil which radius is (30) cm has (40) turns. The coil is placed between poles of electromagnet as you see in the figure (70). If the magnetic flux density which pass through the coil changes from (0T) to (0.5T) in (4s). What is the magnitude of induced electromotive force in the coil, if:

a. Area vector for one turn of the coil is parallel to the magnetic flux density.

b. The magnetic flux density vector makes an angle ($\theta$=30°) with the coil plane.

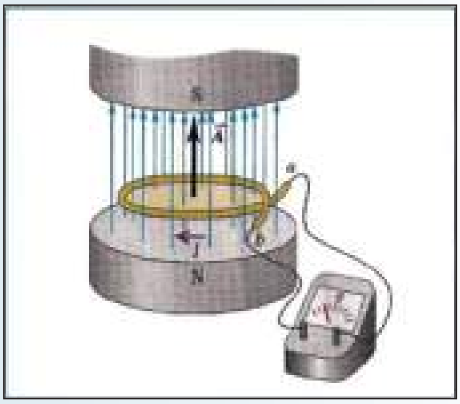


Figure (70)

**P2** A coil for motorcycle generator, it's diameter (4cm) and the number of turns (50) turns rotates inside a constant magnetic field. The flux density is ($\frac{1}{\pi}$ T), and the maximum amount of voltage between edges of the coil is (16V). Power dissipated in generator is (12W), what is the amount of:

a. angular velocity of the coil.

b. maximum amount of current.

**P3** A rectangular shaped coil has number of turns (50) and it's dimensions (4cm, 10cm), rotate with constant with constant angular velocity (15$\pi$rad/sec) inside a constant magnetic field which flux density is (0.8Wb/m²) Calculate:

a. The maximum amount of induced electromotive force.

b. Instantaneous induced electromotive force in the coil after (1/90s) from (zero).

P.4 In figurev(71) conductive circular ring with an area of (626cm²) its resistance (9Ω) is placed in the plane of the paper. A uniform magnetic field is applied with magnetic flux density (0.15T) perpendicular to the plane of the ring. When the ring is pulled from two sides with equal tension forces to reach an area of (26cm²) during a period of time (0.2s) Calculate the induced current in the ring.

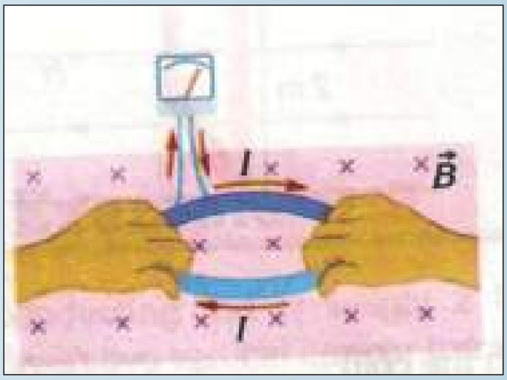


Figure (71)

P.5 A (0.1m) conductor rod as you see in the figure (72) moves with a velocity of (2.5m/s), the total resistance of the circuit (rod and track) is (0.03Ω) and the magnetic flux density is (0.6T). Calculate the amount of:

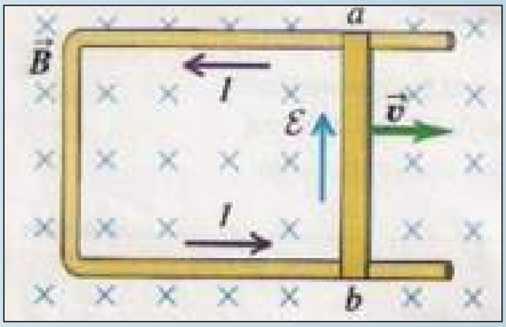


Figure (72)

1. induced electromotive force in endes of the rod.
2. induced current in the ring.
3. Pulling force of the rod.
4. Dissipated power by the total resistance of the circuit.

P.6 If the magnetic energy which is stored in a coil is (360J) when the amount of the current in it is (20A). Calculate:

1. The amount of coefficient of self-inductance.
2. Average induced electromotive force in the coil if the current reverses in (0.1s).

P.7 Two adjacent coils that have a perfect correlation, the self-inductance coefficient of primary coil (0.4H), resistance (16Ω) and self-inductance coefficient of the secondary coil (0.9H). The voltage applied in the primary coil (200V), calculate the amount of instantaneous current, the time rate of the current change in the primary coil at the moment of increase the current (80%) of it's constant amount, and the induced electromotive force on both ends of the secondary coil at that moment.

# CHAPTER 3

# Alternating Current

Contents

3-1 Interoduction

3-2 Alternating current circuts

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3-4 Power in AC circuits with pure resistor

3-5 Effective amount of alternating current ($I_{eff}$)

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3-7 AC Circuits: the load is a capcitor with pure capacitance

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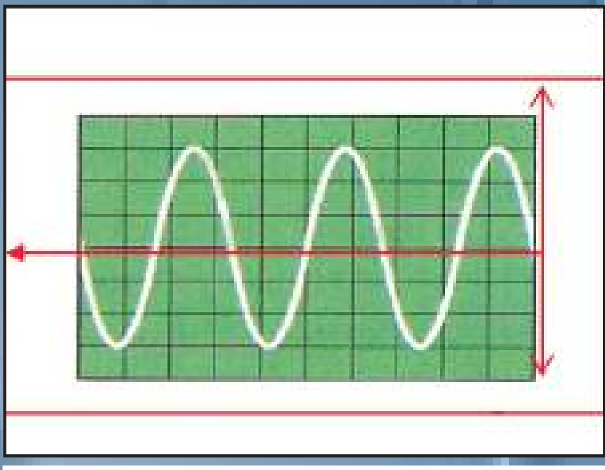
3-9 Power factor

3-10 Electromagnetic oscillation

3-11 Resonance in AC circuits

3-12 Quality factor

3-13 AC circuits with parallel combination of pure resistor, pure inductor and pure capacitor (R-L-C)



## Behavioural targets

**After studying this chapter, the student should be able to:**

- Recognize alternating current circuits.
- Recognize the amount of effective alternating current.
- Apply a mathematical relation of the effective amount of voltage.
- Conduct an experiment showing the effect of changing the frequency of alternating current and self-inductance coefficient in the amount of inductive reactance.
- conclude power factor law.
- Define the quality factor.

| Scientific Terms | |
|---|---|
| Alternating Current | التيار المتناوب ويرمز له (AC) |
| Direct Current | التيار المستمر ويرمز له (DC) |
| Effective current | التيار المؤثر ويرمز له ($I_{eff}$) |
| Root mean square current | جذر معدل مربع التيار ويرمز له ($I_{rms}$) |
| Instantaneous current | التيار الآني ويرمز له (I) |
| Instantaneous potential difference | فرق الجهد الآني ويرمز له ($\Delta V$) |
| Maximum potential difference | فرق الجهد الاعظم ويرمز له ($\Delta V_m$) |
| Sinusoidal potential difference | فرق الجهد جيبي الشكل ويرمز له (~) |
| Phase angle | زاوية الطور |
| Phase difference angle | زاوية فرق الطور ويرمز لها ($\Phi$) |
| Angular frequency | التردد الزاوي ويرمز لها ($\omega$) |
| Frequency | التردد ويرمز له (f) |
| Pharos diagram | المخطط الطوري |
| Pure resistance | مقاومة صرف ويرمز لها (R) |
| Pure inductor | محث صرف ويرمز لها (L) |
| Reactance | الرادة ويرمز لها (X) |
| Capacitive reactance | رادة السعة ويرمز لها ($X_C$) |
| Inductive reactance | رادة الحث ويرمز لها ($X_L$) |
| Average power | القدرة المتوسطة ويرمز لها ($P_{ave}$) |
| Dissipated power | القدرة المستهلكة ويرمز لها ($P_{diss}$) |
| Resonance | الرنين |
| Power factor | عامل القدرة ويرمز له (PF) |
| Quality factor | عامل النوعية ويرمز له ($Q_f$) |

## 3-1 Interoduction

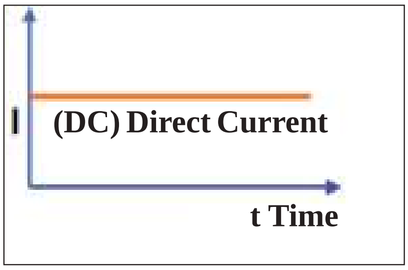


Figure (1)

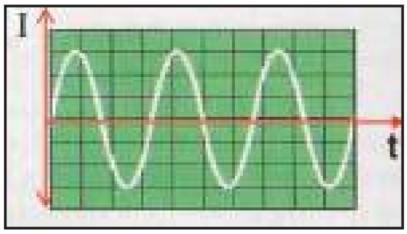


Figure (2)

In our previous study of electricity, we studied direct currents, which flow in electric circuits in one direction and generated by batteries. See figure (1), this current is symbolized by (DC). As for the electric energy which is used in houses, factories and schools in operating electrical appliances (TV, Air conditioners and refrigerators…etc.), this energy is generated in electric energy stations by giant (AC) generators. It alternates current periodically through time, and reverses several times per second, see figure (2), it symbolized by (AC).

The usual frequency of alternating current is (f = 50Hz), in most countries (including Iraq) the direction of the alternating current reverses (100) times per second. In some countries, the frequency is (f = 60Hz).

The alternating current is recommended in electrical circuits because it is easy to transport to long distances with minimum energy loss, and it follows Faraday's law of electromagnetic induction. Thus, the electric transformer is used to increase or decrease (AC) voltage when transferred in power stations.

The electric power is transmite with high voltage and low current using step up transformers in order to reduce power loss in transfer wires ($I^2R$) which appears as heat, while step down transformers are used in consumption sites in cities to reducing voltage and raising current.

## 3-2 Alternating current circuts

In the second chapter, we learned that when a coil rotates with a uniform angular velocity inside a uniform magnetic field, we obtain alternating induced voltage ($V_{ind}$) with sinusoidal curve, expressed as follows:

$$V = V_m \sin(\omega t)$$

V = Instantaneous induced voltage.

$V_m$ = Maximum induced voltage (called voltage peak).

We get ($V_m$) at the moment when the phase angle is [ $\omega t = \frac{\pi}{2}$ ], since [ $\sin\left(\frac{\pi}{2}\right) = 1$ ], then we get:

$$V = V_m$$

Instantaneous voltage (V) alternates and reverses periodically with time between ($+V_m$) and ($-V_m$) twice per period. See figure (3).

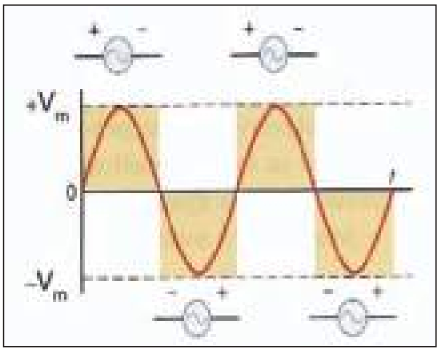


Figure (3)

Since angular frequency ($\omega$) is: $\omega = 2\pi f$

This voltage can be expressed in the following formula:

$$V = V_m \sin(2\pi f t)$$

According to Ohm's law, the current:

$$I = \left(\frac{V_m}{R}\right)\sin(\omega t)$$

So, the flowing current in load (AC) circuit with pure resistance (Identical Resistance), is expressed as follows: $I = I_m \sin(\omega t)$

A sinusoidal function, since I: Instantaneous current, $I_m$: Represents maximum current.

To handle alternating voltage and alternating current in electrical circuits, we draw a diagram called phase vector or (Rotary Vector).

## Phase vector:

Figure (4), shows two phase vectors both rotate counter-clockwise around a fixed point called point of origin (0) with constant angular frequency ( $\omega$ ) .

Phase vector is characterized by:

- Length of voltage phase vector represents the maximum alternating voltage, symbolized ($V_m$). If phase vector represents the current, then, length of phase vector represents maximum current amount, symbolized ($I_m$).
- Projection of phase vector on the vertical axis (y), represents the instantaneous amount of that vector. Voltage will be (V) and Instantaneous current (I).

So, voltage vector incidence will be $V_m \sin(\omega t + \Phi)$, while incident current vector is $I_m \sin(\omega t)$, ($\omega t$) phase angle made by phase vector with the horizontal axis (X).

- When movement starts ($t = 0$), phase vector is congruent with the horizontal axis (X).
- If voltage phase vector ($V_m$) is congruent with current phase vector ($I_m$), then voltage and current alternate together

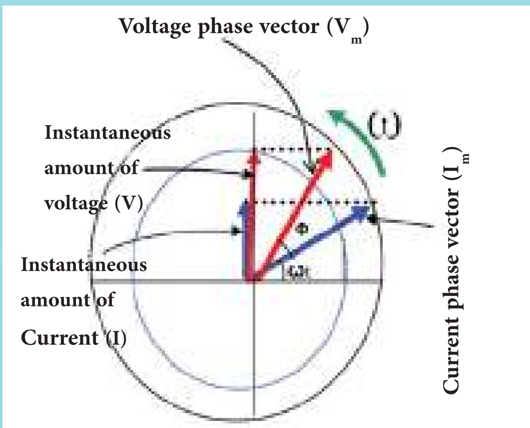


Figure (4)

in one phase. This means that phase difference angle between them is zero ($\Phi = 0$). This happens in case of pure resistance load (identical resistance).

- If the vectors are not congruent, (when the load contains inductor or capacitor or both, as well as resistance), then phase difference angle is generated between them symbolized ($\Phi$).
- Sometimes, it is called (phase constant), which is determined according to load type in the circuit.
- Phase angle ($\omega t$) and phase difference angle ($\Phi$) are measured in degree or (rad).

If ($\Phi$) is positive, voltage phase vector precedes current phase vector by phase difference angle ($\Phi$).

If $(\Phi)$ is negative, voltage phase vector delays from current phase vector by phase difference angle ($\Phi$) (when the current is adopted as a basis).

As you learned earlier:

Phase: is the kinetic state of the oscillating object in terms of position and direction of the movement.

Phase difference: is change in kinetic state of the oscillating object in two different moments or two objects at the same moment.

## 3-3 AC circuits the load is a pure resistor

A pure resistance (Identical Resistance) (R) is connected to alternating voltage source in an electrical circuit. (the alternating current (AC) source is symbolized ~ ). See figure (5).

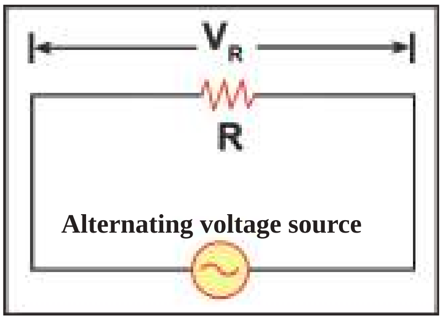


Figure (5)

Figure (6) shows that current wave changes in a curved sinusoidal shape and voltage wave changes in a curved sinusoidal shape too,and both of them change with time in the same manner ,so they change with one phase.

The alternating voltage in this circuit is expressed as follows:

$$V_R = V_m \sin(\omega t)$$

The flowing alternating current in this circuit is expressed as follows:

$$I_R = I_m \sin(\omega t)$$

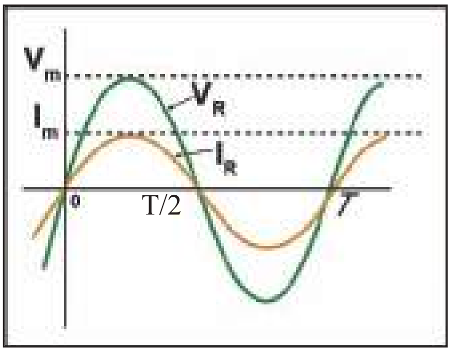


Figure (6)

$I_R$ : Instantaneous amount of flowing current in the resistance (R).

$I_m$ : Maximum amount of flowing current in the resistance (R).

Observing figure (7-a), we find:

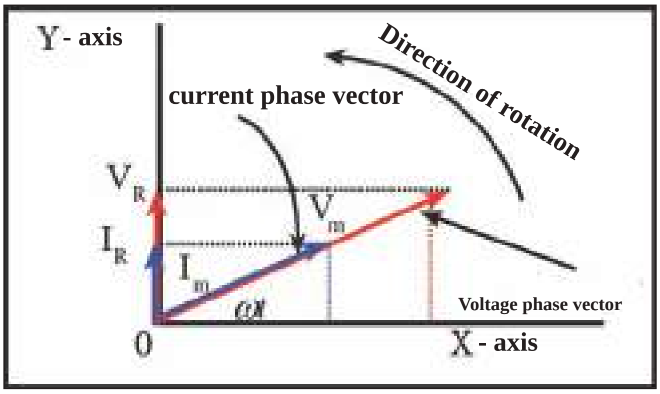


Figure (7-a)

Voltage phase vector ($V_m$) and current phase vector ($I_m$) are congruent and identical, this means that they rotate around point of origin (O) with one phase and counter-clockwise, this means that phase difference angle is ($\Phi = 0$). As for phase angle with which both vectors rotate, it is equal to ($\omega t$).

Simply, alternating current phase vector ($I_m$) and alternating voltage phase vector ($V_m$) of such circuits can be graphed on the horizontal axis X at time period ($t = 0$), i.e. at phase angle [$(\omega t) = 0$], see figure (7-b).

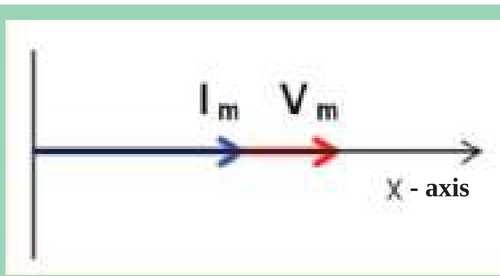


Figure (7-b)

**Think?**

What is the measurement of phase angle ($\omega t$) for both voltage phase vector ($V_m$) and current phase vector ($I_m$) when ($V_R = V_m$) and ($I_R = I_m$)? Explain that.

## 3-4 Power in AC circuits with pure resistor

Since both voltage and flowing current in AC circuit with pure resistor change in one phase in time, Voltage is expressed as follows:

$$V_R = V_m \sin(\omega t)$$

Current flowing through the resistance is expressed as follows:

$$I_R = I_m \sin(\omega t)$$

Instantaneous power is expressed as: $P = I_R V_R$

Figure (8) is a diagram of instantaneous power for current circuit with pure resistance. Note that it is always positive and cosine curve, it changes from maximum power ($P_m = I_m . V_m$) and zero.

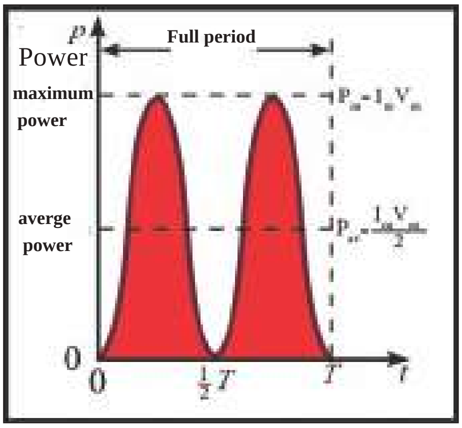


Figure (8)

The positive curve of power in AC circuit (when load is pure resistance), i.e. power in the circuit is totally consumed in the resistance in the form of heat.

Then average power ($P_{av}$) equals half the maximum power ($\frac{I_m.V_m}{2}$), therefore, ($P_{av}$) expressed as follows:

$$P_{av} = \frac{I_m.V_m}{2}$$

## 3-5 Effective amount of alternating current ($I_{eff}$)

Dissipated power (or consumed) in direct current circuit contain pure resistance is constant in magnitude directly proportional to the square flowing current in it $P=I^2R$ , see figure (9), therefore:

The dissipated power in pure resistance does not depend on direction of current.

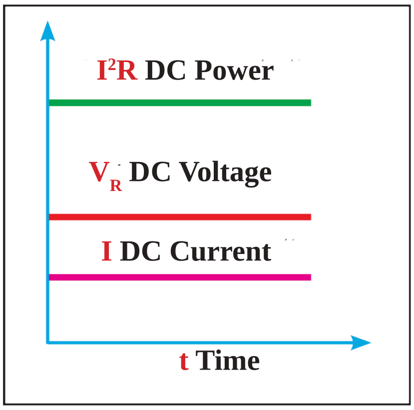


Figure (9)

Note figure (10-b), it shows that the dissipated power of Alternating current with maximum amount ($I_m$) does not equal the power produced by a direct current with the same amount. Why?

To answer this question:

It is found that alternating current changes periodically with time between ($+I_m$) and ($-I_m$) see figure (10-a), and it is not equal the maximum amount at any moment, only at a given moment it does equal the maximum amount, while the direct current is constant.

Therefore, all effects resulting from alternating current change periodically through time too, including thermal effects.

The relation of average power is the same of that used for direct current power:

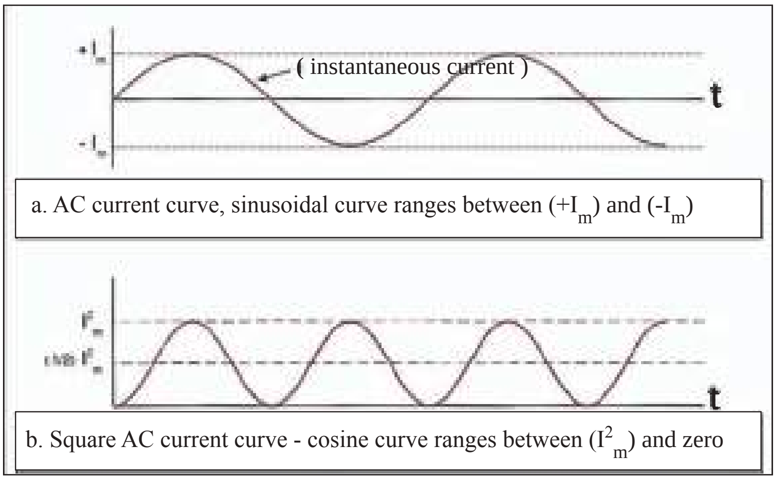
$$P = I^2R$$

$$= [(I_m)^2 \sin^2(\omega t)]R$$

$$P_{av} = \frac{1}{2} I_m^2 R$$

Because the average amount of $\sin^2(\omega t)$ ( for a full period or a an integer number of periods is ($\frac{1}{2}$))

i.e. $\sin^2(\omega t) = \frac{1}{2}$



a. AC current curve, sinusoidal curve ranges between ($+I_m$) and ($-I_m$)

b. Square AC current curve - cosine curve ranges between ($I^2_m$) and zero

Figure (10)

As you know, dissipated power in direct current circuit through the resistance is expressed as follows:

$$P = I_{dc}^2 R$$

Average power of alternating current is equal to direct current power through the same resistance and same period.

$I_{dc}$: is called effective current ($I_{eff}$)

$$I_{dc}^2 R = \frac{I_m^2 R}{2}$$

$$I_{eff}^2 R = \frac{I_m^2 R}{2}$$

Since the resistance is the same, then:

$$I_{eff}^2 = \frac{I_m^2}{2}$$

And by rooting both sides:

$$I_{eff} = \sqrt{\frac{I_m^2}{2}}$$

The effective amount of alternating current is:

$$I_{eff} = \frac{I_m}{\sqrt{2}} = 0.707 I_m$$

scince:

$$\frac{1}{\sqrt{2}} = 0.707$$

Therefore, effective alternating current amount is called root mean square current, symbolized ($I_{rms}$).

Effective Alternating Current is defined as: The amount of alternating current which equals the direct current if it flows through a certain resistance, it will generate the same thermal effect that is generated by the flowing alternating current through the same resistance and same period.

The effective alternating voltage is also expressed by the following relation:

$$V_{eff} = \frac{V_m}{\sqrt{2}} = 0.707\ V_m$$

What does this statement mean "The amount of alternating current in the circuit equals (1 Ampere)"?

Certainly, this does not mean that the maximum current ($I_m$), yet, it means the effective current ($I_{eff}$) equals (1 Ampere).

Note that most (AC) meters like Ammeters and Voltmeters measure the effective current and voltage. Most (DC) meters measure average alternating current. Therefore, the gauge (pointer) reads zero when connected to (AC) circuit.

**Think?**

Your colleague says "The effective current oscillates like sinusoidal function", what do you think? If this not true, how do you correct this?

**Example (1)**

Alternating voltage source with a pure resistance ($R = 100\,\Omega$) is connected to it, the voltage in the circuit is expressed as follows:

$$V_R = 424.2\sin(\omega t)$$

Then calculate the amount of:

1. Effective voltage.
2. Effective current.
3. Average power.

**The solution:**

1. The amount of effective voltage

$$V_R = V_m \sin(\omega t)$$

$$V_R = 424.2\sin(\omega t)$$

$$V_m = 424.2V$$

$$\boxed{V_{eff} = \frac{V_m}{\sqrt{2}} = \frac{424.2}{1.414} = 300V}$$

2. The amount of effective current

$$I_{eff} = \frac{V_{eff}}{R} = \frac{300}{100} = 3A$$

3. The amount of average power

$$P_{av} = (I_{eff})^2 R = (3)^2 \times 100$$

$$= 900W$$

or

$$P_{av} = I_{eff} \times V_{eff}$$

$$= 3 \times 300$$

$$= 900W$$

## 3-6 AC circuits: The load is as pure inductor

Figure (11) shows (AC) circuit, which contains alternating voltage source and pure inductor (i.e. a coil without resistance). The voltage through the inductor is expressed as follows:

$$V_L = V_m \sin(\omega t + \frac{\pi}{2})$$

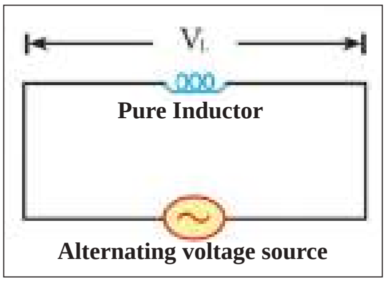


Figure (11)

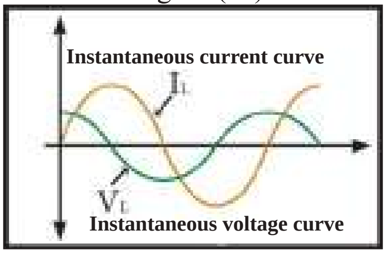


Figure (12-a)

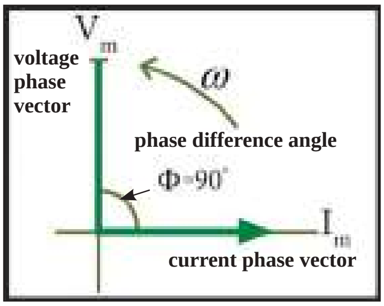


Figure (12-b)

Note figure (12-a):

$V_L$: Instantaneous voltage through the inductor.

$V_m$: Maximum voltage in the inductor.

($\omega t$): Phase angle.

$\Phi = \frac{\pi}{2}$ Phase difference angle between voltage phase vector and current phase vector, see figure (12-b).

The flowing current in this circuit is expressed as follows:

$$I_L = I_m . \sin(\omega t)$$

This means:

Voltage phase vector ($V_m$) in a pure inductor precedes current phase vector ($I_m$) by a phase difference ($\Phi$) which equal to ($\Phi = \frac{\pi}{2} = 90^0$).

In this circuit, the inductor shows the opposition to the change in current, this reverse is called inductive reactance and symbolized by ($X_L$) and it is expressed as:

$$X_L = \omega L = 2\pi f L$$

Inductive reactance ($X_L$) depends on:

1. Coefficient of self-induction of the inductor (L) and it is directly proportional with it ( $X_L \alpha L$ ) if the current frequency (f) is constant.
2. Angular frequency (ω) and it is directly proportional with it ( $X_L \alpha \omega$ ) when self-induction coefficient (L) is constant.

Inductive reactance is measured by (ohm) and symbolized (Ω), because:

$$X_L = 2\pi f L = Hz.Henry = (\frac{1}{sec})(\frac{Volt.sec}{Ampere}) = (\frac{Volt}{Ampere}) = ohm(\Omega)$$

Frequency (f) is measured by (Hz) and self-induction coefficient is measured by (Henry).

How inductive reactance ($X_L$) is affected by circuit current frequency (f) and coefficient of self-induction (L)? What the curve looks like?

To answer this question, do the following activity:

## Activity (1)

**Illustrates the effect of changing the current frequency (f) in an inductor reactance ($X_L$).**

**Tools of activity:**

Electric Oscillator (Alternating voltage source with adjustable frequency), ammeter, voltmeter, a coil of negligible resistance (inductor) and an electrical switch.

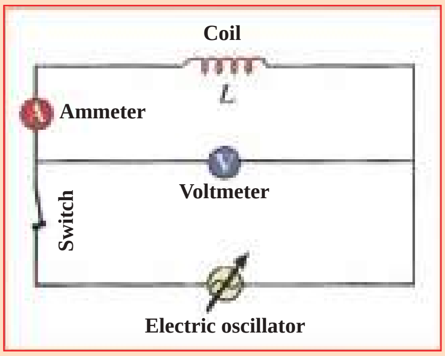


Figure (13)

**Activity steps:**

- Connect a practical electrical circuit (consisting of coil, ammeter, and electric oscillator) in series combination, and then connect the voltmeter in parallel combination on the coil ends. See figure (13).
- Close the circuit, increase electrical frequency of electric oscillator gradually, and maintain voltage constant (by observing voltmeter reading).How would the ammeter reading change in the circuit?

There will be decrease in ammeter reading.

**Conclusion:**

Inductive reactance ($X_L$) is directly proportional with current frequency (f) when self-induction coefficient (L) is constant.

This activity can be drawn as a diagram:

which illustrates the direct proportion between inductive reactance ($X_L$) and current frequency (f), see figure (14).

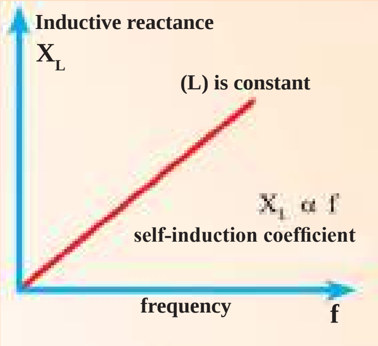


Figure (14)

## Activity (2):

**Illustrates the effect of changing self-induction coefficient (L) in an inductive reactance ($X_L$).**

**Tools of activity:**

Constant frequency voltage source, wrought iron core, ammeter, voltmeter, hollow coil without resistance (inductor) and electric switch.

**Activity steps:**

- Connect the circuit (consisting of coil, ammeter and voltage source in series combination), connect the voltmeter in parallel combination with the coil ends, see figure (15).

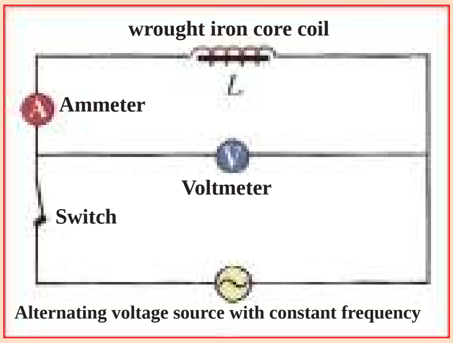


Figure (15)

- Close the circuit and observe ammeter reading.
- Insert the core iron gradually in the coil and keep voltage constant (by observing voltmeter reading).

How would the ammeter reading in the circuit change?

There will be decrease in ammeter reading because there is increase in inductive reactance (inserting core iron inside the coil increases self-induction coefficient of the coil).

**Conclusion:**

Inductive reactance ($X_L$) is directly proportional to coefficient self-induction (L) when current frequency is constant.

This activity can be drawn as a diagram, see figure (16), which illustrates the direct relation between inductive reactance ($X_L$) and coefficient of self-induction (L) when the current frequency is constant (f).

$$X_L \alpha L$$

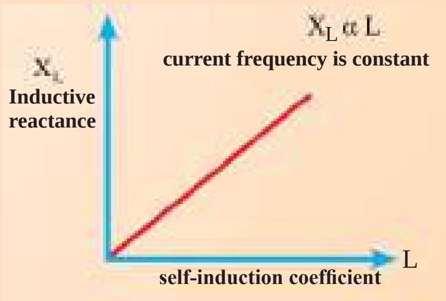



Figure (16)

How do you explain increase in an inductive reactance when current frequency increases according to Lenz's Law?

To answer this question: increase in frequency in current flow in the circuit means increase in time rate of current change ($\frac{\Delta I}{\Delta t}$). This causes increase in the induced electromotive force ($\varepsilon_{ind}$) in the inductor, which hinders of this force ($\varepsilon_{ind} \alpha - \frac{\Delta I}{\Delta t}$) according to Lenz's law:

i.e. the time rate of change in the current is hindered, thus, increasing inductive reactance which represents this reversal of inductor in the current change.

**Remember**

At a very low frequencies, inductive reactance decreases ($X_L = 2\pi\ f\ L$), it is directly proportional to current frequency ($X_L \alpha f$), it could be zero at very low frequencies, and then the coil is said to act as pure resistance (because the coil is not neglecte the resistance).

While at a very high frequencies, inductive reactance ($X_L$) increases enormously that it might cut off the circuit current, then the coil acts as open-switch.

## Power in AC circuit with pure inductor:

Since voltage through pure inductor precedes the flowing current in the circuit by phase difference angle (Φ) which equals ($\frac{\pi}{2}$) i.e. ($\Phi = \frac{\pi}{2}$), note figure (17). Voltage is expressed as follows:

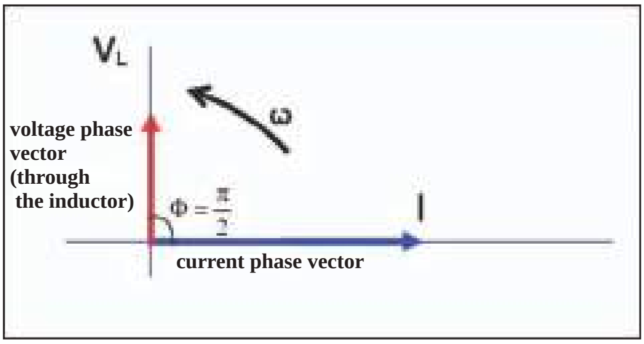


Figure (17)

$$V_L = V_m \sin(\omega t + \frac{\pi}{2})$$

The flowing current through the inductor is given as follows: $I_L = I_m \sin(\omega t)$

When the instantaneous voltage through the inductor and instantaneous current are drawn as time function, we obtain the power curve as sinusoidal function whose frequency is twice the frequency of both voltage or current, containing equal positive parts and negative parts in area. Therefore, average power of one period or an integer of full periods equals to zero, see figure (18).

What the explanation of that?

The reason is: When the current flow in the inductor is changed from zero to maximum amount in one quarter of the cycle, energy moves from the source and stored in the inductor as a magnetic field (represented by the positive parts of the curve). Then all that energy goes back to source when the current changes from maximum value to zero in the next quarter of the cycle (represented by the negative parts of the curve).

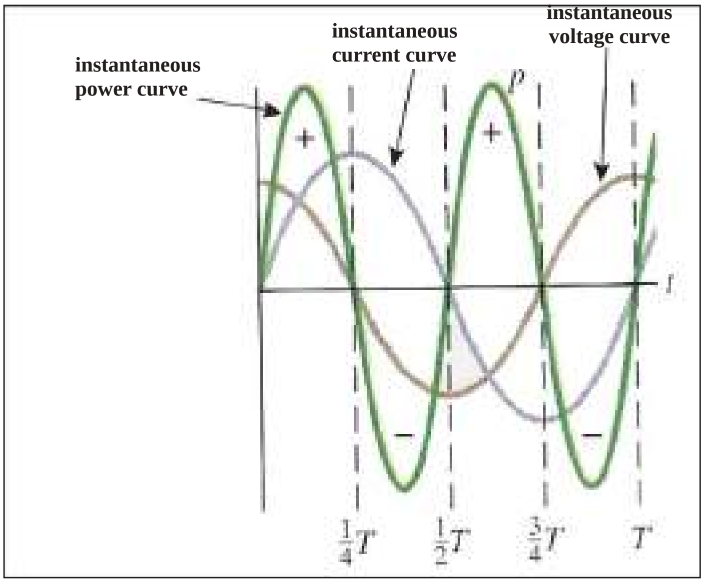


Figure (18)

This means that when the inductor is pure, it does not consume power, and inductive reactance is non ohmic resistance and does not follow Joule's Law because it does not consume power (average power equal to zero).

**Example (2)**

A coil with neglected resistance (pure inductor), whose self-induction coefficient is ( $\frac{50}{\pi}$ mH), is connected to alternating voltage source, its potential difference is (20V), calculate both inductor reactance and current in the circuit when its frequency is:

a. f = 10Hz    b. f = 1MHz

**The solution:**

a. At frequency f = 10Hz

$$X_L = 2\pi f\, L$$
$$= 2\pi \times 10 \times \frac{50}{\pi} \times 10^{-3} = 1\Omega$$
$$I = \frac{V_L}{X_L} = \frac{20}{1} = 20\ A$$

b. At frequency f=1MHz

$$X_L = 2\pi f\, L$$
$$= 2\pi \times 1 \times 10^{6} \times \frac{50}{\pi} \times 10^{-3} = 10^{5}\Omega$$
$$I = \frac{V_L}{X_L} = \frac{20}{10^{5}} = 20 \times 10^{-5} A$$

Discuss the results of this example and show the conclusion.

## 3-7 AC Circuits: The load is a capcitor with pure capacitance

Figure (19-a) shows AC circuit with alternating voltage source and a capacitor only, the potential difference on the capacitor is expressed as follows:

$$V_c = V_m \sin(\omega t)$$

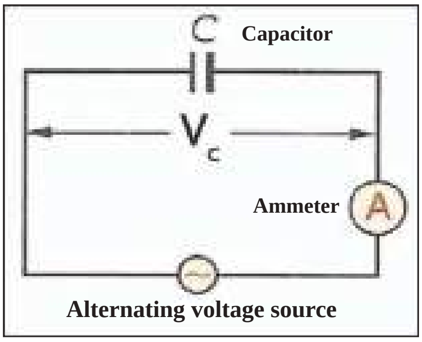



Figure (19-a)

$V_C$: Instantaneous potential difference through the capacitor.

$V_m$: Maximum potential difference through the capacitor.

(ωt): Phase angle of phase vector of potential difference through the capacitor, figure (19-b).

By definition of capacitor capacitance (C):

$$Q = C.V_C$$

Then, it is: $Q = C V_m \sin(\omega t)$

Since the current is: $I_C = \frac{\Delta Q}{\Delta t}$

So $I_C = \frac{\Delta[C V_m \sin(\omega t)]}{\Delta t}$

$$I_C = \omega C V_m \cos(\omega t)$$

Since $I_C = \omega C V_m \sin(\omega t + \frac{\pi}{2})$

because $\sin(\omega t + \frac{\pi}{2}) = \cos(\omega t)$

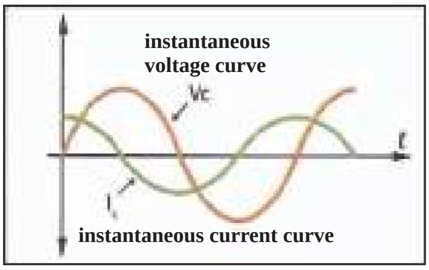



Figure (19-b)

The inverse of (ωC) is called capacitive reactance of the capacitor, symbolized ($X_C$), capacitive reactance is defined as: the opposition by the capacitor to change in voltage of the circuit. i.e.

$$X_C = \frac{1}{\omega C} \quad \text{or} \quad X_C = \frac{1}{2\pi f C}$$

Substituting $\omega C = \frac{1}{X_c}$ in the current equation, we get:

$$I_c = \left(\frac{V_m}{X_c}\right) \sin(\omega t + \frac{\pi}{2})$$

According to Ohm's Law: $I_m = \frac{V_m}{X_c}$

Thus, Alternating current circuit contain a capacitor with a pure capacitance is expressed as:

$$I_c = I_m . \sin(\omega t + \frac{\pi}{2})$$

From the above relation, we conclude that current phase vector ($I_m$) in an AC circuit contain a capacitor with pure capacitance, precedes voltage phase vector ($V_m$) by phase difference angle ($\Phi = \frac{\pi}{2}$, or quarter period), see figure (20) which shows a diagram of voltage phase vector and current phase vector.

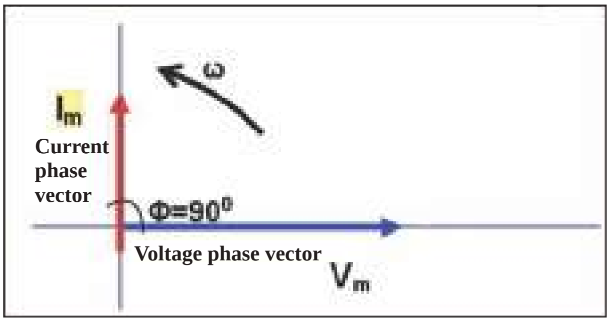


Figure (20)

How capacitive reactance does affected for both frequency voltage source and capacitance of the capacitor ? How would the curve look like? To answer this question, do the following activity:

## Activity (1):

**Illustrates the effect of changing frequency voltage source in capacitive reactance amount:**

**Tools of activity:**

Ammeter, Voltmeter, Parallel-plate capacitor, Electric oscillator, connection wires and an electric switch.

**Activity steps:**

- Connect the circuit (consisting of a capacitor, ammeter and electric oscillator in series combination, and connect voltmeter in parallel combination with the capacitor). See figure (21).

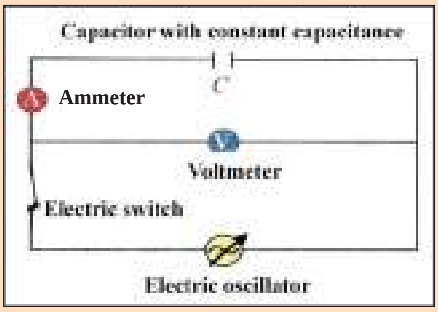


Figure (21)

- Close the circuit and start to increase frequency of the electric oscillator while maintaining potential difference constant between the capacitor plates (by observing voltmeter reading). How the ammeter reading change in the circuit?

We notice an increase in the ammeter reading (increase in the current flow in the circuit with increase in frequency voltage source).

### Conclusion:

Capacitive reactance ($X_C$) is inversely proportional with frequency voltage source ($X_c \alpha \frac{1}{f}$) when capacitance of capacitor is constant (C). This relation can be drawn as a diagram, see figure (22).

It represents the inverse relation between capacitive reactance ($X_C$) and frequency voltage source (f) when the capacitance of capacitor is constant (C) when the circuit has contain capacitor with a pure capacitance.

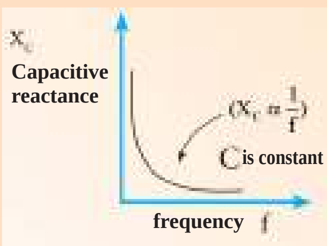


Figure (22)

## Activity (2):

Illustrates the effect of changing capacitance of capacitor in capacitive reactance amount:

**Tools of activity:**

Alternating voltage source with constant frequency, ammeter, voltmeter, parallel-plate capacitor with variable capacitance, an electric switch, connection wires and dielectric.

**Activity steps:**

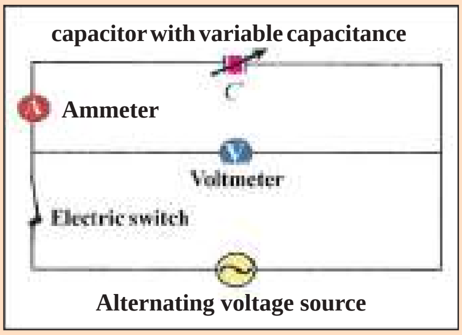


Figure (23)

- Connect the circuit (conisting of capacitor, ammeter and voltage source in series combination, and connect the voltmeter in parallel combination to the capacitor), as in figure (23).
- Close the circuit and observe ammeter reading.
- Increase the capacitance amount of capacitor gradually (by inserting a dielectric between capacitor plates).

How would ammeter reading change in this case?

There is increase in ammeter reading (increase of flowing current in circuit is directly proportional with increase in the capacitance of capacitor).

**Conclusion:**

Capacitive reactance is inversely proportional to the capacitance of capacitor when frequency voltage source is constant.

This relation can be drawn as a diagram, see figure (24) which shows the inverse relation between capacitive reactance ($X_C$) and capacitance of capacitor (C) when the frequency voltage source is constant when the load in the circuit is contain capacitor with a pure capacitance.

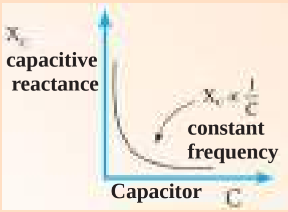


Figure (24)

Capacitive reactance is measured in ohms unit because:

$$X_c = \frac{1}{2\pi fc} = \frac{1}{Hz.Farad} = \frac{1}{(\frac{1}{sec})(\frac{Coulomb}{Volt})} = \frac{sec.Volt}{Ampere.sec} = \frac{Volt}{Ampere} = ohm$$

### Remember

At very high frequencies of the voltage source, capacitive reactance decreases, because it is inversely proportional with frequency ( $X_c \alpha \frac{1}{f}$ ) , it might be zero, and then the capacitor can act as a closed-switch (capacitor outside the circuit). While, at very low frequencies, capacitive reactance increases so much that the current might be cut off, then the capacitor acts as open-switch. When the capacitor is in the direct current circuit.

## Example (3)

A capacitor with capacitance ($\frac{4}{\pi}$ μF) is connected to alternating voltage source with (2.5 V) potential difference. calculate capacitive reactance and current in this circuit. If circuit frequency is : a. 5 Hz b. $5 \times 10^5$ Hz

### The solution:

a. Calculate the capacitive reactance at (5 Hz): $X_C = \frac{1}{2\pi fc}$

$$X_C = \frac{1}{2\pi \times 5 \times \left(\frac{4}{\pi}\right) \times 10^{-6}} = \frac{10^6}{40} = 25 \times 10^3 \Omega$$

$$I = \frac{V_C}{X_C} = \frac{2.5}{25 \times 10^3} = 1 \times 10^{-4} A$$

b. Calculate the capacitive reactance at ($5 \times 10^5$ Hz)

$$X_C = \frac{1}{2\pi fc}$$

$$X_C = \frac{1}{2\pi \times 5 \times 10^5 \times \left(\frac{4}{\pi}\right) \times 10^{-6}} = \frac{1}{4} = 0.25\Omega$$

$$I = \frac{V_C}{X_C} = \frac{2.5}{0.25} = 10A$$

Discuss results of this example and what do you conclude from this?

## Power in AC circuit contains a capacitor with pure capacitance

Since voltage through a capacitor with a pure capacitance is expressed as:

$$V_C = V_m \sin(\omega t)$$

Thus, the flowing current in the circuit precedes voltage by phase difference ($\Phi = \frac{\pi}{2}$), see figure (25). Therefore, current is expressed as:

$$I_C = I_m \sin(\omega t + \frac{\pi}{2})$$

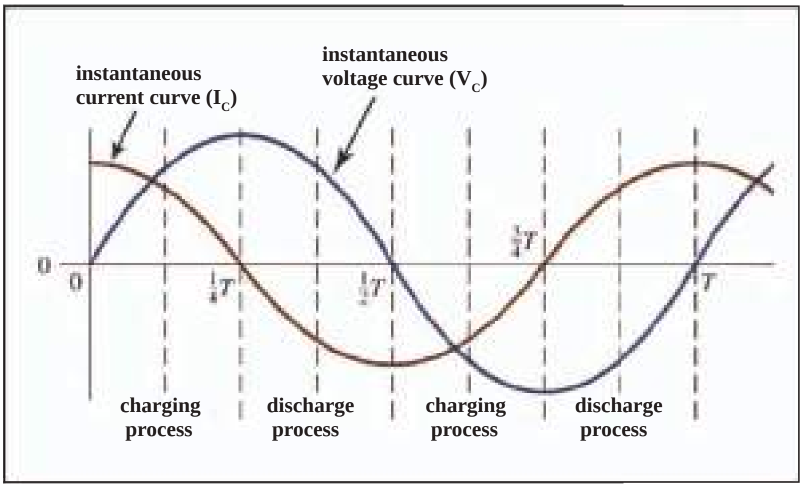


Figure 25

Instantaneous power curve changes as a sinusoidal function, its frequency is twice the frequency of current or voltage, containing positive and negative parts equal in area. Thus, average power of a full period or an integer of periods is zero. See figure (26). What is the explanation for this?

The reason is that, the capacitor charges in the first quarter of the period then all of its charge is discharged in the next quarter, then the capacitor charges with inverse polarity and discharges again consecutively. What do you conclude?

Conclusion a pure capacitor does not dissipate power in (AC) circuit because there is no resistance in that circuit.

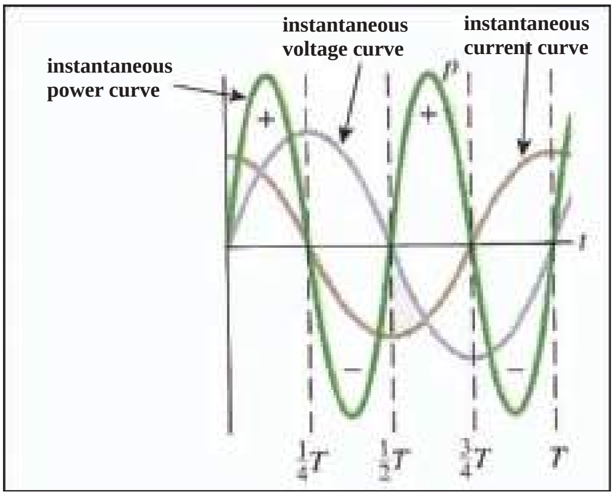



Figure (26)

## 3-8 AC circuits with series combination of pure resistor, pure inductor and pure capacitor (R-L-C)

When a pure resistance, a pure inductor and a capacitor with a pure capacitance are connected in series combination along with an ammeter, see figure (27), the horizontal axis (X-axis is referential axis). Phase vectors of currents in series cobination circuit are congruent on X-axis.

As for voltage phase vectors, they create phase difference angle (Φ) with X-axis, now, let's explain phase vectors for the current and potential differences as follows:

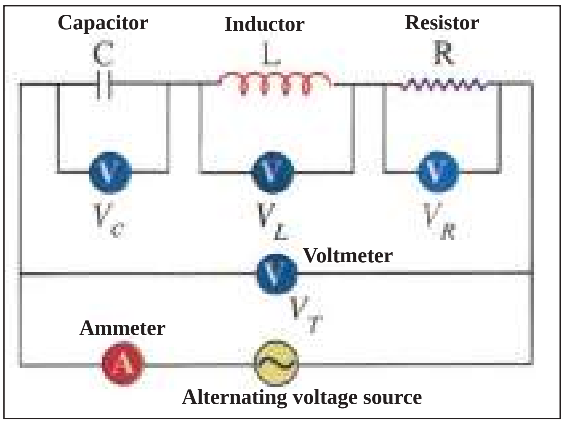



Figure (27)

### 1. Pure resistor:

Voltage phase vector ($V_m$) and current phase vector ($I_m$) in the resistance are in phase (i.e. phase difference $\Phi = 0$).

Thus, voltage in pure resistance is expressed as:

$$V_R = V_m \sin(\omega t)$$

Current in pure resistance is expressed as figure (28).

$$I_R = I_m \sin(\omega t)$$

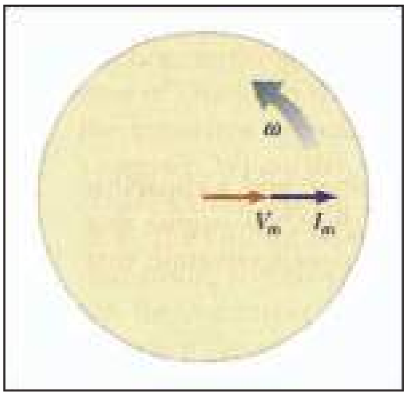


Figure (28)

## 2. Pure capacitor:

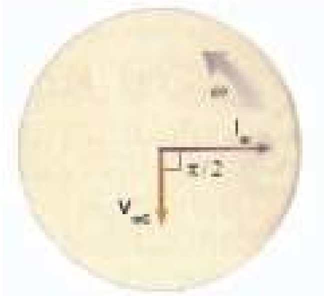


Figure (29)

Phase vector of potential difference through the capacitor ($V_{C\ (max)}$) (delays) from current phase vector ($I_{C\ (max)}$) by phase difference of ($90^0$) equals ( $\Phi = -\frac{\pi}{2}$ ), see figure (29).

The potential difference through a capacitor with pure capacitance is expressed as:

$$V_C = V_m \sin(\omega t - \frac{\pi}{2})$$

Current through a capacitor with pure capacitance is:

$$I_C = I_m \sin(\omega t)$$

## 3. Pure Inductor :

Voltage phase vector through pure inductor ($V_L$) precedes current phase vector ($I_L$) by phase difference angle ( $\Phi = +\frac{\pi}{2}$ ), see figure (30).

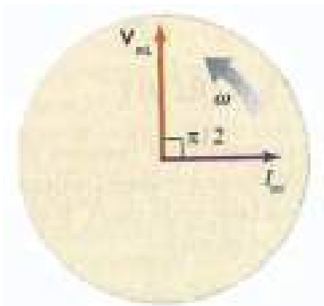


Figure (30)

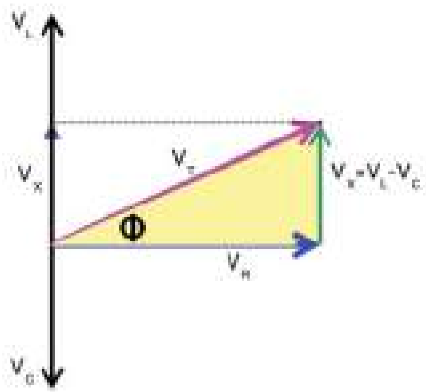
Thus, voltage through pure inductor is:

$$V_L = V_m \sin(\omega t + \frac{\pi}{2})$$

Current through pure inductor is:

$$I_L = I_m \sin(\omega t)$$

We graph the current on the refrence coordinate axis in the (AC) circuit (in series combination) (the current is equal in all parts of the circuit). Then we represent ($V_L$,$V_C$,$V_R$) according to phase vectors as in figure (31).




**Voltage phase vector diagram**

Figure (31)

Total voltage phase vector (Resultant) of the three phase vectors is represented by ($V_T$), it can be calculated as:

$$(V_T)^2 = (V_R)^2 + (V_L - V_C)^2$$

From this diagram, we can calculate phase difference angle (Φ) between the total voltage (Resultant) and current phase vector in the circuit:

$$\tan \Phi = \frac{V_L - V_C}{V_R}$$

## The properties of (R-L-C) circuit

**First:** if ($V_L$) is greater than ($V_C$) the AC circuit in series combination with (R-L-C), has the following:

- Inductive properties.
- Positive phase difference angle ($\Phi$), total voltage phase vector ($V_T$) precedes current phase vector (I) by phase difference angle ($\Phi$) according to Ohm's law, we get:

Resistance (R): $R = V_R / I$

Inductor reactance ($X_L$): $X_L = V_L / I$

Capacitive Reactance ($X_C$): $X_C = V_C / I$

Total impedance in the circuit (Z): $Z = \frac{V_T}{I}$

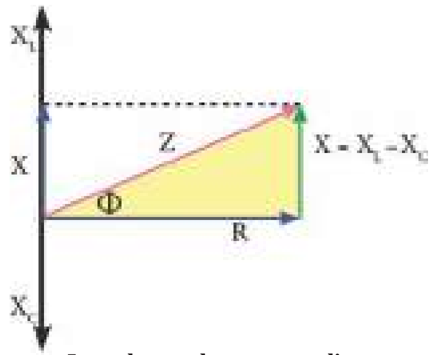
It the opposition of resistance and the reactance.

Impedance diagram is drawn as in figure (32-a), if ($X_L$) is greater than ($X_C$), then the circuit has the following:

Inductive properties and a positive phase difference angle ($\Phi$), then we get:

$$Z^2 = R^2 + X^2$$

$$X = X_L - X_C$$



**Impedance phase vector diagram**

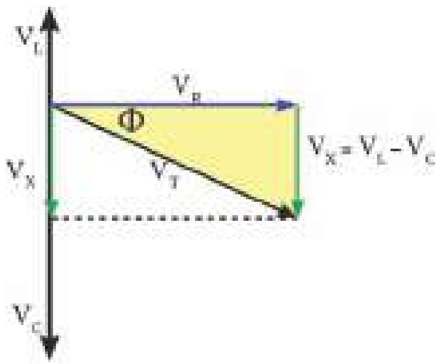
Figure (32-a)

The reactance (X) equals the difference between the two reactance (inductor reactance and capacitive reactance)

$$Z^2 = R^2 + (X_L - X_C)^2$$

Or compute phase difference angle ($\Phi$) from impedance triangle

$$\tan\Phi = \frac{X}{R} = \frac{X_L - X_C}{R}$$



**Voltage phase vector diagram**

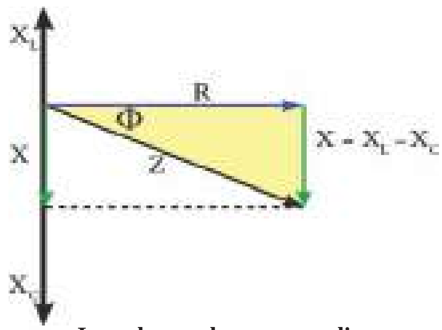
Figure (32-b)

**Second:** If ($V_L$) is smaller than ($V_C$), then the (AC) circuit in series combination, which contains (R-L-C), see figure (32-b), has the following properties:

Capacitive properties.

- Negative phase difference angle ($\Phi$) (Total voltage phase vector delays from current phase vector by phase difference angle $\Phi$).

A diagram of phase impedance of this circuit can be drawn, see figure (32-c) when ($X_C > X_L$).



**Impedance phase vector diagram**

Figure (32-c)

**Third:** If ($V_L$) equals ($V_C$), then, the (AC) circuit is series combination (R-L-C) has the following:

- Pure resistance properties (Ohmic) (The state of electric resonance).
- Zero phase difference angle (Φ) (Total voltage phase vector is congruent on current phase vector), see figure (33-a).

A diagram of phase impedance can be drawn for this circuit, see figure (33-b).

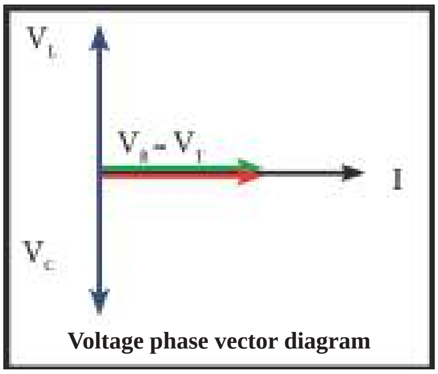



Figure (33-a)

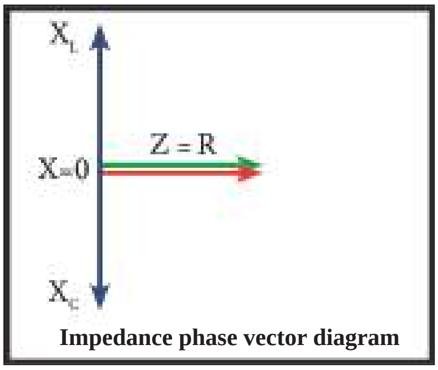



Figure (33-b)

**Example (4)**

A coil with self-induction ($L = \frac{\sqrt{3}}{\pi} mH$) is connected to alternating voltage source (100 V) potential difference, Phase difference angle (Φ) between total voltage and current phase vector is ($60^0$), the current flow in the circuit is (10 A), then calculate:

1. Coil resistance. 2. Source frequency.

**The solution:**

1. Calculate total impedance in the circuit:

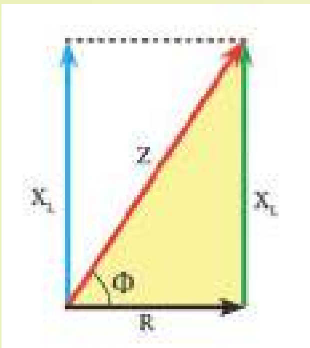
$$Z = \frac{V_T}{I} = \frac{100}{10} = 10\Omega$$

Then draw pharos diagram of impedance and calculate (R) and ($X_L$), see figure below:

$$\cos\Phi = \frac{R}{Z}$$

$$\cos 60^\circ = \frac{R}{10} \Rightarrow \frac{1}{2} = \frac{R}{10}$$

$$R = 5\Omega$$




$$Z^2 = R^2 + X_L^2$$

$$(10)^2 = (5)^2 + X_L^2$$

$$X_L^2 = 75$$

$$X_L = 5\sqrt{3}\,\Omega$$

2. To calculate frequency:

$$X_L = 2\pi fL$$

$$5\sqrt{3} = 2\pi f \times \frac{\sqrt{3}}{\pi} \times 10^{-3}$$

$$f = 2500Hz$$

## 3-9 Power factor

In (AC) circuits, power is consumed in the resistance only, as thermal power. As for power in a pure inductor, it is stored in its magnetic field in one quarter of the period, then goes back to the source in the next quarter. Similarly, power in capacitors is stored in the electric field in one quarter of the period then goes back to source in the next quarter. One can conclude that power is not consumed in the inductor if it is a pure inductor, and power is not consumed in the capacitor if the capacitor is pure.

Consumed power in the resistance is called real power ($P_{real}$) and measured by (Watt), it is expressed as follows:

$$P_{real} = I_R V_R$$

From the diagram of voltage vector, figure (34) : $\cos\Phi = \frac{V_R}{V_T}$

Thus:

$$V_R = V_T \cos\Phi$$

Therefore, the real power is:

$$P_{real} = I_R V_T \cos\Phi$$

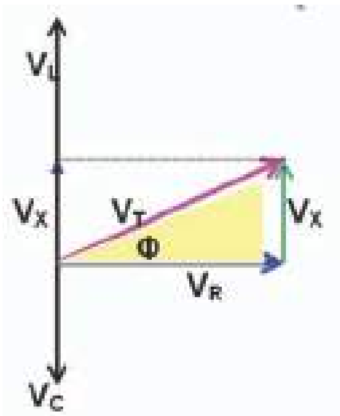


Figure (34)

Since the current is equal in (AC) circuit with (R-L-C) in series combination:

$$I_R = I_L = I_C = I$$

Substitute in the previous equation to get:

$$P_{real} = I_T V_T \cos\Phi$$

The quantity ($I.V_T$) is called apparent power, which is the total power, supplied for the circuit. It is measured by (Volt . Ampere) (V . A) and expressed as follows:

$$P_{app} = IV_T$$

The ratio of real power ($P_{Real}$) to apparent power ($P_{app}$) is called power factor (pf); power factor is expressed as:

$$pf = \frac{P_{real}}{P_{app}} = \cos\Phi$$

or

$$pf = \cos\Phi$$

Amount of power factor in (AC) circuit changes according to phase difference angle (Φ) in the circuit, if:

- Load in the circuit is pure resistance, phase difference angle (Φ) between voltage phase vector ($V_R$) and current phase vector (I) is zero. Power factor is integer (1) because:

$$pf = \cos\Phi = \cos 0 = 1$$

Thus: Real power (consumed power) = apparent power (supplied), i.e.

$$P_{real} = P_{app}$$

- Load in a pure inductor circuit, phase difference angle (Φ) between voltage phase vector ($V_L$) and current phase vector (I) is ($90^0$), power factor is zero because ($\cos 90^0 = 0$)

$$pf = \cos \Phi = \cos 90^0 = 0$$

- Load in the circuit is a capacitor with pure capacitance, phase difference angle (Φ) between voltage phase vector ($V_C$) and current phase vector (I) is ($90^0$), power factor is zero, because: ($\cos 90^0 = 0$)

$$pf = \cos\Phi = \cos 90^0 = 0$$

**Example (5)** An alternating current circuit with pure resistance, pure capacitor and pure inductor (RLC) connected in series combination.

The circuit is connected to alternating voltage source (200V) and:

$R = 40\Omega$, $X_L = 120\Omega$, $X_C = 90\Omega$. Calculate the following:

1. Total impedance.
2. Current flow in the circuit.
3. Phase difference angle between total voltage phase voctor and current phase vector. Draw impedance phase diagram. What are the properties of this circuit?
4. Power factor.
5. Real power consumed in the resistance.
6. Apparent power (supplied power for the circuit).

**The solution:**

1. Draw phase diagram of impedance, see figure below:

1. $Z^2 = R^2 + (X_L - X_C)^2$

$= (40)^2 + (120 - 90)^2$

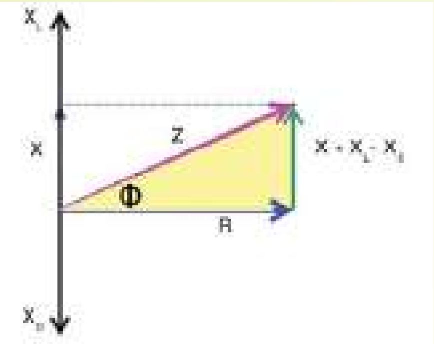
$= 1600 + 900 = 2500$

$Z = 50\Omega$

2. $I = \dfrac{V_T}{Z} = \dfrac{200}{50} = 4A$

3. $\tan\theta = \dfrac{(X_L - X_C)}{R}$

$= \dfrac{120 - 90}{40} = \dfrac{30}{40} = \dfrac{3}{4}$



Impedance phase diagram

The circuit has inductive properties because:

$\theta = 37^\circ$

$X_L > X_C$

4. $pf = \cos\theta = \frac{R}{z} = \frac{40}{50} = 0.8$ Power factor

5. $p_{Real} = I^2R$

$= (4)^2 \times 40 = 16 \times 40 = 640$ watt Real power

6. $p_{app} = I_T \times V_T$

$= 4 \times 200 = 800$ VA Apparent power

## 3-10 Electromagnetic oscillation

Electromagnetic Oscillation circuit consists of a pure capacitor with a variable capacitance and a pure inductor. In the previous chapters, you studied three elements: capacitors, resistors and inductors.

Suppose we have a simple circuit consists of a pure capacitor and a pure inductor, such circuit is called inductor-capacitor (L-C) circuit. We find that the current and potential difference both change as a sinusoidal function with time, see figure (35). These changes in voltage and current in (L-C circuit) are called electromagnetic oscillation.

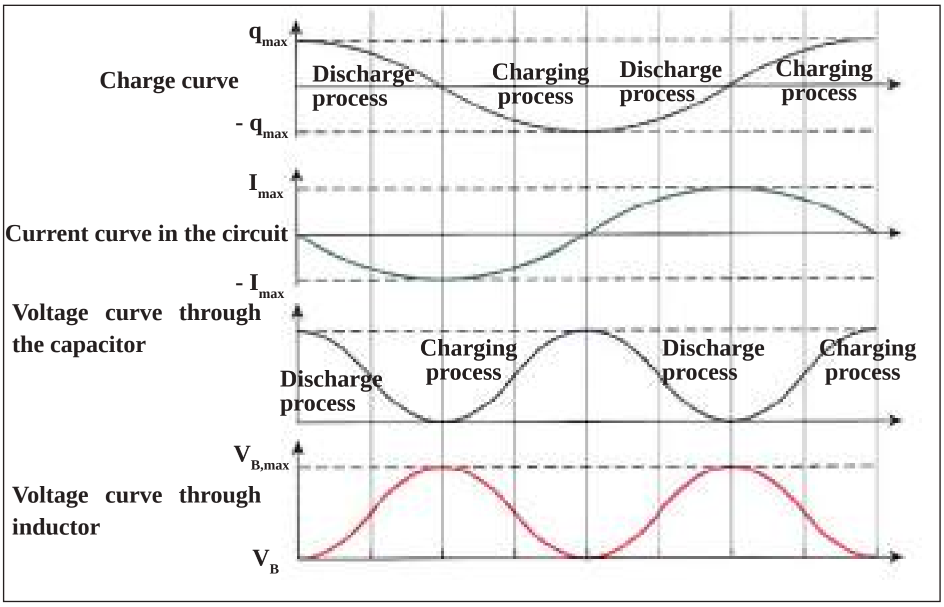



Figure (35)

Now you know that stored energy in the electric field between plates of the capacitor with a capacitance (C) is expressed mathematically as:

$$PE_{electric} = \frac{1}{2} \times \frac{Q^2}{C}$$

Q: Stored charge in any of the plates of the capacitor (with a capacitor with a pure capacitance C).

Stored energy in the magnetic field of a pure inductor with self-induction coefficient (L), is expressed as follows:

$$PE_{magnetic} = \frac{1}{2} \times LI^2$$

I: Current flow through the pure inductor.

Figure (36), represents exchange operations of stored energy in electric field between the plates of a capacitor and stored energy in the magnetic field of the inductor during a full period.

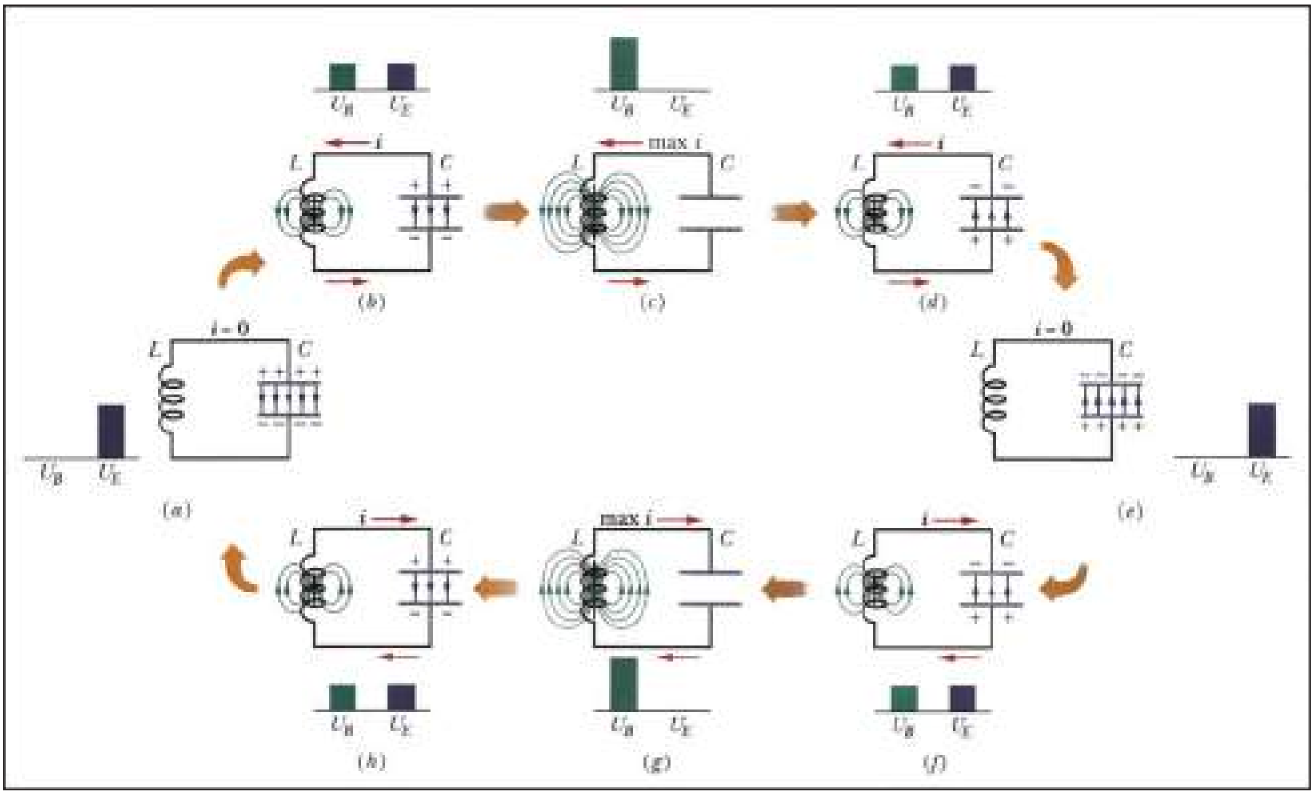


Figure (36)

Initially, figure (a) the capacitor fully charged, then the total energy in this circuit is stored in the electric field between the plates of the capacitor, then, the capacitor discharges its charge through the inductor, figure (b). At this moment, a current flows in the inductor and generates magnetic field. Thus, part of the total energy of the circuit is stored in the electric filed of the capacitor plates, while the other part of energy is stored in the magnetic field of the inductor.

Figure (c) Shows that the capacitor is fully discharged, this means that the flowing of current through the inductor is at maximum value. Thus, all energy in the circuit is stored in the magnetic field of the inductor. Then, the capacitor is charged again and stores energy in the electric field between plates of the capacitor, then the capacitor is discharged and stores the energy in the magnetic field of the inductor and so forth, energy storage continues between the capacitor and the inductor without decrease, because the circuit has not resistance, which causes energy loss.

While, the amplitude of energy oscillation in electromagnetic oscillation circuit which contains a capacitor and a coil (not neglect resistor), fades in time because the circuit has resistance. See figure (37), it shows that the stored charge in the capacitor plates and the current flow in the inductor both change as a sinusoidal function with time. And, since the stored energy in the electric field between the plates of the capacitor depend on square charge ($Q^2$) stored in any of the plates while the stored energy in the magnetic field of the inductor depends on square current ($I^2$). This means, electric energy and magnetic energy both range from zero to maximum value as time function.

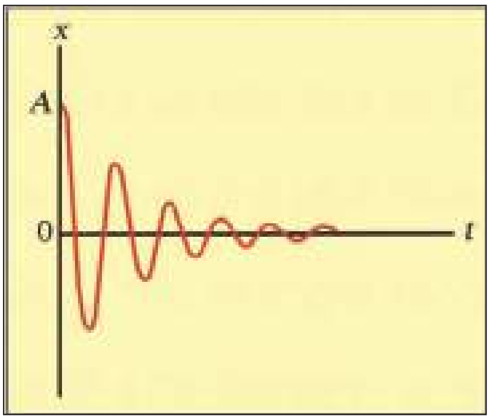


Figure (37)

Resonance can be achieved in electromagnetic oscillation circuit if this circuit is tuned with frequency of desired signal (i.e. reception circuit frequency equals frequency of desired signal). This is the case with tuning TV or radio stations, by changing capacitor capacitance in the Oscillated circuit. For electric resonance to happen, inductive reactance ($X_L = \omega L$) must be equal to capacitive reactance, ( $X_C = \frac{1}{\omega C}$ ).

Normal frequancy of oscillated circuit is expressed as: $f_r = \frac{1}{2\pi\sqrt{LC}}$ or $\omega_r = \frac{1}{\sqrt{LC}}$

## 3-11 Resonance in AC circuits

The practical importance of (AC) circuits (L-R-C) in series combination lies in the way these circuits used with various frequency sources, which made average power that transfering to the circuit in maximum value.

Reception circuits in radios are the best example of tuning circuits; simply, it is an (L-R-C) circuit in series combination, see figure (38). It shows effect of resistance on current curve at resonant frequency. When resistance is small (200Ω for example), current curve will be thin (sharp) and huge. If resistance is big (1000Ω for example), current curve will be wide and small.

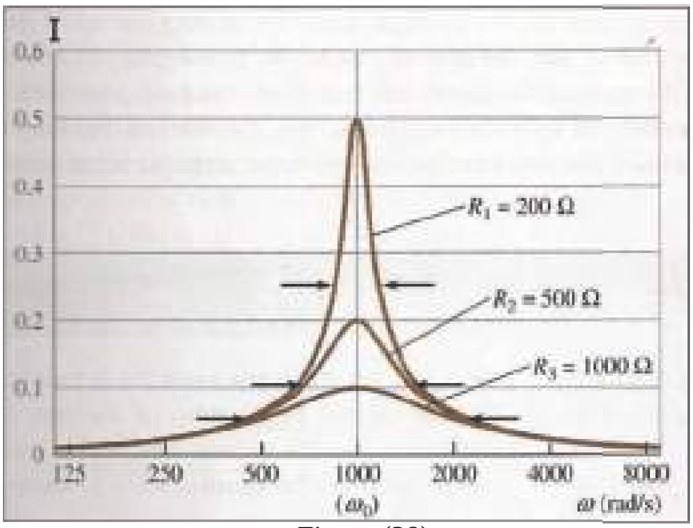


Figure (38)

At certain frequency, radio signal produces a current that changes within reception circuit. This current has maximum value if reception circuit (tuning circuit) frequency is equal to received signal, then, inductive reactance ($X_L = \omega L$), is equal to capacitive reactance ( $X_C = \frac{1}{\omega C}$ ) . This makes circuit impedance minimum (Z = R).

This case is called Electric Resonance.

i.e. $\omega L = \frac{1}{\omega C}$

ω: Angular frequency ($\omega = 2\pi f$)

L: Self-induction coefficient of the inductor, C: Capacitor capacitance, so: $\omega_r^2 = \frac{1}{LC}$

From which we derive angular frequency of resonance $\omega_r = \frac{1}{\sqrt{LC}}$ or resonance frequency $f_r = \frac{1}{2\pi\sqrt{LC}}$.

Resonance frequency ($f_r$) of the circuit can be changed either by changing capacitor capacitance (C) or changing coefficient of self-induction (L) of the inductor. We find that the current changes when the frequency changes and reaches maxiumum value (peak) at a certain frequency called resonance frequency.

If frequency of the circuit (in series combination with R-L-C) is greater than resonance frequency, the circuit has inductive properties, because: ($X_L > X_C$ and also $V_L > V_C$).

If frequency of this circuit is smaller than resonance frequency, the circuit has capacitive properties, because: ($X_L < X_C$ and also $V_L < V_C$)

Nevertheless, if frequency of this circuit equals resonance frequency, the circuit is pure resistance properties, because: ($X_L = X_C$ and $V_L = V_C$)

## 3-12 Quality factor

Resonance happens in (AC) circuit in series combination (with R L& C) when the angular frequency of the circuit is equal to resonance frequency, i.e. $\omega = \omega_r$ Then, average power ($P_{av}$) will be at maximum. Average power and angular frequency of various resistances can be drawn as a diagram, see figure (39).

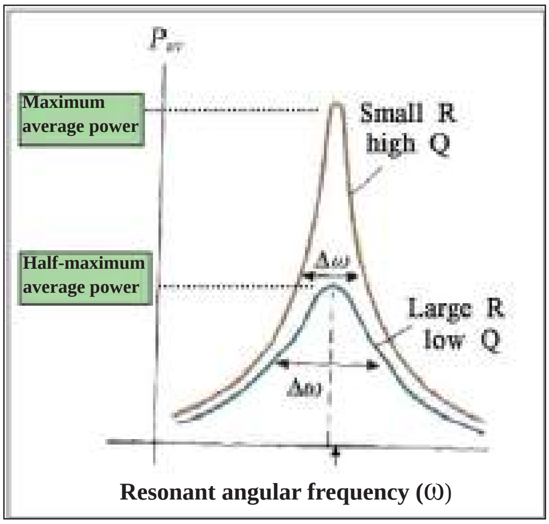



Figure (39)

-When average power drops to half- maximum, we get two values of the angular frequency, see figure (39). ($\omega_1$ and $\omega_2$) on both sides of angular resonance ($\omega_r$), The difference between angular frequency at half-maximum average power is called angular frequency width ($\Delta\omega = \omega_2 - \omega_1$) and it is directly proportional with resistance (R) and inversely proportional with self-induction coefficient of the coil.

$$\Delta\omega = \frac{R}{L}$$

The ratio of resonance angular frequency ($\omega_r$) to angular frequency width ($\Delta\omega$) is called (Quality factor) (Qf).

Quality factor of the resonance circuit is defined as:

(ratio of resonance angular frequency ($\omega_r$) to angular frequency width ($\Delta\omega$))

$$Qf = \frac{\omega_r}{\Delta\omega}$$

So,

$$Qf = \frac{\frac{1}{\sqrt{LC}}}{R/L}$$

Then, quality factor is expressed as:

$$Qf = \frac{1}{R} \times \sqrt{\frac{L}{C}}$$

When the resistance in the circuit is small, it makes average power curve sharp, and angular frequency width ($\Delta\omega$) will be small, and then quality factor (Qf). of the circuit is high.

However, when the resistance in the circuit is big, average power curve will be wide, and angular frequency width ($\Delta\omega$) is big. Then, quality factor (Qf) of this circuit will be low.

**Example (6)**

AC circuit in series combination with pure resistance ($R = 500\Omega$) and pure inductor ($L = 2H$) and a capacitor with apure capacitance ($C = 0.5\mu F$) and electric oscillator with constant potential difference (100 V), and the circuit is in resonance. Calculate:

1. Resonance angular frequency.
2. Inductive reactance, capacitive reactance and resultant reactance.
3. Current flow in the circuit.
4. Voltage through (resistance, inductor, capacitor and resultant reactance).
5. Phase difference angle between total voltage, current and power factor.

**The solution:**

1. Resonance angular frequency: $\omega_r = \dfrac{1}{\sqrt{LC}}$

$$\omega_r = \frac{1}{\sqrt{2 \times 0.5 \times 10^{-6}}} = 1000 \text{ rad/s}$$

2. Inductive reactance: $X_L = \omega_r L = 1000 \text{ rad/s } (2H) = 2000\Omega$

Capacitive reactance: $X_C = \dfrac{1}{\omega_r C} = \dfrac{1}{1000 \text{rad/s} (0.5 \times 10^{-6})} = 2000\Omega$

Resultant reactance: $X = X_L - X_C = 0$

3. Since the circuit is resonant, total impedance is $Z = R = 500\Omega$

$$I = \frac{V}{Z} = \frac{100V}{500\Omega}$$

$$I = 0.2A$$

4. $V_R = I.R = 0.2 \times 500 = 100V$

$V_L = I.X_L = 0.2A\ (2000\Omega) = 400V$

$V_C = I.X_C = 0.2A\ (2000\Omega) = 400V$

$V_X = V_L - V_C = 0$

5. $\tan\Phi = \dfrac{X}{R} = 0$

Phase difference angle Φ= zero (voltage phase vector and current phase vector have one phase in the resonant circuit). $pf = \cos\Phi$

$= \cos 0^\circ = 1$

## 3-13 AC circuits with parallel combination of pure resistor, pure inductor and pure capacitor (R-L-C)

The pure resistance, pure inductor and pure capacitor are connected in parallel combination and this group is connected in series combination to alternating voltage source, see figure (40).

When drawing pharos diagram of currents, the horizontal axis (X) is taken as (reference axis), thus, pharos vectors of voltages in the circuit is coincide with X-axis.

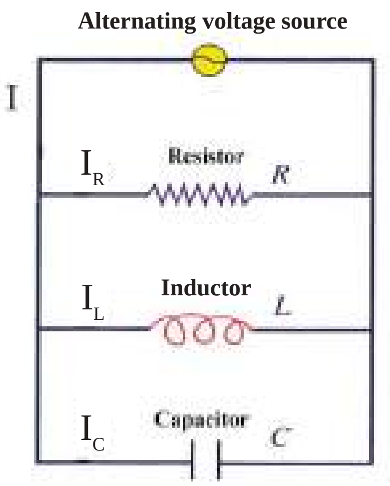



Figure (40)

As for currents phase vectors, each of them create phase difference angle (Φ) with X-axis. In this type of connection, two things are achieved:

**First:** potential differences between each element of this circuit are equal.

**Second:** the main current is distributed to all sections of the parallel-circuit. The main current (I) in section point of the flowing currents (in component parts) does not equal algebraic total of these sub-currents ($I_R$, $I_L$,$I_C$), because there is phase difference angle (Φ) between each of the phase vectors of these currents and voltage phase vector in the circuit, which is coincide with horizontal reference axis (X).

**If:**

The amount of current phase vector through the capacitor ($I_C$) is greater than the amount of current phase vector though the inductor ($I_L$), the parallel-circuit has:

- Capacitive properties.
- Phase difference angle (Φ) between total current phase vector ($I_T$) and voltage phase vector (V) is positive.
- Total current phase vector ($I_T$) precedes voltage phase vector (V) by phase difference angle (Φ), see figure (41).

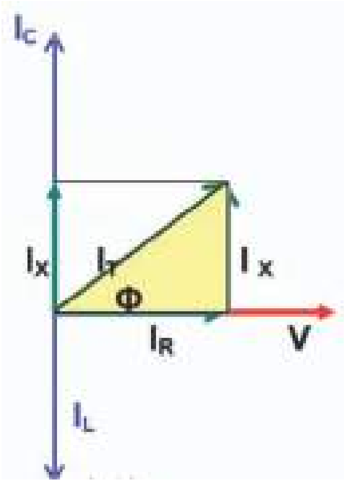


Figure (41)

**But if:**

The amount of current phase vector through the capacitor ($I_C$) is less than the amount of current phase vector through the inductor ($I_L$), then the parallel-circuit has:

- Inductive properties.
- Phase difference angle (Φ) between total current phase vector ($I_T$) and voltage phase vector (V) is negative.
- Total current phase vector ($I_T$) delays from voltage phase vector (V) by phase difference angle (Φ), see figure (42).

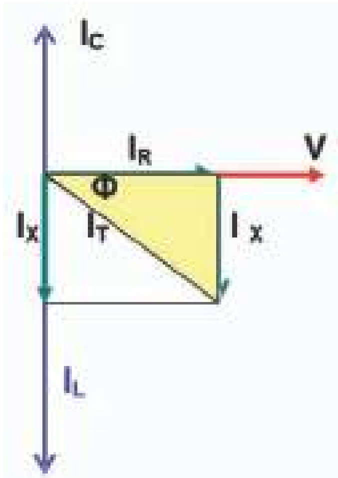


Figure (42)

**Nevertheless, if:**

The amount of current phase vector through the capacitor ($I_C$) is equal to current phase vector though the inductor ($I_L$), the parallel-circuit has:

- Pure resistance properties (ohmic).
- Phase difference angle (Φ) between total current phase vector ($I_T$) and voltage phase vector (V) is zero.
- Total current phase vector ($I_T$) is coincide with voltage phase vector (V) see figure (43).

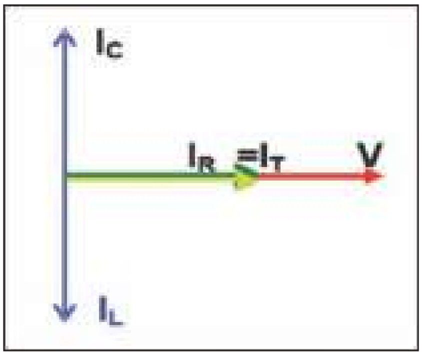


Figure (43)

**Example (7)**

An (AC) circuit in parallel combination (a pure resistance R, a capacitor with a pure capacitance C and a pure inductor L) all connected in parallel combination. All connected to alternating voltage source with potential difference (240V). The resistance is (80Ω), inductor reactance (20Ω) and capacitive reactance (30Ω), calculate the following:

1. Current flow in all sections of the circuit.
2. Calculate main current in the circuit then draw pharos diagram of currents vector.
3. Total impedance in the circuit.
4. Phase difference angle between main current phase vector and voltage phase vector in the circuit. And what are the properties of this circuit?
5. Power factor.
6. Real power (consumed in the circuit) and apparent power (supplied to the circuit).

**The solution:**

1. Since the circuit is in parallel combination, then: $V_R = V_L = V_C = V_T = 240V$

$$I_R = \frac{V_R}{R} = \frac{240V}{80\Omega} = 3A$$

$$I_C = \frac{V_C}{X_C} = \frac{240V}{30\Omega} = 8A$$

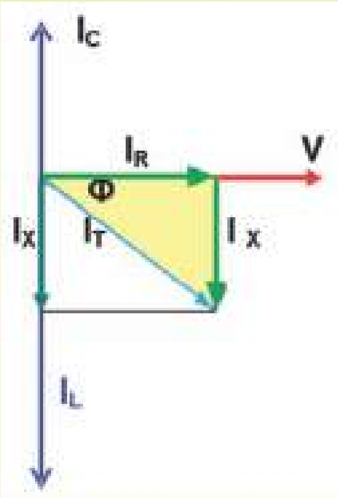
$$I_L = \frac{V_L}{X_L} = \frac{240V}{20\Omega} = 12A$$

2. Draw pharos diagram of currents as in figure below, from which we calculate main current in the circuit:

$$I_{total} = \sqrt{I_R^2 + (I_C - I_L)^2}$$

$$I_{total} = \sqrt{3^2 + (8 - 12)^2}$$

$$I_{total} = \sqrt{25} = 5A$$




3. $$Z = \frac{V}{I_{total}} = \frac{240}{5} = 48\Omega$$

4. $$\tan \Phi = \frac{I_C - I_L}{I_R} = \frac{8 - 12}{3} = -\frac{4}{3}$$

$$\Phi = -53^{\circ}$$

The circuit has inductive properties because phase difference angle (Φ) between main current phase vector and voltage phase vector is negative and in the fourth quarter.

5. To calculate the power factor (P.f) from current phasor diagram.

$$P.f = \cos\Phi = \frac{I_R}{I_T} = \frac{3}{5} = 0.6$$

6. To calculate real power (consumed in the circuit):

$P_{Real} = I_R . V_R$ , its measured by (watt).

$$P_{Real} = 3 \times 240 = 720W$$

To calculate apparent power (supplied to the circuit):

$P_{app} = I_T V_T$ , its measured by (VA).

$$P_{app} = 5 \times 240 = 1200VA$$

# Questions of chapter 3

**Q1** Choose the correct statement for the following:

1. An (AC) circuit in series combination, the load is a pure resistance (R), average power of full period (or an integer of periods) is:

   a. Zero, average current is also zero.

   b. Zero, average current is half maximum current.

   c. Half maximum power, average current is zero.

   d. Half maximum power, average current is half maximum current.

2. An (AC) circuit in parallel combination with a pure inductor, a pure capacitor and a pure resistance (L-C-R). It can not have:

   a. Capacitor current precedes inductor current by phase difference ($\Phi = \pi$).

   b. Capacitor current precedes resistance current by phase difference ($\Phi = \frac{\pi}{2}$).

   c. Resistance current and capacitor current have the same phase difference ($\Phi = 0$).

   d. Inductor current delays from resistance current by phase difference ($\Phi = \frac{\pi}{2}$).

3. In an electromagntic Oscillation circuit, when the current is zero,the stored energy in the electric field between plates of the capacitor is:

   a. Zero b. Maximum value c. Half-maximum value d. 0.707 of maximum value

4. An (AC) circuit, with electric oscillator and constant potential difference, a constant pure capacitor is connected to it, when oscillator voltage frequency is increased:

   a. Current increases in the circuit.

   b. Decreases current in the circuit.

   c. Current cut off in the circuit.

   d. Any of the above, depending on capacitance of capacitor.

5. An (AC) circuit in series combination with pure inductor, pure capacitor and a pure resistance (L-C-R), all power of this circuit:

   a. Dissipates through resistance. b. Dissipates through capacitor.

   c. Dissipates through inductor. d. Dissipates through the three elements.

6. An (AC) circuit in series combination with a pure inductor, pure capacitor and a pure resistance (L-C-R), and electric oscillator, when the oscillator frequency is lass than resonance frequency of this circuit, then it has:

a. Inductive properties because ($X_L > X_C$).

b. Capacitive properties because ($X_C < X_L$).

c. Pure ohmic properties because ($X_L = X_C$).

d. Capacitive properties because ($X_C > X_L$).

7. An (AC) circuit in series combination with a pure inductor, a pure capacitor, and a pure resistance (L-C-R) when the total impedance of the circuit is minimum and the current is maximum, so the power factor in this circuit is:

a. Larger than (1).

b. Less than (1).

c. Zero.

d. Integer (1).

8. An (AC) circuit in series combination with resistance coil (L-R), to make power factor in this circuit equal to integer one, the circuit is connected to a capacitor:

a. In series combination with the coil provided that inductive reactance ($X_L$) is smaller than capacitive reactance ($X_C$).

b. In parallel combination with the coil provided that inductive reactance ($X_L$) equals capacitive reactance ($X_C$).

c. In series combination with the coil provided that inductive reactance ($X_L$) is greater than capacitive reactance ($X_C$).

d. In series combination with the coil provided that inductive reactance ($X_L$) equals capacitive reactance ($X_C$).

9. An (AC) circuit in parallel combination with a pure inductor, a pure capacitor, and a pure resistance (L-C-R), this circuit has inductive properties if:

a. Inductive reactance ($X_L$) is greater than capacitive reactance ($X_C$).

b. Capacitive reactance ($X_C$) is greater than inductive reactance ($X_L$).

c. Inductive reactance ($X_L$) equals capacitive reactance ($X_C$).

d. Capacitive reactance ($X_C$) is smaller than resistance.

10. When a coil rotates with a uniform angular velcocity inside a uniform magnetic field, an alternating induced voltage obtained, if the phase angle is ($\omega t$) then the maximum value of this voltage is equals to:

a. $\frac{\pi}{\sqrt{2}}$ b. $\frac{\pi}{2}$ c. $\pi$ d. $2\pi$

**Q2** Prove that both inductive reactance and capacitive reactance are measured by Ohm.

**Q3** Illustrate by a diagram how inductive reactance changes with current frequency and capacitive reactance changes with voltage frequency.

**Q4** An (AC) circuit with pure resistance, pure inductor and pure capacitor (R-L-C) connected in series combination; the whole group is connected to alternating voltage source. What is the relation between voltage phase vector and current phase vector in the following cases?

a. Inductive reactance equals capacitive reactance ($X_L = X_C$)

b. Inductive reactance is greater than capacitive reactance ($X_L > X_C$)

c. Inductive reactance is smaller than capacitive reactance ($X_L < X_C$)

**Q5** An (AC) circuit with a pure resistance, a pure inductor, and a pure capacitor (R-L-C) in series combination, the whole group is connected to alternating voltagec source. Explain how resistance, inductive reactance and capacitive reactance would change if the angular frequency of the source is doubled?

**Q6** What does the followings depend on?

1. Total impedance of (AC) circuit, in series combination with a pure resistance,a pure inductor, and a pure capacitor (R-L-C).
2. Power factor in (AC) circuit, in series combination with a pure resistance, a pure inductor and a pure capacitor (R-L-C).
3. Quality factor in (AC) circuit in series combination with a pure resistance, a pure inductor and a pure capacitor (R-L-C).

**Q7** What do positive parts and negative parts in instantaneous power curve represents in (AC) circuit containing only:

1. Pure inductor
2. Pure capacitor

**Q8** Explain followings

a. Why is it recommended to use an inductor to control in discharge current of fluorescent lamp not to use a pure resistance.

b. What are the characteristics of electric series resonance circuit which contains (a pure resistance and a pure capacitor) and an electric Oscillator?

c. What the power factor in (AC) circuit (mention the reason) if load is:

1. Pure resistance. 2. Pure inductor. 3. Pure capacitor.

4 . Coil and capacitor, in series combination, the circuit is not resonant.

**Q9** What does mean by:

1. Power factor?

2. Quality factor?

3. Effective alternating current?

4. Electric oscillation circuit?

**Q10** An (AC) circuit with a pure resistance, a pure inductor and a pure capacitor (R-L-C) in series combination, the whole group is connected to alternating voltage source. The circuit is resonant. Mention properties of this circuit, and relation between total voltage phase vector and current phase vector, if their angular frequency is:

1. Greater than the resonance angular frequency.

2. Smaller than resonance angular frequency.

3. Equal to resonance angular frequency.

**Q11** A lamp is connected in series combination with a pure capacitor and alternating current source. At which, high or low angular frequencies, does the lamp glow brighter? And when it becomes less glowing? (if source voltage is constant), explain.

**Q12** An electric lamp is connected in series combination with a pure inductor and alternating current source. At which, high or low angular frequencies, does the lamp glow? And when it becomes less glowing? (if source voltage is constant), explain.

## Problems of chapter 3

**P.1.** AC source of voltage, connected from its two ends to a pure resistor (250Ω). The potential difference between the two ends of source is given by:

($V_R$= 500 sin (200πt)).

1. Write the relation that gives current in the circuit.
2. Calculate effective voltage and effective current.
3. Calculate frequency and angular frequency of the source.

**P.2.** An oscillating electromagnetic circuit consisting of capacitor with capacitance of ($\frac{50}{\pi}$ μF) and a pure inductor with self-induction coefficient is ($\frac{5}{\pi}$ mH). Calculate:

1. Natural frequency of the circuit.
2. Angular frequency of the circuit.

**P.3.** An electrical oscillator with a constant potential difference of (1.5V), if its frequency changes from (1Hz to 1MHz). Calculate both the impedance and current in the circuit if both ends are connected between oscillator poles:

1. Pure resistor with (R = 30Ω).
2. Pure capacitor with (C = $\frac{1}{\pi}$ μF).
3. Pure inductor with ( L= $\frac{50}{\pi}$ mH).

**P.4.** A coil is connected to two poles of a battery with a potential difference of (20V). The current is (5A) in the circuit. If the battery is removed from the coil and the coil is connected to the poles of an (AC) source. The effective voltage is (20V) with afrequency of ($\frac{700}{22}$ Hz) and the current is (4A) in the circuit. Calculate:

1. Self-inductance coefficient of the coil.
2. Phase difference angle between total voltage phase vector and current phase vector, draw impedance phase diagram.
3. Power factor.
4. Both of real and apparent powers.

**P.5.** A pure resistance (150Ω) is connected with a coil neglected resistance that has self-inductance coefficient is (0.2H) and to a pure capacitor. This group is connected to poles of (AC) source of voltage with a frequency of ($\frac{500}{\pi}$ Hz) and potential difference between the poles (300V). Calculate the amount of:

1. The capacitance of a capacitor that makes total impedance in the circuit (150Ω).
2. Power factor in the circuit, phase difference angle between total voltage and current.
3. Draw impedance phase diagram.
4. Current in the circuit.
5. Both of real (consumed) power and apparent (supplied) power.

**P.6.** An (AC) circuit parallel combination contains a pure resistor, capacitor with a pure capacitance (20μF) and a pure inductor and alternating voltage source potential difference between two ends (100V) a frequency of ($\frac{100}{\pi}$ Hz), the real power is (80W) and the power factor is (0.8), and the circuit has inductive properties.

1. The current in the resistor and the current in the capacitor.
2. Total current.
3. Phase difference angle between total current and voltage, phasor diagram of currents.
4. Self-inductance coefficient of the inductor.

**P.7.** A resistor, an inductor and a capacitor are connected in series and connected to the ends of (200V) source with frequency ($\frac{100}{\pi}$ Hz). Resistance of inductor is (20Ω) and coefficient of self-induction is (0.5H) and it is connected to (10Ω) resistor. The power factor in the circuit is (0.6). The circuit has capacitive property. Find:

1. Current in the circuit.
2. Capacitance of capacitor.
3. Draw phasor diagram of impedance then calculate the phase difference angle between total voltage phase vector and current phase vector.

**P.8.** AC source of voltage, angular frequency (400 rad/s) and potential difference between two end (500V), they are connected between the two poles in series a capacitor of capacitance (10μF) and coil self-inductance coefficient (0.125H) and resistor (150Ω), what amounts of:

1. Total impedance and current in the circuit.
2. Potential difference on resistor, inductor and capacitor.
3. Phase difference angle between total voltage phase vector and current phase vector, what are the properties of this circuit?
4. Power factor.

**P.9.** An alternating current circuit contains (a pure resistor, a pure capacitor and a pure inductor) in parallel. The circuit is connected to ends of (480V) source and frequency is (100Hz). The real power in circuit is (1920W). The capacitive reactance is (32Ω) and inductive reactance is (40Ω), Calculate the amount of:

1. Current on each resistor, capacitor, inductor and main current in the circuit.
2. Draw the diagram of currents phase vector.
3. Phase difference angle between main current phase vector and voltage phase vector in the circuit, what are the porperties of this circuit?
4. Power factor in the circuit.
5. Total impedance in the circuit.

**P.10.** Resistor with (30Ω) resistance is connected to a pure capacitor in parallel. This system is connected via poles of alternating voltage with frequency (50Hz), total impedance of the circuit is (24Ω), and the actual power is (480W). What is the amount of capacitance of capacitor. Draw the phasor diagram of currents.

**P.11.** An alternating current circuit connected in series which has coil with resistance (500Ω) and a variable capacitor, when the circuit has (50nF) cpacitance and alternating voltage of (400V). Angular frequency is ($10^4$ rad/s) and real power (consumed) equals apparent power (supplied) in the circuit. Calculate:

1. Coefficient of self-induction of the coil and current in the circuit.
2. Inductive reactance and capacitive reactance.
3. Phase difference angle between total voltage phase vector and current phase vector, what is the amount of power factor.
4. Quality factor of the circuit.
5. Capacitance of capacitor that makes the total voltage phase vector delay falls behind the current phase vector by phase difference angle of ($\frac{\pi}{4}$).

# CHAPTER 4

# Electromagnetic Waves

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4-2 Maxwell and electromagnetic theory.
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4-9-3 Space waves.
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4-10-2 Remote sensing.
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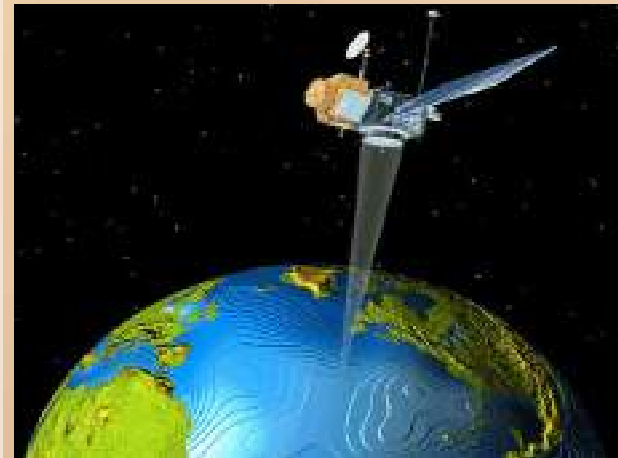


## Behavioural targets

**After studying this chapter, the student should be able to:**

- Mention the electromagnetic waves and their most important properties.
- Know how the electromagnetic waves propagate.
- Know how to generate electromagnetic waves in an oscillating circuit.
- know how to transmit and receive electromagnetic waves.
- Explain the origin of creating the electromagnetic wave.
- Illustrate how the transmission and reception antenna work for radio waves.
- Learn methods of detecting electromagnetic waves.
- Understand modulation process of electromagnetic waves and how to transmit the information.
- Learn some electromagnetic applications such as (Radar, Remote sensing, Mobile).

| Scientific Terms | |
|---|---|
| Displacemant current | تيار الازاحة |
| Oscillator | مولد ذبذبات |
| Transmitter | مرسل |
| Receiver | مستقبل |
| Electric dipole | ثنائي قطب كهربائي |
| Antenna | هوائي |
| Oscillation circuit | دائرة مهتزة |
| Amplifier | مضخم |
| Modulation | تضمين |
| Analog Modulation | تضمين تماثلي |
| Amplitude Modulation | تضمين سعوي |
| Frequency Modulation | تضمين ترددي |
| Phase Modulation | تضمين طوري |
| Ground wave | موجة ارضية |
| Sky wave | موجة سماوية |
| Space wave | موجة فضائية |
| Detection | كشف |

## 4-1 Introduction

In our daily life, there are many wave phenomena, some of which require physical medium to propagate. This medium can be gaseous, liquid or solid.

For example, sound waves propagate in various physical media; such are mechanical longitudinal waves which result from vibration of molecules of its transfer medium.

There are waves that do not require physical medium to propagate, these are the electromagnetic waves. You have already learned that electromagnetic spectrum has a wide range of frequencies, which differ according to source, ways of generating, detection technology and penetration of various media. Figure (1) shows types of these waves:

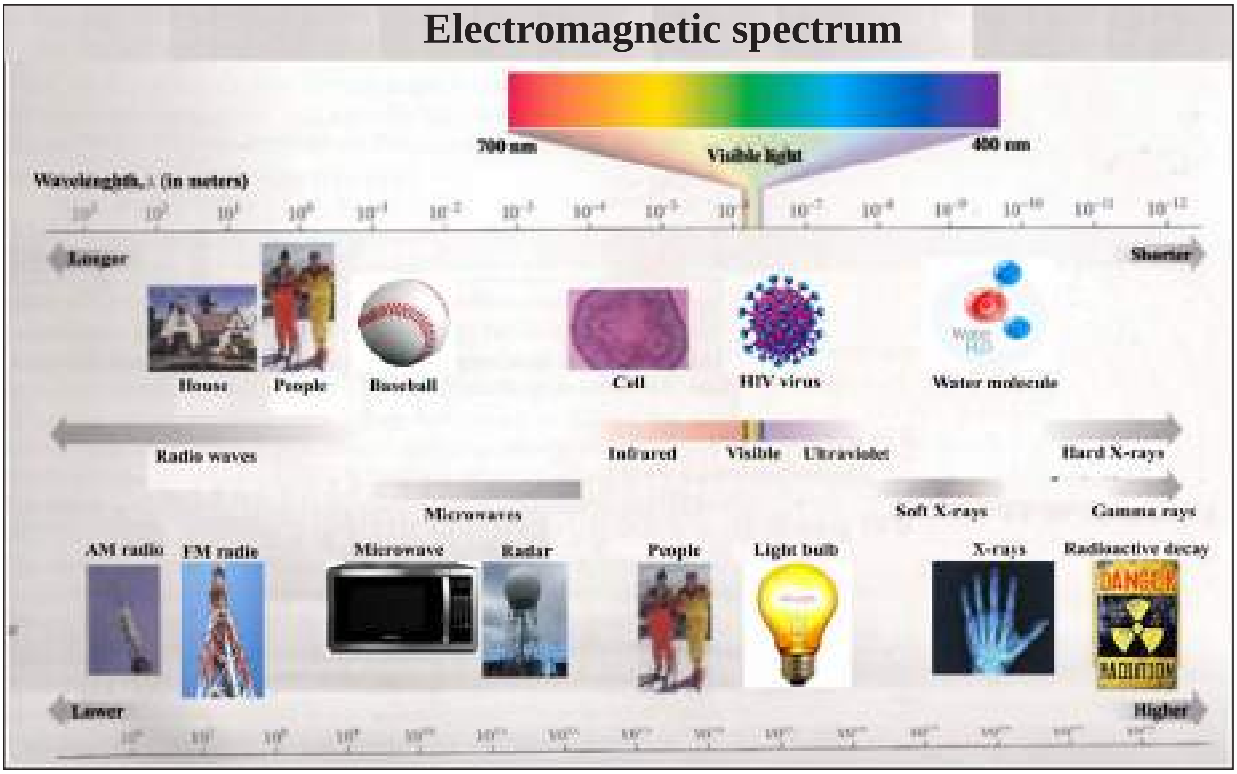



Figure (1) Electromagnetic spectrum [For reference only (not required)]

## 4-2 Maxwell and electromagnetic theory

One of the major contributions in physics in the nineteenth century is discovery of electromagnetic waves, which came as a result of studies and research conducted by Faraday, Ampere and Gauss. It is found that when the variable  magnetic field that penetrates A conductor, an induced electromotive force is generated on both sides of the conductor; this process is called electromagnetic induction. This process produces a variable electric field in space; this electric field generates a variable magnetic field perpendicular to the electric field and concordant with phase, the opposite is true. See figure (2).

According to these facts, Maxwell (1860) succeeded in relating laws of electric and magnetic fields he expressed this relation by the following:

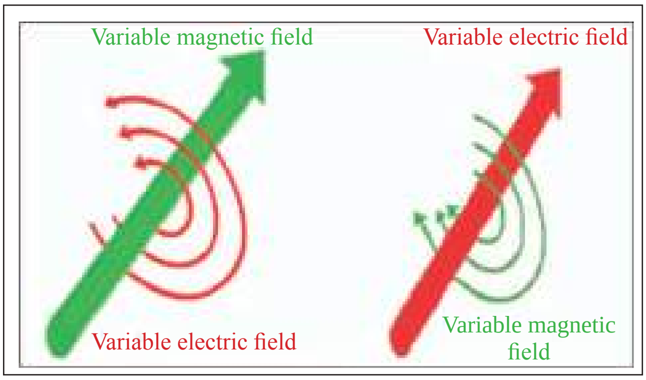


Figure (2) Electromagnetic Induction

1. Static electric charge point in space generates an electric field around it, the electric field lines stem either from or to the location of that charge.
2. There is no magnetic monopoles (lines of the magnetic field are closed).
3. Time-varying electric field generates time-varying magnetic field around it, perpendicular to it and concordant in phase.
4. Time-varying magnetic field generates time-varying electric field around it, is perpendicular to it and concordant in phase.

Maxwell concluded that both time-varying and correlative electric and magnetic fields may propagate in the form of a wave in space, this wave is called (electromagnetic wave).

The origin of the electromagnetic wave is the oscillating electric charges. This oscillation causes electric and magnetic fields both time-varying, correlative, perpendicular on each other and perpendicular to their line of propagation, the electromagnetic wave propagates in vacuum with speed of the light ( $3 \times 10^8 m/s$ ).

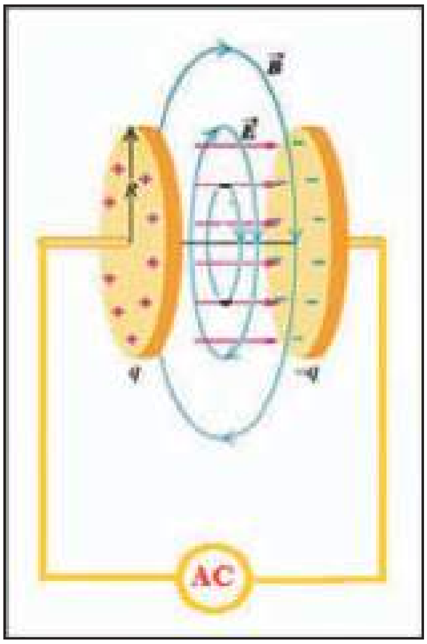


Figure (3) illustrates how a magnetic field is generated from a time-varying electric field

Maxwell found that the magnetic field not only produced by a normal conduction current, but can also be produced by time-varying electric field.

For example, when connection two-plates capacitor through an alternating voltage source, the time-varying electric field (E) between the two plates generates an electric current, which in turn, generates time-varying perpendicular magnetic field (B), see figure (3).

This current is called (Displacement Current) ($I_d$); i.e. displacement current ($I_d$) is directly proportional to time rate of change in electric field ( $\frac{\Delta E}{\Delta t}$ ).

$$I_d \propto \frac{\Delta E}{\Delta t}$$

It is worth noting that displacement current accompanies the electromagnetic wave propagating in space, unlike conduction current that travels through the conductor only.

**The major properties of the electromagnetic waves are:**

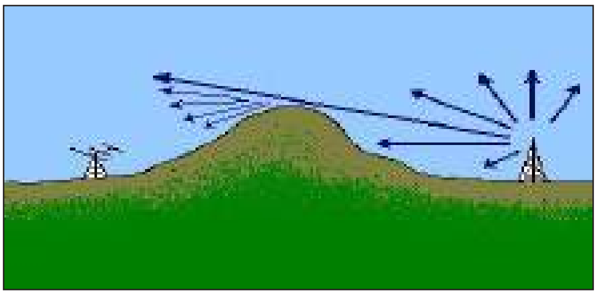


Figure (4) Diffraction of electromagnetic radiation

1.Electromagnetic waves propagate in vacuum in straight lines, they are reflected, refracted, interfered, polarized and diffracted from their path, see figure. (4).

2.It consist of two electric and magnetic fields, which are correlative and change with time both two planes perpendicular to each other and perpendicular to the wave propagation line, and both oscillating in the same phase, see figure (5).

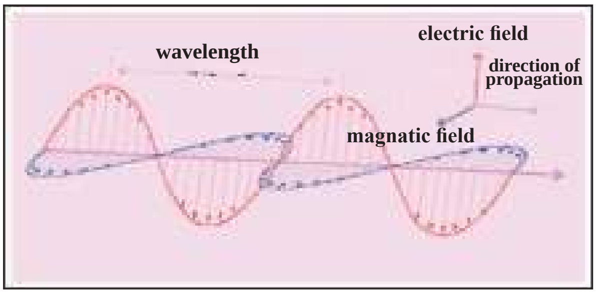



Figure (5) Distribution of electric and magnetic fields in electromagnetic wave

3.Electromagnetic waves are transverse waves, because both electric and magnetic fields oscillate perpendicular to the line of propagation, of the electromagnetic wave, see figure (5).

4. Electromagnetic wave propagates in vacuum at the speed of light, when it travels within a material medium, its speed reduces according to physical properties of that medium. The electromagnetic wave generated by oscillation of electric charges; some of these waves can be generated by oscillator.

5. Energy of electromagnetic wave is equally distributed between electric and magnetic fields when it is propagate in vacuum.

## 4-3 Generating electromagnetic waves by oscillating charges

The German Scientist Henry Hertz was the first to generate electromagnetic waves in 1887. He lit a spark between poles of the secondary coil in induction coil device, see figure (6), when there is enough voltage slope between them. He succeded to receive these waves in a hole between the ends of a metal ring. He noticed that a spark flashes at a certain position without connecting wires between the transmitter and the receiver. Hertz notice that the spark is not received unless the ring has a specific diameter and placed in a situation where the line separating the two ends of its holes is parallel to the line between the two poles that generates the spark. You also learned form your previous study that static point charge is generated

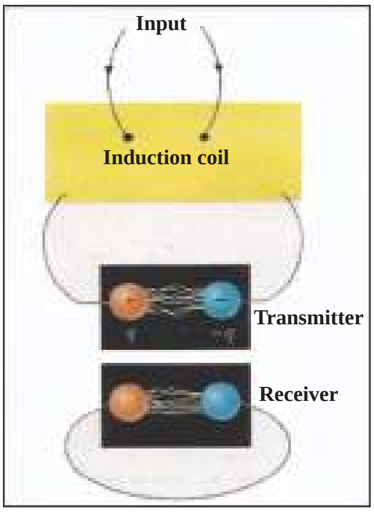



Figure (6) Represents hertz devices for generating electromagnetic waves.

around it an electric field only. While the moving charge at constant velocity has constant electric and magnetic fields. As for accelerated charges, they generate two oscillating electric and magnetic fields that propagate through space.

To illustrate the generation of electromagnetic waves, two metal bars (electric dipole) are plugged to alternating voltage source (electric oscillator), below a description of how to generate electromagnetic waves:

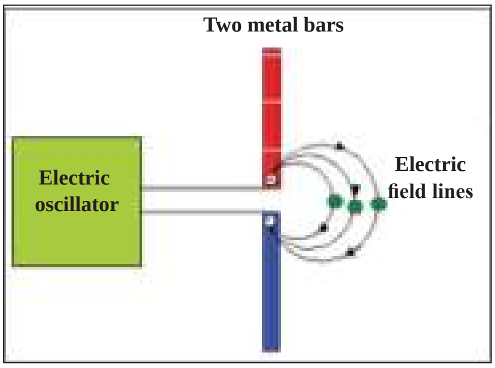



Figure (7) How to generate electromagnetic waves in antenna.

1. When connecting the poles of the oscillator to the ends of close bars, positive charges begin to move in the upper bar upwards, while negative charges in the lower bar move downwards, see figure (7). The shape of electric force lines around the bars move from the positive end to the negative end, while magnetic force lines they are circles perpendicular to electric filed lines, as indicated by direction symbol ( ⊕ ) which  is green color, indicating the lines enter the plane of the paper.

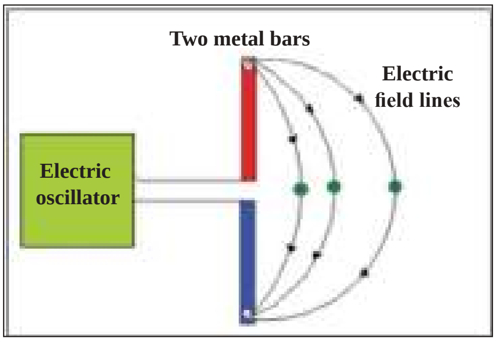



Figure (8) illustrates the moving away in the electric field lines when the voltage increases on the transmitting antenna wire.

2. At the moment when the effective electromotive force (emf) reaches maximum amount, charges reach the far two ends of the bars, then their velocity becomes zero, see figure (8).

3. When effective electromotive force (emf) decreases, the direction of charges is reversed. Positive and negative charges moved toward each other, thus the lines of both (electric and magnetic) fields converge, see figure (9). They form a closed ring when negative  with positive charges reach a start point movement these rings spread a part in space.

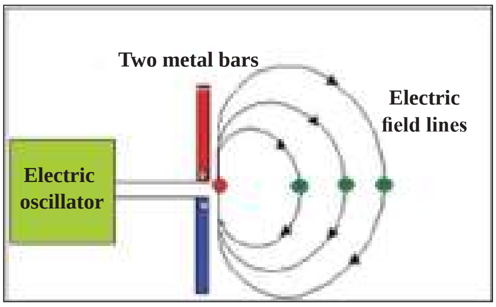



Figure (9) illustrates the convergence of the electric field lines when the voltage decreases.

4. When the effective electromotive force (emf) begins to grow again in the opposite direction at the moment of the two charges are reversed on the electric dipole (polarity reverses); the negative charge will be in the upper bar and the positive charge will be in the lower bar, move away in opposite directions, see figure (10). This time, the electric field is turns opposite to the previous direction, so is the magnetic field (indicated by red dot ( ⊙ ) ).

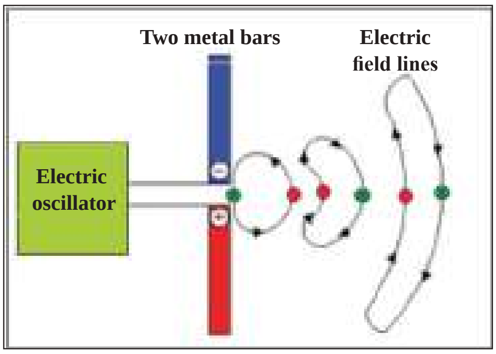



Figure (10) Illustrates the separation of the electric field lines from the antenna at the moment of voltage is reversed.

These fluctuations, which occur on both electric and magnetic fields, create closed rings of electric and magnetic force lines in perpendicular planes, that propagate away from the electric dipole. These are considered frontiers (border) of electromagnetic waves, see figure (11).

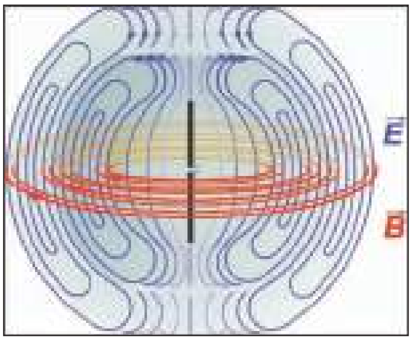


Figure (11) Illustrates the emission of electromagnetic waves from the transmitter antenna after the electric and magnetic field lines accompanying it are closed.

## 4-4 Principles of transmission and reception of electromagnetic waves

Have you ever wondered how can you hear the sound of the radio? How this sound can reach you through the space and from long distance? This is done through transferring information from audible (Carried) wave to the (Carrier) radio wave (as will be mentiond later). These waves are broadcasted via transmission station and received by receiver device (radio). Transmission and reception process depends on two basic devices:

**1. Electromagnetic waves oscillation circuit.**

**2. Antenna.**

### 1. Oscillation circuit (Resonance circuit):

The oscillation circuit consists of a coil (L) (neglected ohm resistance) connected with a variable capacitance of capacitor (C) as in figure (12).

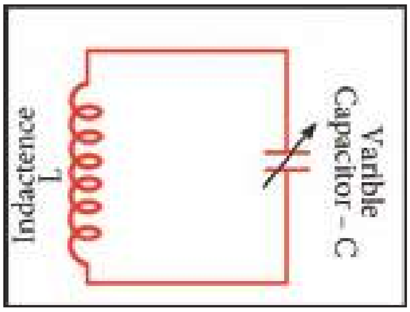


Figure (12) illustrates the oscillation circuit diagram.

This circuit can generate a resonance frequency ($f_r$) through tuning process, according to the following relation:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

### 2. Antenna:

The antenna consists of two separate metal wires connected to alternating voltage source charging the two wires with two charges of equal in amount and different in types, see figure (13). The engergy emitted from the transmitting antenna is dissipated in space in the from of electromagnetic waves, and the power of the antenna in transmitting or receiving depends on:

(1) The amount of voltage supplied for Antenna.

(2) Frequency of transmitted or received signal.

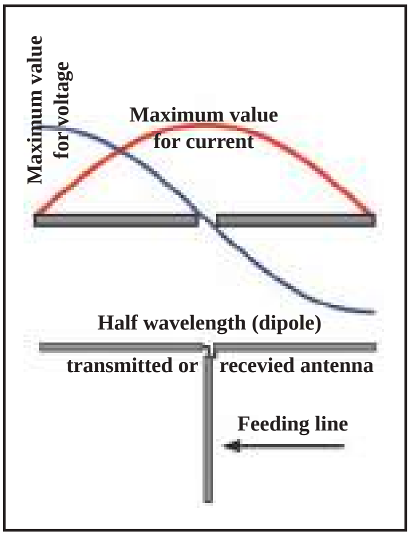


Figure (13) illustrates how voltage and current are distributed along the antenna wire.

It has been practically found that the antenna has the maximum signal energy when its length is half the transmitted or received wavelength. For clarification we use the figure (13). The phase difference between generated current and the electromotive force is ($90^0$) as you see in the figure, the voltage is maximum at the two ends of the antenna ($V_{max}$) and the current is maximum ($I_{max}$) in the middle of antenna (feeding point of antenna poles with current signal desired to be transmit) at this point, the impedance is little, while the impedance is high at the ends of the antenna. Therefore, antenna can be fed by maximum power amount of oscillation circuit compared to other length.

One pole of the antenna can be grounded, as shown in figure (14), to be transmitting or receiving antenna with length of quarter wave. The ground works to form the pole voltage image with the same length thus another pole is formed in the ground with quarter wave to complete the properties of the half-wave antenna. This antenna is called quarter-wave antenna.

**DO you know?**

Usually when we touch the radio antenna, the receiver intensity increases, because the antenna becomes aquarter of awavelength. Moreover, the capacitance of the capacitor decreases, so the quality factor increases, and the picking becomes sharp and good.

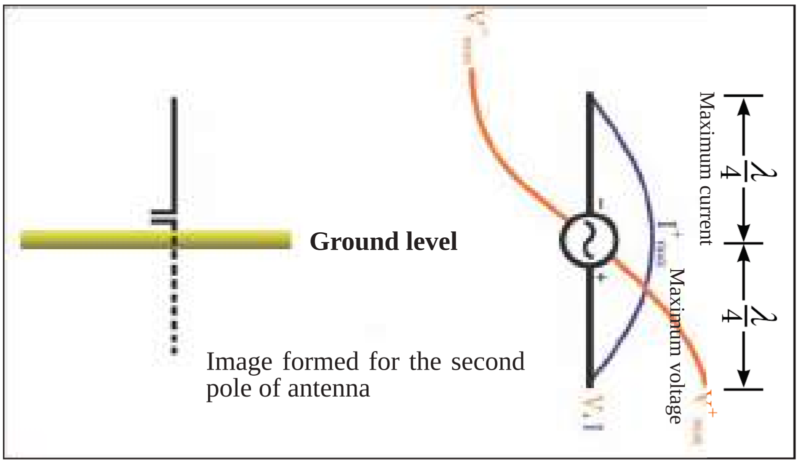



Figure (14) illustrates grounded antenna and distribution of voltage and current along the antenna and the ground

**Example (1)**

A tuning circuit is set in a broadcast radio station, circuit inductor was (6.4 µH) and capacitance is (1.9 pF).

a. What is frequency of wave received by the device? b. What is the wavelength?

**The solution:**

a. Frequency is calculated from the following relation:

$$f_r = \frac{1}{2\pi\sqrt{Lc}} = \frac{1}{2\pi\sqrt{6.4\times10^{-6}\times1.9\times10^{-12}}}$$

$$= \frac{1}{2\times3.14\sqrt{12.16\times10^{-18}}}$$

$$= 45.665\times10^{6}\ \text{Hz}$$

b. Wavelength is calculated from the following relation:

$$\lambda = \frac{c}{f_r}$$

$$= \frac{3\times10^{8}}{45.665\times10^{6}} = \frac{300}{45.665} = 6.57\text{m}$$

**Example (2)**

Half-wave antenna is needed to transmit wireless signals with the following frequencies: (20 KHz, 200 MHz), calculate the antenna length for these frequencies, show what type of antenna is best for parctical use.

**The solution:**

Calculate the antenna length for (20kHz) frequency

We first calculate wavelength ($\lambda$):

$$\lambda = \frac{c}{f}$$

$$= \frac{3 \times 10^8}{20 \times 10^3}$$

$$= \frac{3}{20} \times 10^5 m = 15km$$

**DO you know?**

The receiving antenna for the stations that receive satellite television channels is located within a metal receptacle, (LNB) and it is in the from of a small metal wire grounded in this receptacle.

Antenna Length $\ell$ of half-wave ($\frac{\lambda}{2}$) is: $\ell = \frac{\lambda}{2} = 7.5km$

It is worth noting that this antenna is not practically possible. To transmit such signal we use high frequency wave called modulation (to be discussed later).

Calculate the antenna length for frequency (200MHz):

we first calculate wavelength ($\lambda$):

$$\lambda = \frac{c}{f}$$

$$= \frac{3 \times 10^8}{200 \times 10^6} = \frac{3}{2} = 1.5m = 150cm$$

Antenna length for half-wave is practically appropriate:

$$\ell = \frac{\lambda}{2} = 75cm$$

When this antenna is grounded, it becomes quarter wave antenna; its length is calculated as follows:

$$\ell = \frac{\lambda}{4} = \frac{150}{4} = 37.5cm$$

This length is appropriate from a practical point of view.

## 4-5 How transmission and reception circuits works

### 4-5-1 Transmission circuit:

Figure (15) shows basic components of transmission device, which consists of:

a. Electromagnetic oscillation circuit: which consists of a coil and acapacitor with varying -capacitance.

b. Antenna: which contains a coil placed against the electromagnetic oscillation circuit coil and a capacitor with varying-capacitance, these are attached with a metal wire or to grounded wire.

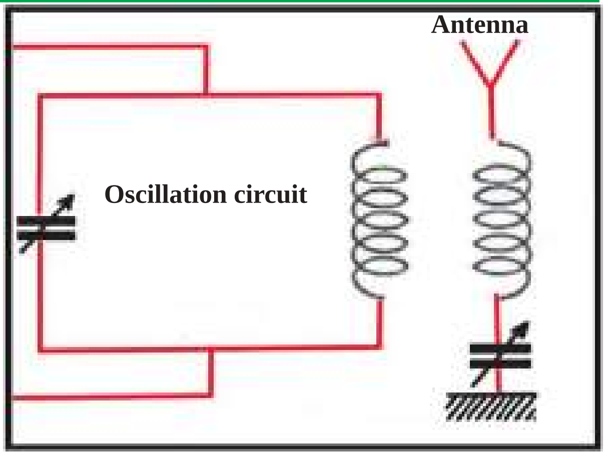


Figure (15) Transmission device of electromagnetic wave

### How the transmission device works?

1. When the oscillation circuit is supplied with energy, it generates electric signal waves, its frequency is controlled by the changing capacitor capacitance of the electromagnetic oscillation circuit (or self - induction coefficient of the coil).
2. Electric signal waves in the electromagnetic oscillation circuit generate alternating induced current in antenna coil; its frequency is equal to the frequancy of the electric signal waves that generated by the oscillation circuit.
3. The induced current in antenna coil produces electromotive force in antenna wire; its frequency equals the frequency of the induced current in the coil. This force generates electromagnetic waves broadcasted by the antenna wire into space.

### 4-5-2 Reception circuit:

Figure (16) shows the basic components of reception circuit:

a. Oscillation circuit: consisting of a coil and capacitor with varying-capacitance.

b. Antenna: consisting of metal wire attached to a coil.

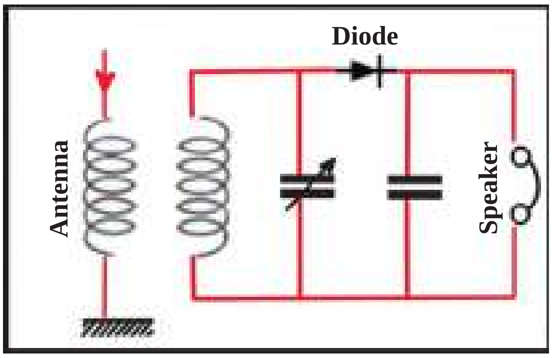


Figure (16) Diagram of electromagnetic wave receiver device

### How does it work?

1. The antenna receives electromagnetic waves from space. These waves create alternating current with equal frequency to that of the waves.
2. The alternating inductive current in the antenna coil generates electric signal with frequency equal to that of the induced current. This signal is received by the antenna.
3. Capacitance of the capacitor is adjusted until it reaches resonance state, then, an alternating induced current is generated in the electromagnetic oscillation circuit coil, its frequency equals the frequency of the current in the antenna.

## 4-6 Detection of electromagnetic waves with a radio frequency

Electromagnetic waves can be detected either by their electric field or by magnetic field

### 4-6-1 Detecting electromagnetic waves by using their electric field:

The electric circuit is connected as in figure (17).

The electric field of the wave ($E_y$) makes the charges oscillate in the antenna when ($E_y$) vibration is positive, the upper part of antenna is positive, and then its polarity is inversed diractly soon. When electric field vector keeps reflecting in the wave; the charge moves up and down the antenna in a time-varying pattern. During this process, the alternating current induces an oscillating potential in the resonance circuit attached to the antenna via mutual induction.

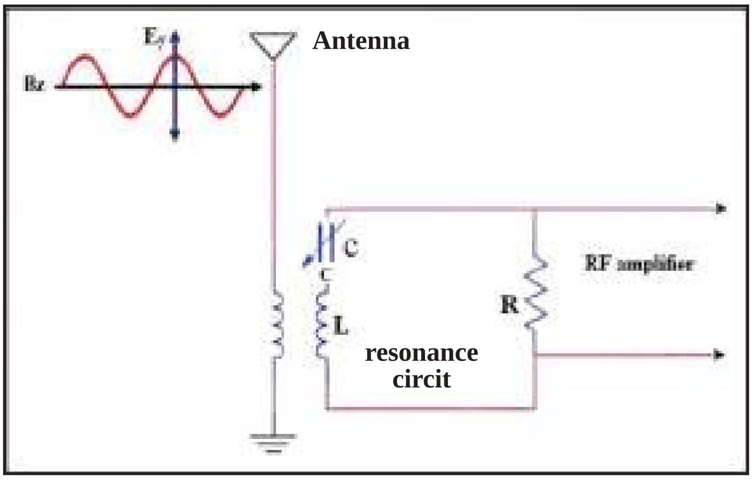



Figure (17) Diagram of receiver device that receive electromagnetic waves by using its electric field

When capacitance amount changes to reach resonance state between wave frequency and resonance circuit frequency, we receive the signal of electromagnetic wave.

### 4-6-2 Detecting of electromagnetic waves by using their of magnetic field:

The electric circuit is connected as in figure (18). The antenna in this circuit consists of aring conductive wire, since the electromagnetic field of the electromagnetic wave is time-varying, an induced electromotive force (induced emf) is generated in the antenna ring.

The antenna ring should be vertical on magnetic flux direction (therefore, mini-radio devices have different receiver of stations according to their direction).

The received signal in the antenna can be tuned by resonance circuit, by changing capacitance of the capacitor in the circuit.

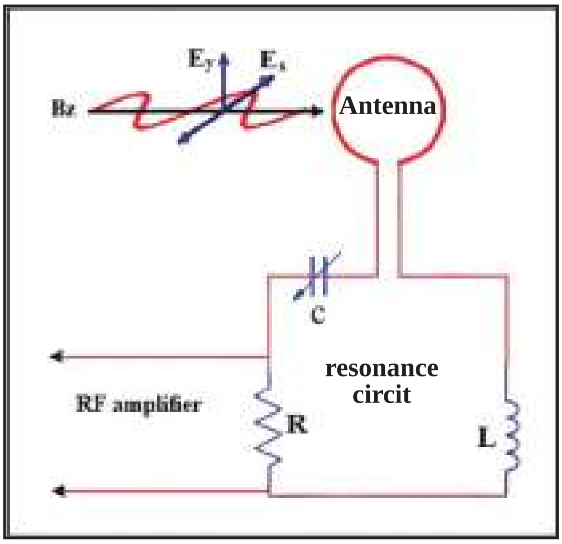



Figure (18) Diagram of receiver device that receive electromagnetic waves by using its magnetic field

## 4-7 Modulation

Modulation process means conveying information signal (called the carried wave), (picture, sound or phone call) low frequency over a high frequency wave (called Carrier wave).

In radio broadcast, for example, audible sound waves are transformed into electrical signals through the acoustic receiver (called audio waves) in the same frequency, then, these electrical signals are transmitted to the oscillating resonant circuit to be modulated on the radio waves (carrier waves) which have higher frequency than that of the acoustic signal. Then, these signals are sent to the transmission antenna to be transformed into electromagnetic waves to be transmitted efficiently over long distances without perceptible fading.

Analog modulation is varying one or more properties of high-frequency current wave (amplitude of oscillation - frequency of oscillation - phase of oscillation).

There are three types of Analog Modulation:

1. **A**mplitude **M**odulation (AM).
2. **F**requency **M**odulation (FM).
3. **P**hase **M**odulation (PM).

There is another type of modulation that can be performed to reduce external effects on the signal and encode it; it is called Digital Modulation, see figure (19) which illustrates process transferring phone calls by converting analog modulation into digital modulation when transmitted and inverse the process when receipted.

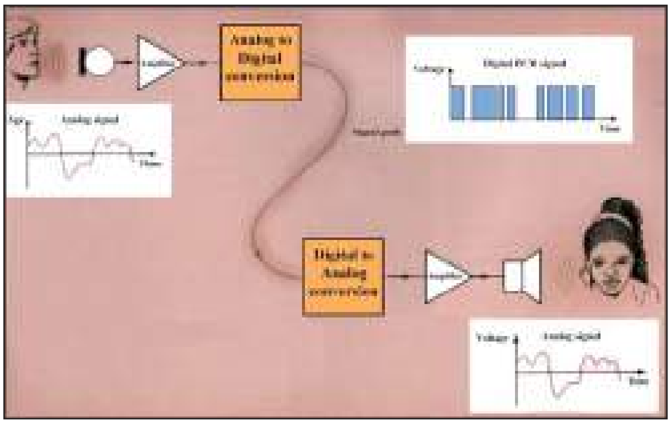


Figure (19) Illustrate the process of transmitting phon calls after digital modulaion [For reference only (not required)]

### 4-7-1 Amplitude modulation (AM):

Figure (20) shows how to modulate a low- frequency information wave on a high- frequency carrier wave, we obtain a wave that shows the information in the form of changes in amplitude with constant frequency, based on that Amplitude Modulation is a change in the amplitude of the carrier wave as a linear function with the amplitude of the carried wave according to the frequency of carried signal.

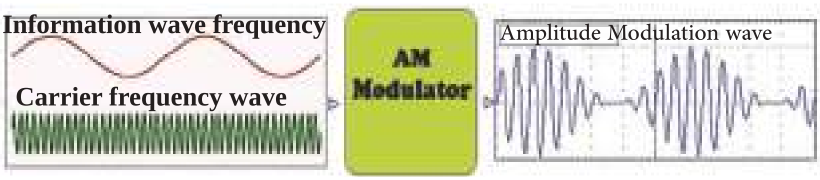



Figure (20) Amplitude Modulation

### 4-7-2 Frequency modulation (FM):

Figure (21) shows the frequency modulation, the amplitude of the carried wave reduces the frequency of carrier wave and the opposite is true. Note that on the right side, the amplitude of the carrier wave does not change so the frequency modulation is change frequency of carrier wave as a linear function with the frequency of the carried wave according to amplitude of carried wave.


Figure (21) Frequency Modulation

### 4-7-3 Phase modulation (PM):

Figure (22) shows the phase modulation, it describes change in amplitude of information wave in the form of changes in phase of carrier wave. Phase modulation is a change in the phase of the carrier wave as a linear function with amplitude of carried wave according to frequency of carried signal.


Figure (22) Phase Modulation

## 4-8 Range of radio waves

Due to wide variation in the properties of radio-electromagnetic waves in terms of their generating and propagation methods, they are divided into several regions:

a. **V**ery-**L**ow **F**requency region (VLF) (3kHz - 30kHz), and Low Frequency region (30kHz - 300kHz) (LF) these are mainly used in marine navigation.

b. **M**edium **F**requency region (MF) (300kHz - 3MHz), mainly used in regular radio broadcast.

c. **H**igh-**F**requency region (HF) (3MHz - 30MHz), it is mainly used in some phones and communication between airplanes, ships, and so on.

d. **V**ery-**H**igh **F**requency region (VHF) (30MHz - 300MHz), it is used in television sets, radio transmitters, air traffic control systems, police communications systems and so on.

## 4-9 Propagation of electromagnetic waves

Electromagnetic waves propagate at various velocities ( $\nu$ ) in various media according to electric permittivity (ε) and magnetic permeability (μ) of the medium through which these waves propagate according to the following equation:

$$\nu = \frac{1}{\sqrt{\in \mu}}$$

Since the values of these constants in vacuum equal to:

$$\in_0 = 8.854 \times 10^{-12} \frac{F}{m} \qquad \mu_0 = 4\pi \times 10^{-7} \frac{H}{m}$$

From the values of these constants it is possible to calculate speed of light in vacuum (c):

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

$$= \frac{1}{\sqrt{12.5663 \times 10^{-7} \times 8.854 \times 10^{-12}}} = 2.997964 \times 10^{8} \text{m/s}$$

This number is approximated to $3 \times 10^{8} \frac{m}{s}$

**Radio waves propagate in the atmosphere in several ways:**

### 4-9-1 Ground waves

These include waves with frequencies range between (530 kHz - 2 MHz).

They are travels close to earth surface. Ground waves when propagate are taken a path very close to the earth's surface, and their propagation path bends with the curvature of the earth's surface, see figure (23). These waves take advantage. to build communication systems with limited distance, due to the limited broadcast transmission ability of these waves.

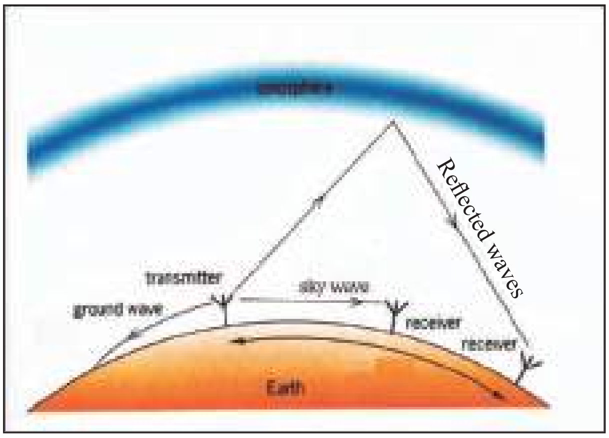



Figure (23) Illstrates how the ground and sky waves propagate

### 4-9-2 Sky waves

These waves include all frequencies between (2-30) MHz; this type of communication depends on the presence of ionosphere layers, which are highly ionizing layers, that reflected sky waves to earth, see figure (24).

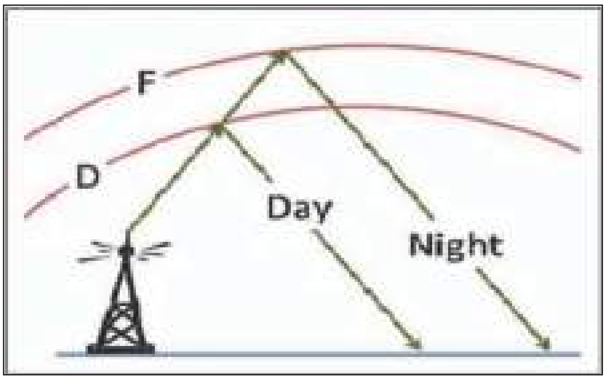


Figure (24) Illstrates two layers of the ionosphere: (F-layer) during the night and (D- layer) during the day.

Ionosphere layers are highly ionized at midday and slightly ionized at night. The ionized layer close to earth disappears during night, which is called (D-layer) while (F-layer) remains, see figure (24).These layers work oppositly from some types of radio waves directed to them from ground broadcast stations, therefore, receive of sky waves during the day has lower range than it is during the night because of radio waves reflection from (D- layer) lower region and during the night received waves is clear because of the reflection waves from (F-layer) upper region.

### 4-9-3 Space waves

These waves include all frequencies above (30 MHz), i.e. Very-High Frequency range (VHF). These are microwaves that propagate in straight lines and do not reflect from ionosphere layer, but, are transmitted through it. These waves can be invested in communication between continents by using of artificial satellites in synchronous orbit with earth rotation around its axis (they are called satellite), that act as repeaters (stations to boost signal and resend it). Figure (25) Illstrates communications via satellites, these satellites receive weak signals from earth stations to re-broadcast them to earth to be received by other earth stations thousands of kilometers away.


Figure (25) Illstrates the work of satellites in communication

## 4-10 Some applications of electromagnetic waves

### 4-10-1 Radar

The word RADAR is an abbreviation for initials of the following phrase **Radio Detection and Ranging** which means detection and determination of distance by radio waves. Radar is an electronic system used to detect moving or stationary targets and locating position. It sends radio waves to the target, and receives the waves that reflect from the target. Transmission and reception time indicates range and distance of the target, while direction of reflected waves indicates target location.

Figure (26)

### The main components of the radar:

Although different in size, RADARS are similar in function, figure (27) shows basic components of the radar:

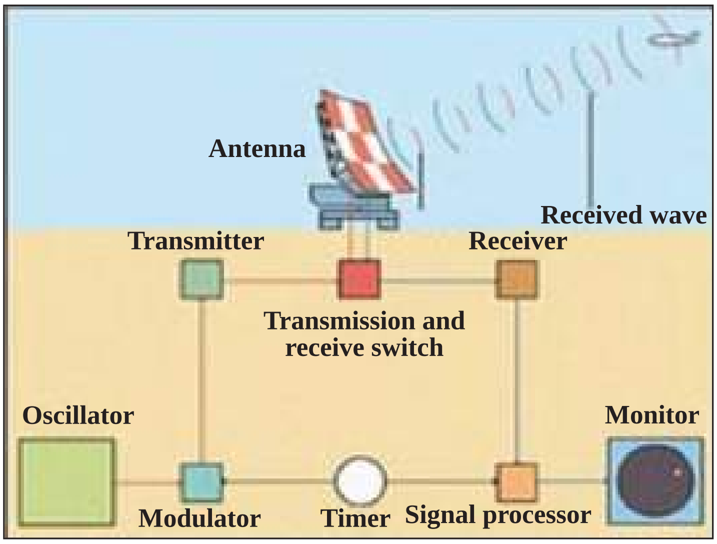



Figure (27)

1. Oscillator: a device that generates an electrical signal with constant frequency and low power.
2. Modulator: works to carry the audio waves on the radio waves.
3. Transmitter: works to reduce time of the pulse which reached to the modulator, sending it with high -power pulse to the antenna.
4. Transmission and reception switch: a switch works to open and close transmission and reception circuit.
5. Antenna: works to transmit radar waves (microwaves or radio waves) in the form of narrow bands directed to the target, and receives when they reflect off the target.
6. Timer: time controls the work of the main components of the radar.
7. Receiver: receives reflected waves, which gather by means of the antenna, it amplifies them and display them on the signal processor.

8. Signal processor: works to pick reflected signal from small moving targets, it also blocks the reflected signal from big stationary targets.

9. Monitor: works to display waves, which reflect from the target as bright points.

## 4-10-2 Remote sensing

It is one of the fields of science, which provide us with information about earth surface without physical contact with the surface, like images from airplane or satellite. This is done by investing electromagnetic light waves to the end of reflected radio frequencies or emitted from earth objects, the air or sea water that remote sensing devices on satellites, airplanes or balloons can sense them. See figure (28). The process of photographing and analyzing to be ready for use in branches of knowledge such as geology, civil engineering, meteorology, agriculture and military applications and others.

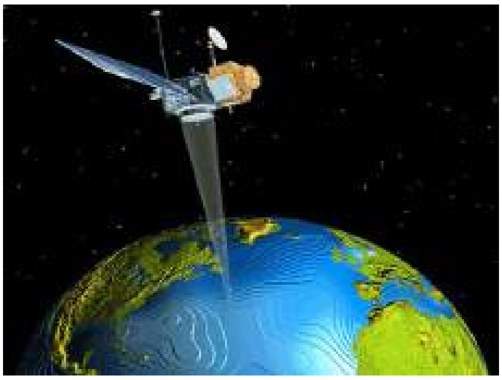


Figure (28)

There are two types of Remote Sensing:

**1. Remote Sensing according to energy source: as two types of images are used:**

a. Active images: it depends on an energy source installed on the satellite itself, to light the target and receive the reflected rays from it, see figure (29).

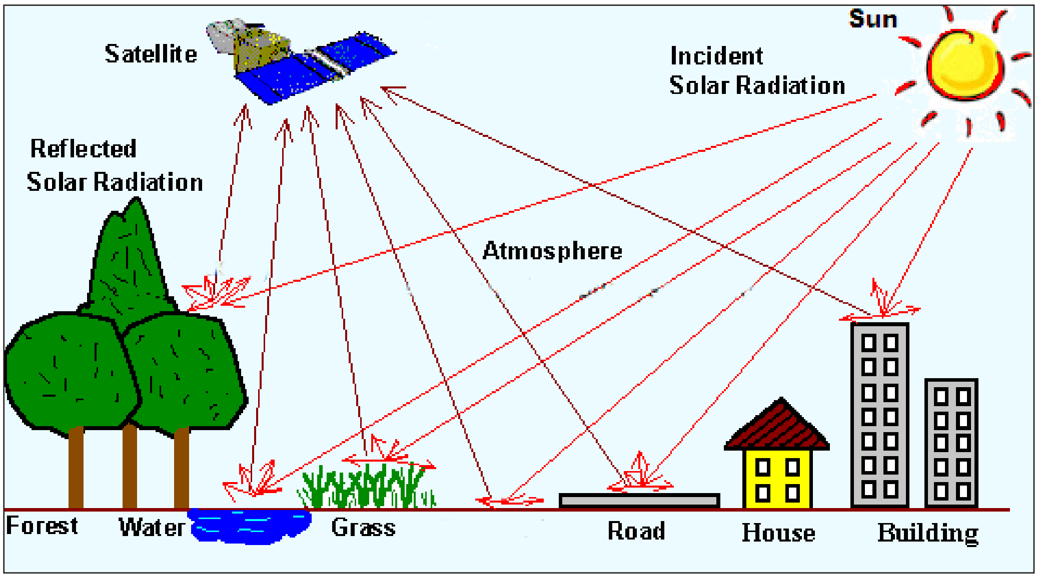



Figure (29) Illstrates how the satellite receives the electromagnetic waves rediated by the earth

b. Passive Images: These depend on the source of radiation, which emit from the target itself.

**2. Remote Sensing by wavelength:** The received target images can be divided according to wavelength into three sections:

a. Visible ray images.

b. Infrared ray images.

c. Micro ray images.

### Use the fields of remote sensing:

This technology is used in several fields including:

1. Discover mineral and petroleum ores.
2. Monitoring river movements, drying up of lands, lakes and controlling floods by comparing images taken at different times.
3. Study construction projects and urban planning of cities, villages and large facilities.
4. Study natural plants and  soil quality distribution.
5. It is used military applications. Some satellites are equipped with infrared sensors, these can detect heat emitting from trucks, planes, rockets, persons and any movement on the earth's surface. Sensors work at any weather condition.
6. Remote sensing is used in imaging of stars and planets using digital cameras installed of artificial satellites devoted especially scientific for space research.

## 4-10-3 Mobile phone

Before discovering the mobile phone, communication used to be done by radio telephones, like the one used by police. In this system, there is one central transmission station (antenna) in the city, and only (25) communications channel are avaible to the user, this means that a limited number of people can use the radio telephone at the same time.

As for mobile phone system, the city is divided into cells, each cell has a tower provided with transmission and reception sets, see figure (30). Since mobile phones and transmitting stations use low power (0.6 – 3 watt), the same frequencies can be used in remote cells, like the ones marked in dark color in figure (30). This method helps millions of people use their phones without interference since the same frequency can be used on more than cell.

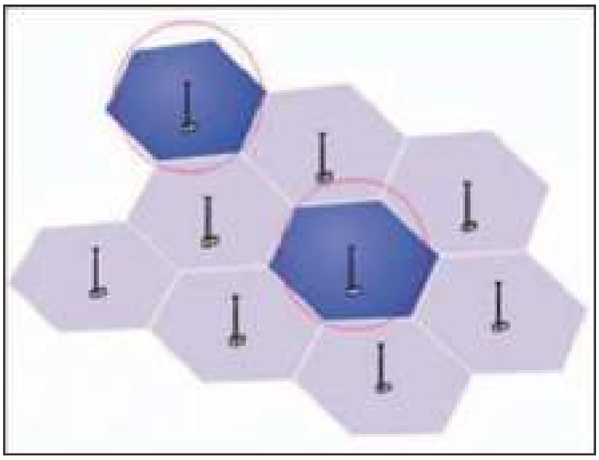


Figure (30) illustrates how the city divided into cells with communication tower

Mobile phones use over (1664) channels. The speaker can move from cell to another while using the phone, this means that the range of the mobile is wide and the speaker can speak to anyone hundreds of kilometers away without disconnecting, see figure (31).

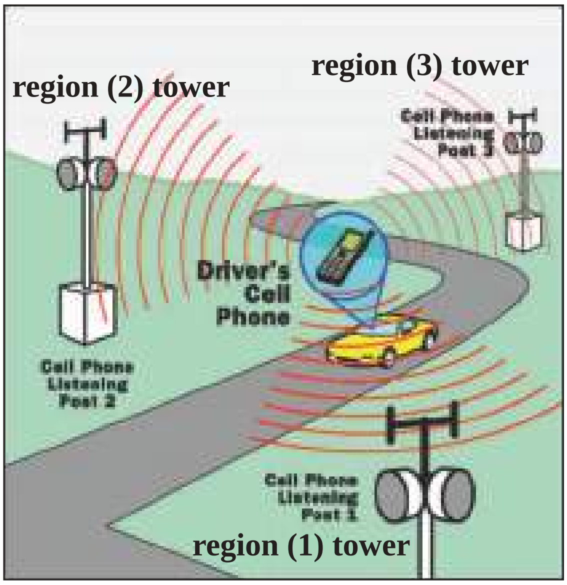



Figure (31) illustrates how it possible to transfer the receiving speaker from one communication cell to another

# Questions of chapter 4

**Q1** Choose the correct statement for the following:

1. Displacement current ($I_d$) is proportional to:
   a. Time rate of change in magnetic field.
   b. Time rate of change in electrical field.
   c. Time rate of change in conduction current.
   d. Time rate of change in polarization current.

2. Oscillation of free electrons in a conductor produces waves called:
   a. X-ray waves.
   b. Gamma ray waves.
   c. Infrared waves.
   d. Radio waves.

3. Speed of electromagnetic wave in various media is determined by:
   a. Electric permittivity of that medium only.
   b. Magnetic permeability of that medium only.
   c. Sum of permittivity and permeability of that medium.
   d. Inverse of square root product of the permittivity and permeability for that medium.

4- Electromagnetic waves that are used in radar is:
   a. Ultraviolet ray waves. b. Gamma ray waves.
   c. X-ray waves. d. Microwave.

5. Radio waves are generated when:
   a. Flowing of direct current passes in a conductor wire.
   b. Movement of an electric charge at constant velocity in a conductor wire.
   c. Movement of an accelerated electric charge in a conductor wire.
   d. Static electric charges in a conductor wire.

6. To get high efficiency in transmission and reception , half-wave antenna length is used because the amount of:
   a. Voltage are maximum at feeding point.
   b. Voltage are minimum at feeding point.
   c. Voltage and current are maximum at feeding point.
   d. Voltage and current are minimum at feeding point.

7. An electric charge can be accelerated in a conductor when affected by:
   a. Static electric field.
   b. Oscillated electric field.
   c. Statics electric and magnetic fields.
   d. Static magnetic field.

8. In Frequency Modulation (FM), we get modulated wave with capacitance that is:
   a. Constant and constant frequency too.
   b. Varying and also varying frequency.
   c. Constant and varying frequency.
   d. Varying and constant frequency.

9. Ionosphere layer in the atmosphere reflects radio frequencies which are:
   a. (2-30) MHz range.
   b. (30-40) MHz range.
   c. Over than (20) MHz.
   d. All radio frequencies.

10. The process of transmitting and receiving of electromagnetic waves depend on:
   a. Diameter of antenna wire.
   b. Density of antenna wire.
   c. Electromagnetic oscillation circuit and antenna.
   d. All above choices.

11. In radio broadcast, the acoustic detector does:
   a. Transform audible sound waves into audible waves with the same frequency.
   b. frequency modulation.
   c. Amplitude modulation.
   d. Separates audible frequencies from radio frequencies.

12. Remote sensing images, which depend on power source from the satellite, are called:
   a. Passive images.
   b. Active images.
   c. Images of radiation emitting from the target itself.

**Q2** Are all conductive wires, which have current, radiate electromagnetic waves? explain this.

**Q3** When electromagnetic rays propagate in space or in various media? what dose oscillate?

**Q4** What are the factors that determine speed of the electromagnetic waves propagation in various media?

**Q5** Is the receipt of the radio waves during the day less range than it is during the night; explain this?

**Q6** What is the difference between active and passive images?

**Q7** What is meant by the following terms: carrier wave, carried wave, modulated wave?

**Q8** We often see in cinamas or television, policemen trying to locate secret wireless signal station using a driving car nearby, the car has a device on top of it, this device has a coil that revolves slowly from the back of the car, explain how this device works?

## Problems of chapter 4

**P.1.** A radio is used to detect a radio station at frequency of (840) kHz, if resonance circuit has inductor of (0.04) mH, what is capacitance of capacitor need to detect this station?

**P.2.** What is wavelength range covered by AM broadcasting station with frequencies are in range from (540) kHz to (1600) kHz?

**P.3.** What is the minimum length of a car antenna needed to receive a signal of frequency(100) MHz ?

**P.4.** What is wavelength of electromagnetic waves radiated by a source with frequency (50) Hz ?

**P.5.** What is frequency of the following electromagnetic waves with wavelength:

a. 1.2m  b. 12 m  c. 120 m

**P.6.** An explosion occurred (4) Km away from an observer, what is time between observer's seeing of the explosion and hearing the sound of the explosion? (Suppose speed of sound is 340 m/s)

# CHAPTER 5

# Physical Optics

Contents


5-1 Introduction

5-2 Interference of light waves

5-3 Young double slits experiment

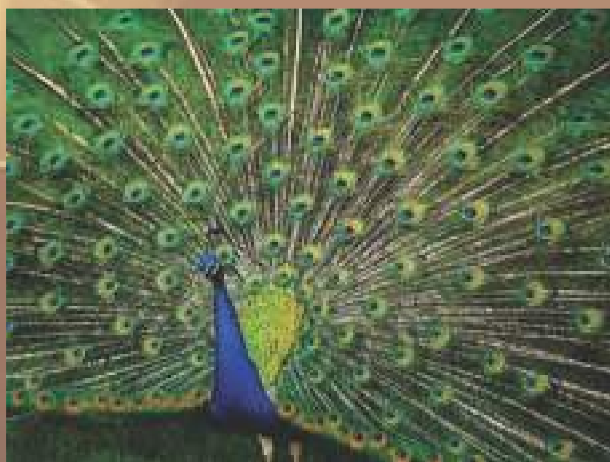
5-4 Interference in thin films

5-5 Diffraction of light waves

5-6 Diffraction grating

5-7 Polarization of light

5-8 Scattering of light

## Behavioural targets

**After studying this chapter, the student should be able to:**

- Define the concept of interference in light.
- Mention the conditions of interference.
- Conduct an experiment to create a fringe of light interference.
- Recognize some of the phenomena that occur as a result of light interference.
- compare between the diffraction and interference of light by understanding the concepts of diffraction and interference.
- Recognize the evidence of the young double slits experiment.
- Distinguish between polarized light and unpolarized light.
- Mention some methods to obtain a polarized light.
- Define the phenomenon of scattering of light.

| Scientific Terms | |
|---|---|
| Interference of light waves | تداخل الموجات الضوئية |
| Young double Slits Experiment | تجربة شقي يونك |
| Double Slit | الشق المزدوج |
| Interference in thin Films | التداخل بالاغشية الرقيقة |
| Wave Light Diffraction | حيود موجات الضوء |
| Diffraction grating | محزز الحيود |
| Polarization of light | استقطاب الضوء |
| Polarized waves | موجات مستقطبة |
| Polarizer | المستقطب |
| Analyzer | المحلل |
| Random directions | اتجاهات عشوائية |
| Polarization of Light by Reflection | استقطاب الضوء بالانعكاس |
| Brewster angle | زاوية بروستر |
| Scattering of Light | استطارة الضوء |

## 5-1 Introduction

You have learned in your previous studies some phenomena of light. In this chapter you will learn some more phenomena, such as Interference, diffraction and Polarization.

What are meant by these phenomena? How do they occur? Which laws describes them?

## 5-2 Interference of light waves

To understand the concepts of Interference of waves, we conduct the following activity:

### Activity (1)

Interference of waves:

**Tools of activity:**

A ripple tank, power supply, vibrator, pecker with two tapered ends as two-point sources ($S_1$, $S_2$) emitting circular waves propagating on the surface of water of the same wavelenght.

**Activity steps:**

- We get the ripple tank ready to work as it touches both sides of the pointer the surface of the water in the container.
- When the operating the motor, we see the interference pattern on the water surface as a result of superposition of waves generated by vibration of the symmetrical pointer sources ($S_1$, $S_2$), figure (1).

Now the following question comes to mind: Do both sources as explained ($S_1$, $S_2$) in figure (1). emit waves of the same phase? And what is the type of interference which is produced?

Figure (1)

From our observation for the produced waves at the water surface, it appears that there are two kinds of interference which are:

1. When the two waves are in same phase and same amplitude at a certain point, the two waves will combine with each other and in this case the resulting wave amplitude will be equal to the twice amplitude of any of the original waves.

This kind of interference is called constructive interference, as seen in figure (2-a). This is resulted from overlapping two crests or two troughs for two waves resulting strengthening.

2. If the interference is a result of combination of two sequence of waves which are out of phase and equal in amplitudes, in which case the crest of a wave overlaps the trough of another wave, in this case the result will be that the effect of one of the waves cancels the effect of the other wave. This means that the amplitude of the resulting wave will be zero. This kind of interference is called destructive interference, as in figure (2-b).

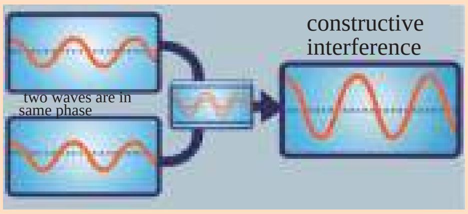


Figure (2-a)

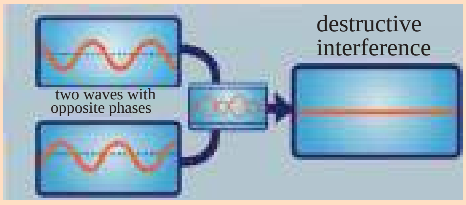


Figure (2-b)

On the basis of the above information we can say that the interference in the light waves is one of its general characteristics, the light interference is the phenomenon of redistribution of light energy resulting from the superposition of two or more sequences of coherent light waves when its propagates in one plane at the same time and in the same media. This will take a place according to the principle of wave superposition. (The displacement of the resulting wave at any instant will be equal to the sum of the two displacements for the two overlapped waves at the same instant).

Permenent interference takes place in the following cases:

1. If the two waves are coherent.
2. If they vibrate in the same plane and in the same media and pass trough the same point at the same time.

It is worth mentioning that the coherent waves in light are the waves which are:

1. Equal in frequency.
2. Equal in amplitude.
3. The phase difference between them is constant.

The optical path is the displacement done by the light in vacuum by the same period of time which is done in the transparent material media.

In order to calculate the optical path difference between two light emitted waves with the same phase by the sources ($s_1$, $s_2$) which are arriving the point (p) precisely after knowing the type of interference produced for these waves, given that the phase difference ($\Phi$) between the waves arriving the point (p) is determined by the optical path between these waves by the following relation:

$$\Phi = \frac{2\pi}{\lambda}\Delta\ell$$

$\Delta\ell$ : represents the optical path difference between the two waves.

$\Phi$: represents the phase difference between the two waves.

If the optical path length ($\ell_1 = 2.25\,\lambda$) for the emitted waves by a source ($s_1$) which arrives the point (p).

The optical path length $\ell_2 = 3.25\,\lambda$ for the emitted waves from the source ($s_2$) which arrives the point (p), as in figure (3-a), then the optical path difference for the two waves ($\Delta\ell$) will be:

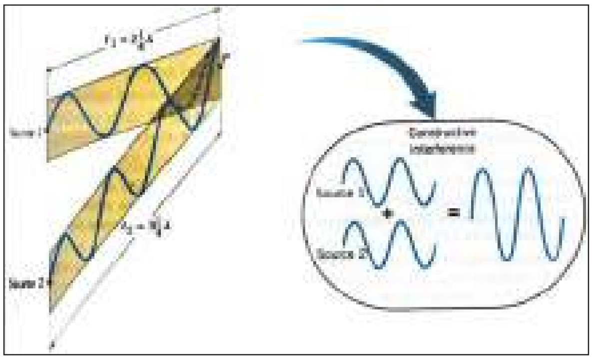


Figure (3-a) Constructive Interference

$$\Delta\ell = \ell_2 - \ell_1$$
$$\Delta\ell = 3.25\lambda - 2.25\lambda$$
$$\Delta\ell = 1\lambda$$

This means that the two emitted waves from the sources ($s_1$, $s_2$) arrive the point (p) at the same moment, and coincide in the phase, at which time a constructive interference takes place at the point (p) when the phase difference ($\Phi$) between them equals zero or an even numbers of ($\pi$ rad) such as $\Phi = 0, 2\pi, 4\pi, 6\pi ....$ rad .

This means that the optical path difference ( $\Delta\ell$ ) is either zero or an integer numbers of the wavelength

$$\Delta\ell = 0, 1\lambda, 2\lambda, 3\lambda, .....$$

On that basis the condition of constructive interference is given by:

$$\Delta\ell = m\lambda \qquad m = 0, 1, 2, 3......$$

If the length of the optical path ( $\ell_1 = 1\lambda$ ) for the emitted waves from the source ($s_1$) arrived to the point (p) and the optical path length ( $\ell_2 = 1.5\lambda$ ) for the emitted waves from the source ($s_2$) arriving the point (p).

Then the optical path difference ( $\Delta\ell$ ) for the two waves will be: (note figure (3-b)).

$$\Delta\ell = \ell_2 - \ell_1$$
$$\Delta\ell = 1.5\lambda - 1\lambda$$
$$\Delta\ell = 0.5\lambda$$
$$\Delta\ell = \frac{1}{2}\lambda$$

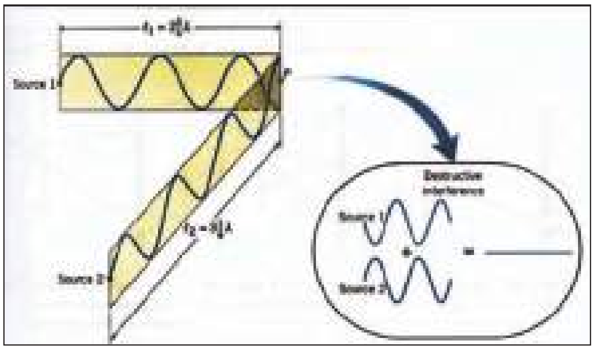


Figure (3-b) Destructive Interference

That means, the two emitted waves from the two sources ($s_1$, $s_2$) reach a point (p) at the same moment and are opposite in phase so destructive interference happened at point (p) when phase difference between them, the phase difference ($\Phi$) equals to odd numbers from ($\pi$ rad).

i.e: $\Phi = \pi, 3\pi, 5\pi ....$rad

That means the optical path difference ( $\Delta\ell$ ) between them in the case of destructive interference equals an odd numbers of half wavelengths. That means:

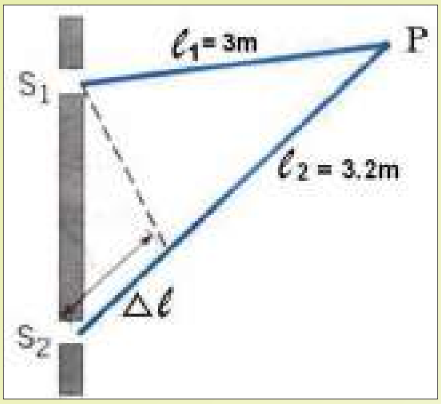
$$\Delta\ell = \frac{1}{2}\lambda, \frac{3}{2}\lambda, \frac{5}{2}\lambda ......$$

So the condition for destructive interference is:

$$\Delta\ell = \left(m + \frac{1}{2}\right)\lambda \qquad m = 0, 1, 2, 3.......$$

**Example (1)**

In this diagram, the sources ($s_1$,$s_2$) are coherent emitting waves of length ($\lambda$ = 0.1m), the emitted waves interfere at the point (p) at the same time. What is the type of the interference produced at this point when one of the two waves cuts optical path of (3.2 m) and the other has optical path of (3 m):




**The solution:**

To know what type of interference produced between the two waves, it requires to find (m) from the two interference conditions as mentioned earlier of the following:

$$\Delta\ell = m\lambda$$

$$\Delta\ell = \left(m + \frac{1}{2}\right)\lambda$$

$$\Delta\ell = \ell_2 - \ell_1 \Longrightarrow \Delta\ell = 3.2 - 3$$

$\Delta\ell = 0.2m$ The optical path differance

$\Delta\ell = \left(m + \frac{1}{2}\right)\lambda$ First possibility

$$0.2 = \left(m + \frac{1}{2}\right) \times 0.1 \Longrightarrow 2 = m + \frac{1}{2}$$

$$\therefore m = 1\frac{1}{2}$$

This does not satisfies the condition of destructive interference because the value of (m) must be integers numbers such as (0, 1, 2, 3, …..).

$\Delta\ell = m\lambda \qquad m = 0, 1, 2, 3......$ Second possibility

$$0.2 = m \times 0.1 \Longrightarrow m = 2$$

So this satisfies the condition of a constructive interference because:

$$m = 0, 1, 2, 3, ......$$

Note: this question can be solved in another way using the equation of phase difference.

**Question:**

With regard to the last example, what happens when:

a. One of the waves makes optical path of (3.2 m) and the other makes optical path of (3.05 m).

b. One of the waves makes optical path of (3.2 m) and the other makes optical path of (2.95 m).

## 5-3 Young double slits experiment

The scientist Young was able to prove through his experiment in 1801 the nature of the light waves as he was able to calculate the wavelength of light which was used in his experiment.

In his experiment Young used a barrier with a tiny slit and monochromatic light, then the light was projected on a barrier containing two identical narrow slits called (double slit) these two slits are situated at the same distance from the slit of the first plate. Then he put a screen at a distance of some meters from the two slit barrier. The result obtained by Young was the appearance of some bright regions and some other dark regions consequently and this was called the fringe, note figure (4). Now the question is how the bright and the dark fringes have happened in Young's experiment.

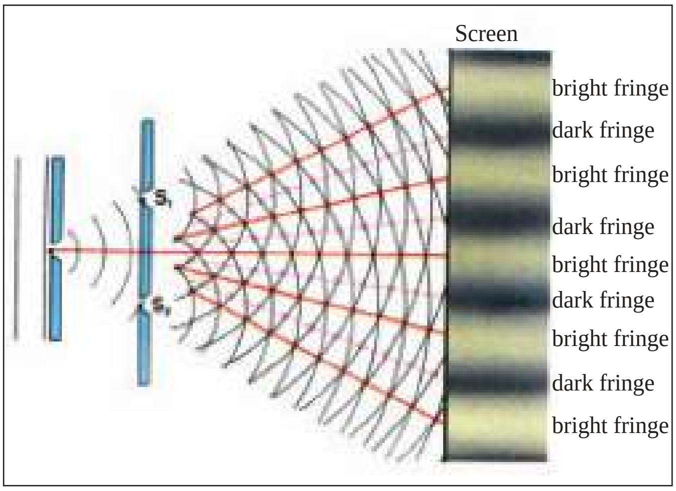



Figure (4) Young's double slite experiment

The answer to that question relies on figure (5). Try to find out the reason for obtaining this fringe by remembering the conditions of obtaining both the constructive and destructive interference as you knew before. The slits ($s_1$, $s_2$) lighted with a monochromatic light are coherent light sources, and the emitted waves from them will have the phase difference fixed at all the times. This is the basic condition of the interference. The type of the interference at any point depend on the difference between their optical path length in order to arrive that point.

Figure (5) explains the above information as we observe in the parts (a-b), bright fringe occurs, while in part (c) a dark fringe formed. This depends on the difference in the distances between the slits and the screen.

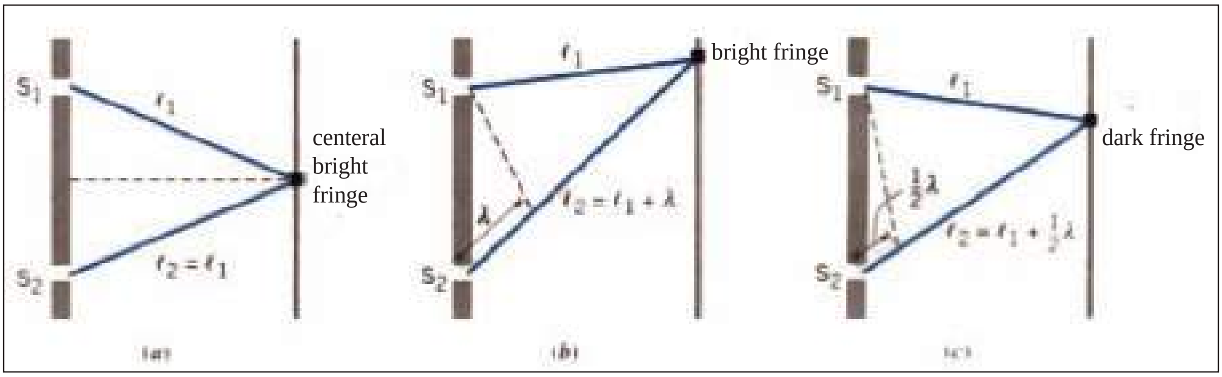



Figure (5) Fringe formed

The question now is the following: where would be the location of the bright and the dark fringes on the screen? As the distance between the slits (d) is very short compared to their distance from the screen (L), i.e $(d << L)$. So the optical path difference between the rays shown in

Figure (6) giving the following relation:

Optical path difference= d sin θ

The condition for the constructive interference for obtaining bright fringe is:

$$d \sin\theta = m\lambda$$

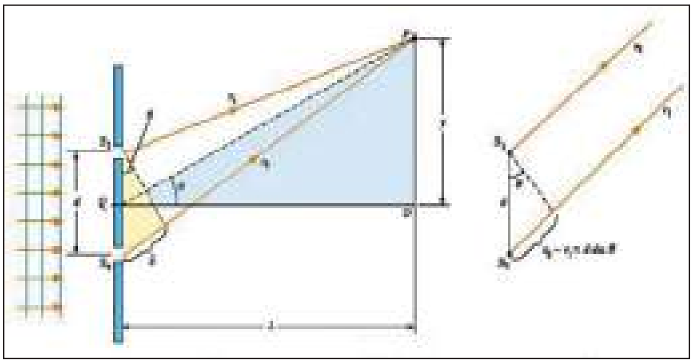


Figure (6)

Whereas we get a dark fringe (result of destructive interference), if:

$$d \sin\theta = \left(m + \frac{1}{2}\right)\lambda$$

m is an integer number:

$$m = 0, \pm 1, \pm 2, \pm 3, .....$$

In order to calculate the distance between the center of the bright or the dark fringe from the center of the central bright fringe (y) as in the following relation:

$$\tan\theta = \frac{y}{L}$$

Since:

θ: is the diffraction angle.

y: is the distance from the center of the bright or the dark fringe from the bright central fringe.

L: is the distance between the screen and the two slits barrier, as in figure (6).

It is important to mention that Young's experiment regarded as important from the practical point of view in order to measure the wavelength (λ) for the used monochromatic light.

As the diffraction angle θ is small then:

$$\tan\theta \cong \sin\theta$$

By then we have: $y = L\tan\theta \cong L\sin\theta$

Then the position of the bright and the dark fringes from the center (O) can be determined as follows:

Bright fringe: $y_m = \frac{\lambda L}{d} m, \qquad (m = 0, \pm 1, \pm 2, .....)$

Dark fringe: $y_m = \frac{\lambda L}{d}\left(m + \frac{1}{2}\right), \qquad (m = 0, \pm 1, \pm 2, .....)$

The figure (7) explains the positions of the interference fringes resulted on the screen. The spaces between the adjacent fringes are called fringe spacing ($\Delta y$) given by the following:

$$\Delta y = y_{m+1} - y_m$$

$$\Delta y = \frac{(m+1)\lambda L}{d} - \frac{m\lambda L}{d}$$

$$\text{Fringe Spacing} \quad \Delta y = \frac{\lambda L}{d}$$

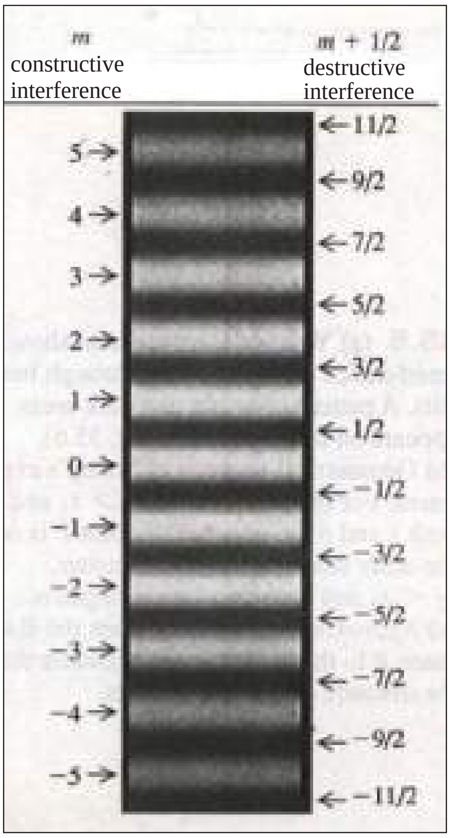



Figure (7) Explains the positions of the interference fringes

**Remember:**

1. The amount of fringe spacing ($\Delta y$) increases when the distance between the two slits and the screen (L) is increases.
2. The amount of the fringe spacing ($\Delta y$) increases if the distance between the slits (d) decreases.
3. The amount of the fringe spacing ($\Delta y$) increases when the monochromeatic light wavelength used increases in Young's experiment.

Perhaps you may ask? If the white light is used in Young's experiment. How would the colour of the central light fringe appear on either side of the central fringe?

The central fringe appears in white colour and on both sides white colour spectra will appear continuously. Gradually each spectra of the violet colour changes to the red colour, as in figure (8).

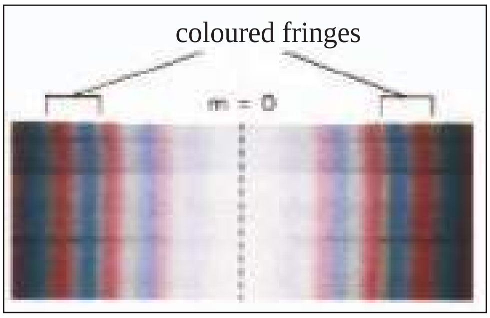



Figure (8)

What do you expect to happen if the two sources of the light are incoherent? Would the constructive and destructive interference happen? In fact both constructive and destructive interference take place consequently with a very high speed, so the eye can not follow such rapid change, because both of the sources are emitted waves with random change phases, and a high speed making it impossible to obtain a constant phase difference between the interfered waves at any point of the medium. So the eye can see sustainable lighting as a result of vision persistence.

**Think?**

In the case of using red light in the two slit Young's experiment, you will observe the distances between the interference fringe larger than what it is if you use the blue light. Why?

## Example (2)

If the distance between the two slits in Young's experiment equals (0.2mm) and the distance screen is (1m) from the two slits. The distance between the third bright fringe and the central fringe is (9.49 mm), as in figure (9). Calculate the used light wavelength in this experiment?

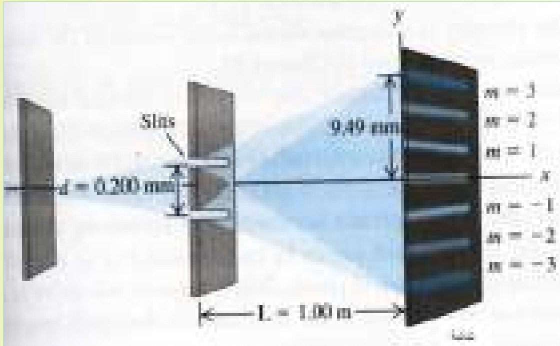



Figure (9)

### The solution:

by applied the following relation:

bright fringe

$$\lambda = \frac{y_m d}{mL} = \frac{(9.49 \times 10^{-3} m)(0.2 \times 10^{-3} m)}{(3)(1m)}$$

$$\lambda = 633 \times 10^{-9} m$$

$$\lambda = 633nm$$

**Think?**

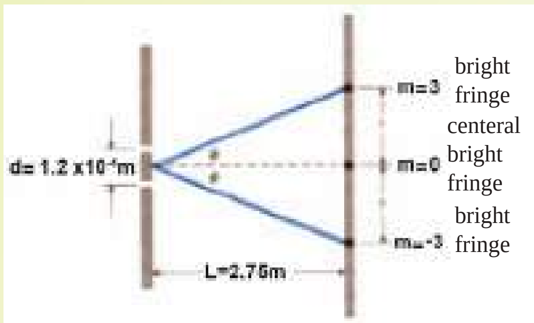
Does the third brighted fringe (m = -3) give the same wavelength?

## Example (3)

In the given diagram, red light of wavelength ($\lambda$ = 664 nm) is used in the experiment of Young. The distance between the two slits is ($d = 1.2 \times 10^{-4}$m) and the distance between the screen and the two slits is (L = 2.75 m). Find the distance (y) on the screen between the third bright fringe and the central fringe.

Not thats $\tan 0.951 = 0.0166$ , $\sin 0.951^0 = 0.0166$

### The solution:




We first calculate the measurement of the angle θ for the third bright order (m = 3)

$$d \sin\theta = m\lambda$$

$$1.2 \times 10^{-4} \sin\theta = 3 \times 664 \times 10^{-9}$$

$$\sin\theta = 0.0166$$

$$\theta = 0.951^0$$

And from this we find:

$$y = L \times \tan\theta$$

$$y = 2.75 \times \tan 0.951$$

$$y = 0.0456 \, m$$

$$y = 4.56 \, cm$$

This is the distance of the bright fringe of third order from the centeral bright fringe

The question can be solved in another way by using the following law: $y_m = \frac{mL\lambda}{d}$

## 5-4 Interference in thin films

In our daily lives we sometimes see the floating oil spill on the surface of the water colourful with bright colours. We also see sometimes soap bubble with the colours of the rainbow colours, as in the figure (10). The cause of interference between white light waves reflected from the front and the back of the thin films surface.

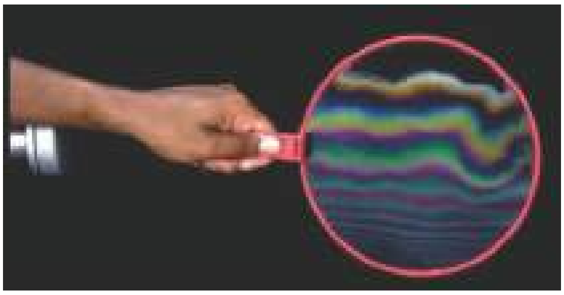


Figure (10) Interference in thin films

The Interference in the thin films depends on two factors:

a. The thickness of the film: The waves reflected from the back surface makes a distance more than that reflected waves from the front surface path which is equal to twice the thickness of the film.

b. Phase shifts: The reflected waves from the front surface get a phase shifts as (π rad).

Understanding the concept of interference in thin films notice figure (11). This show that the incident light waves on the film some of it is reflected from front surface of the thin film and get phase shift equals (π rad) because each wave reflected from a media with refractive index greater than the refractive index of the media which came from it, will get a shift in phase by ($180^0$), The remainder of the light wave transmitted in the film and suffer refraction incide the film, when it reflected from the back surface of the film, (with thickness t), will not suffer phase shift, it will make extra optical path equals twice the film's optical thickness (2nt). So there is interference between the two opposite waves from the front surface and the back surface according to the amount of the phase difference.

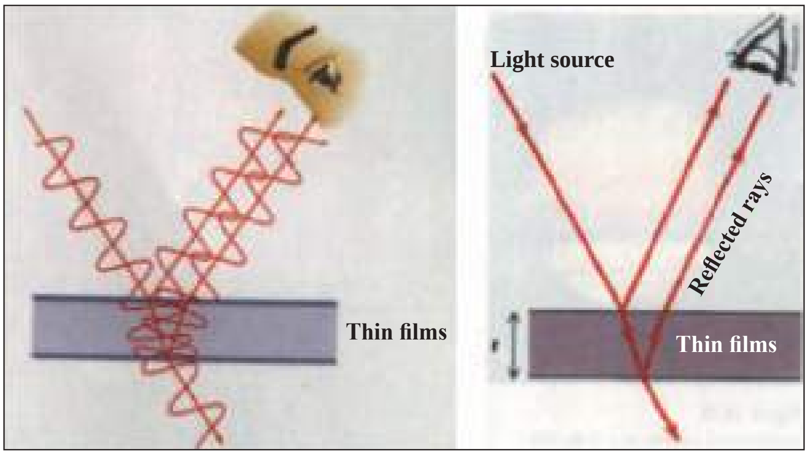



Figure (11) Interference in thin films

If the optical thickness of the film (nt) equals an odd number for the quarter wavelength of the monchromatic incident light. $\left(1\times\frac{1}{4}\lambda, 3\times\frac{1}{4}\lambda, 5\times\frac{1}{4}\lambda, 7\times\frac{1}{4}\lambda, .....\right)$ the interference will be constructive as the following relation:

$$2nt + \frac{1}{2}\lambda = \lambda, 2\lambda, 3\lambda, ......$$

That is: $nt = \left(1 \times \frac{1}{4}\lambda, 3 \times \frac{1}{4}\lambda, 5 \times \frac{1}{4}\lambda, 7 \times \frac{1}{4}\lambda, .....\right)$

The film appears lighted by the colour of the incident light on it: (constructive interference).

if the optical thickness for the film (nt), equals an even numbers of a quarter wavelength of the incident monochromatic light, then $\left(2 \times \frac{1}{4}\lambda, 4 \times \frac{1}{4}\lambda, 6 \times \frac{1}{4}\lambda, 8 \times \frac{1}{4}\lambda, .....\right)$, the interference will be destructive as the relation:

$$2nt + \frac{1}{2}\lambda = \frac{1}{2}\lambda, \frac{3}{2}\lambda, \frac{5}{2}\lambda, .....$$

$$2nt = 0, \frac{2}{2}\lambda, \frac{4}{2}\lambda, \frac{6}{2}\lambda, .....$$

i.e: $nt = 0, \frac{2}{4}\lambda, \frac{4}{4}\lambda, \frac{6}{4}\lambda, .....$

The film appears dark (destructive interference).

**Remember:**

Wavelength of light ($\lambda_n$) in any medium has refractive index (n), given by: $\lambda_n = \frac{\lambda}{n}$

## 5-5 Diffraction of light waves

Have you ever tried to look at a lighted lamp through two fingers of your hand when bringing them close together, or you looked at the sunlight by getting your eyelashes as close as possible in order to see bright and dark beams respectively. This is as a result of the light diffraction and interference. To understand the light diffraction we do the following activity:

### Activity (2)

Light diffraction:

**Tools of activity:**

Glass plate, Pin, Black paint, , monochromatic light source.

**Activity steps:**

- Paint the glass plate with black paint.
- Make a thin slit in the glass plate using the tip of pin .

- Look through the slit to the light source. What do you notice?

  You will notice bright regins interspersed with some dark regins and the middle region is wide and very bright. The bright fringe gradually decreases in intensity as you move away from the central bright fringe.

  The appearance of bright and other dark regins on both sides of the slit Indicate that the light deviating from its path. Notice figure (12).

  The condition required to obtain either bright or dark fringe are as follows:

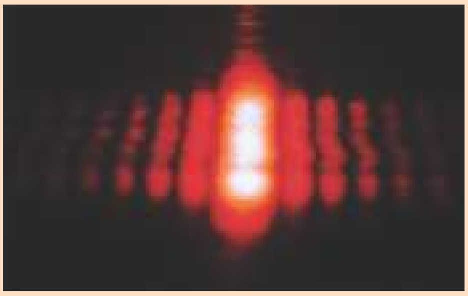


Figure (12)

- The condition for obtaining a dark fringe is:

$$\ell.\sin\theta = m\lambda$$

- The condition for obtaining a bright fringe is:

$$\ell.\sin\theta = \left(m + \frac{1}{2}\right)\lambda$$

where $\ell$ is the width of the slit , $m = \pm 1, \pm 2, \pm 3, .......$

Figure (13) shows the bright intensity of the fringe on the screen, which is at its maximum value at the central point. The bright intensity of the fringe decreases as it is further from the center point.

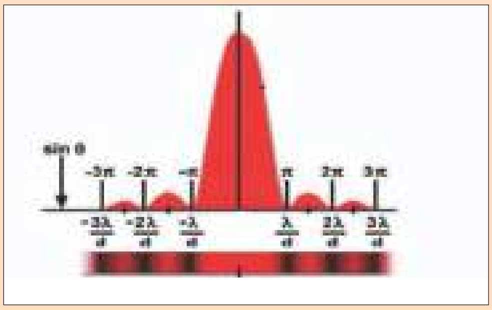


Figure (13) the bright intensity of the fringe on the screen

## 5-6 Diffraction grating

A diffraction grating is a useful optical device to study spectra, analysis of the light sources and to measure the wavelength of light, it contains a large number of parallel grooves with equal width. Grating can be made by printing grooves on a glass plate in a ruling very accurate machine. The widths between the grooves will be transparent as its doing separate slits and the groove its dark region.

Ranging Number of the slits (line) in each centimeter will be between: $(1000 - 10000)$ line , i.e line per centimeter.

Therefore, the grating constant (d) is very small and (d) is the distance between every two successive grooves, as in figure (14).

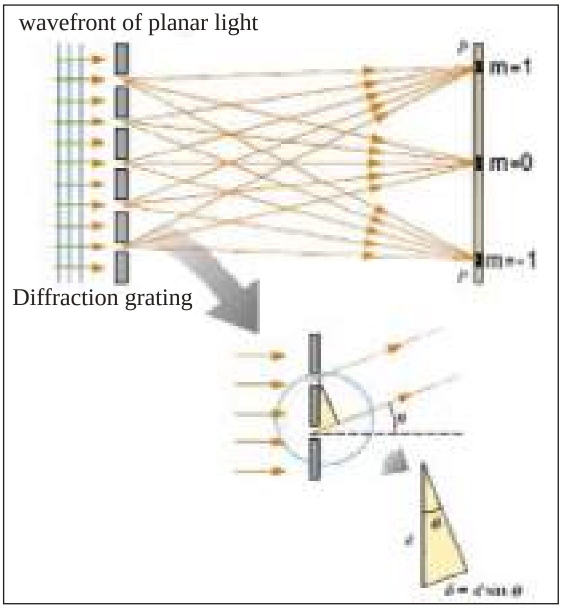



Figure (14) Diffraction grating

If diffraction grating have $5000 \frac{\text{line}}{\text{cm}}$ for example, then the grating constant will be:

$$d = \frac{(w)\ \text{The width of the grating}}{(N)\ \text{Number of slits}}$$

$$d = \frac{w}{N}$$

So: $d = \frac{1\text{cm}}{5000} = 2 \times 10^{-4}\text{cm}$

The difference of optical path between two rays out from any two adjacent slits in the diffraction grating equals ($d \sin \theta$). If this difference was equal to one wavelength ($\lambda$) or the integers number of the wavelengths ($m\lambda$), then the waves will make as a result of its interference a bright fringe on the screen as in the following relation:

$$d \sin\theta = m\lambda \qquad m = \pm 1, \pm 2, \pm 3, .....$$

The above relation can be used in order to calculate the wavelength for a monochromatic light by using apparatus called (spectrometer), as in figure (15).

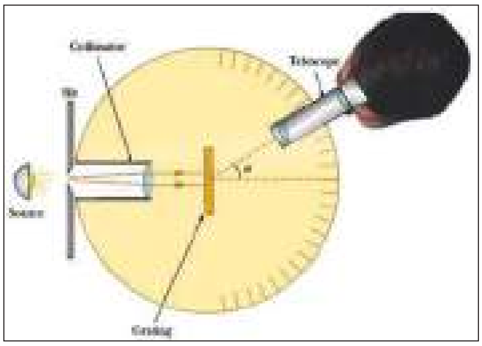


Figure (15) Spectrometer

**Example (4)**

Monochromatic light from Helium-Neon laser. The wavelength of ($\lambda$= 632.8nm) falls vertically over diffraction grating in which each cm contains (6000 line). Find the diffraction angles ($\theta$), for the first and second bright fringe.

Note thats $\sin 49^0 = 0.7592$, $\sin 21.3^0 = 0.3796$

**The solution:**

$$d = \frac{w}{N}$$

$$d = \frac{1\text{cm}}{6000}$$

Grating constant $d = 1.667 \times 10^{-4}\text{cm}$

1. ($m = 1$) for the bright fringe

$$d \sin\theta = m\lambda$$

$$1.667 \times 10^{-4}\text{cm} \times \sin\theta_1 = 1 \times 632.8 \times 10^{-7}\text{cm}$$

$$\sin\theta_1 = \frac{1 \times 632.8 \times 10^{-7}\text{cm}}{1.667 \times 10^{-4}\text{cm}}$$

$$\sin\theta_1 = 0.3796$$

Then:

$\theta_1 = 21.3^0$ represents the diffraction angle at the first bright fringe.

2. (m = 2) for the bright fringe

$$d \sin\theta = m\lambda$$
$$1.667 \times 10^{-4} cm \times \sin\theta_2 = 2 \times 632.8 \times 10^{-7} cm$$
$$\sin\theta_2 = 0.7592$$

From this we: $\theta_2 = 49^0$. This represents the diffraction angle in the second bright fringe.

## 5-7 Polarization of light

When studying the diffraction and interference phenomena, you find that these phenomena prove the wave nature of light. However, it does not prove reality of the light wave is a longitudinal or transverse? To understand this, we conduct the following activity:

### Activity (3)

#### Polarization of waves:

**Tools of activity:**

A rope which is fixed at one of the ends to a wall and a barrier with a slit.

**Activity steps:**

- Pass the free end of the rope through the slit of the barrier, such that the slit is vertical upwards and the rope line is perpendicular to the slit.
- Tighten the rope and then hit it so that it creating transverse wave which passes through the slit as in figure (16-a).
- Now we make the slit horizontal and tighten the rope and then hit it.

We observe that the transverse waves cannot pass through the slit, see figure (16-b).

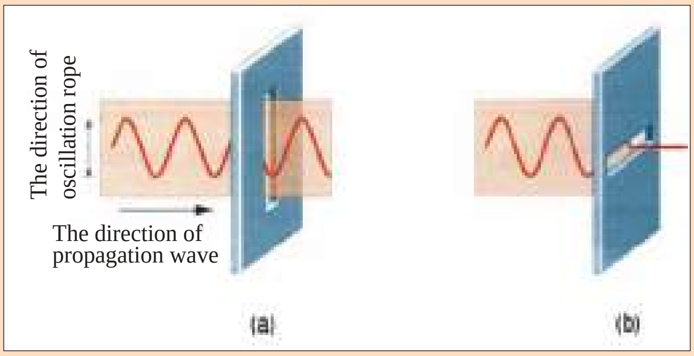



Figure (16)

You can reach the same result with the light waves, if you use a slice of tourmaline, which is a transparent material which allows passing the light waves which vibrates electrical field in the vertical direction. This will obscure light waves which vibrates electrical field in the horizontal direction. This happens as a result of internally absorbed. To understand this we carry out the following activity:

## Activity (4)

### Polarization of light waves

**Tools of activity:**

Two slices of tourmaline and a source of light.

**Activity steps:**

- Take a slice of tourmaline and place it on the way of the light source.
- Rotate the slice about its central and perpendicular axial. Observe if the amount of emerging light varies.
- Put the two slices of the tourmaline as shown in figure (17).
- Fix one of the slices and start rotating the other one slowly about the light rays and notice the sharpness of the emerging light as shown in figure (17).

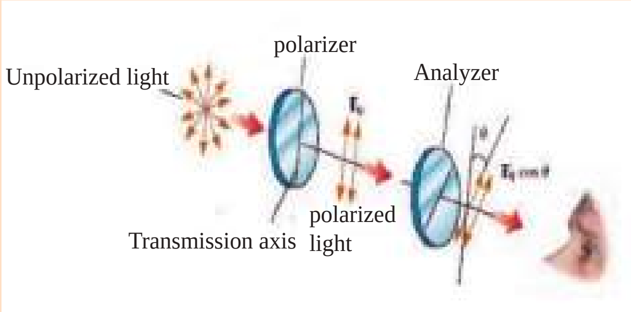



Figure (17) Polarization of light Waves

We may ask why the amount of light intensity varies when the second slice is rotated given that it has the same material construction?

Unpolarized light is transverse waves and its electric field vibrates in all directions. The crystallization of the tourmaline will have the molecules arranged as long chain which does not allow light waves to pass through, unless the level of its electric field vibration perpendicular to the line of the chain. Whereas it observes the rest of the waves. This operation is called Polarization and the light waves are called Polarized light waves.

The slice which performs this operation the Polarizer and the second slice is called the Analyzer.

In case of polarized light the electric field vibration for the electromagnetic waves will be in the one direction, as shown in figure (18-a).

In the case of unpolarazed light, the vibration of the electric field for the electromagnetic waves will be emitted in (Random Directions) and in parallel planes which are perpendicular to the propagation line of the wave, as in figure (18-b).

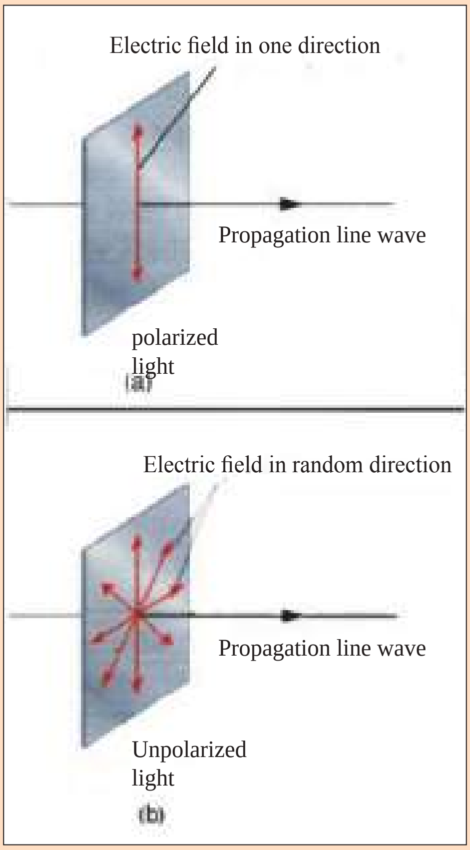



Figure (18)

It would be possible to obtain polarized light such as (tourmaline calcite) from the one which is not polarized.

The direction of the axis of polarized material is the direction of light polarization itself which passes through the material, see figure (19).

To understand the effect of the polarized material in the intensity of the light passing through, we look at the following activity:

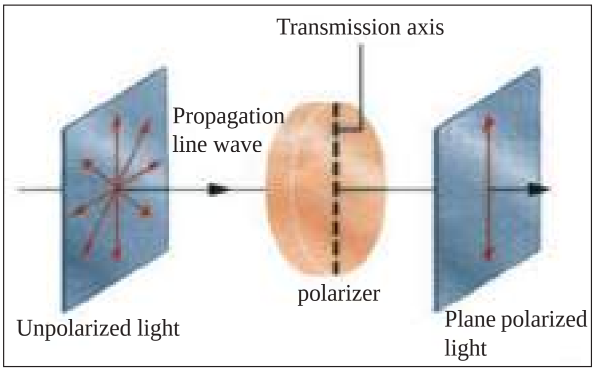



Figure (19)

## Activity (5)

### The polarized material and the intensity of the polarized light passing through

**Tools of activity:**

A monochromatic light source, Two slices of tourmaline and aphotocell.

**Activity steps:**

- We put the light source in front of the polarizer plate. Then we put the second plate analyzer behind it. We notice the decrease in the intensity of the light passing through the two plates.
- We start rotating the analyzer plate until the intensity of the light completely disappears. See figure (20).

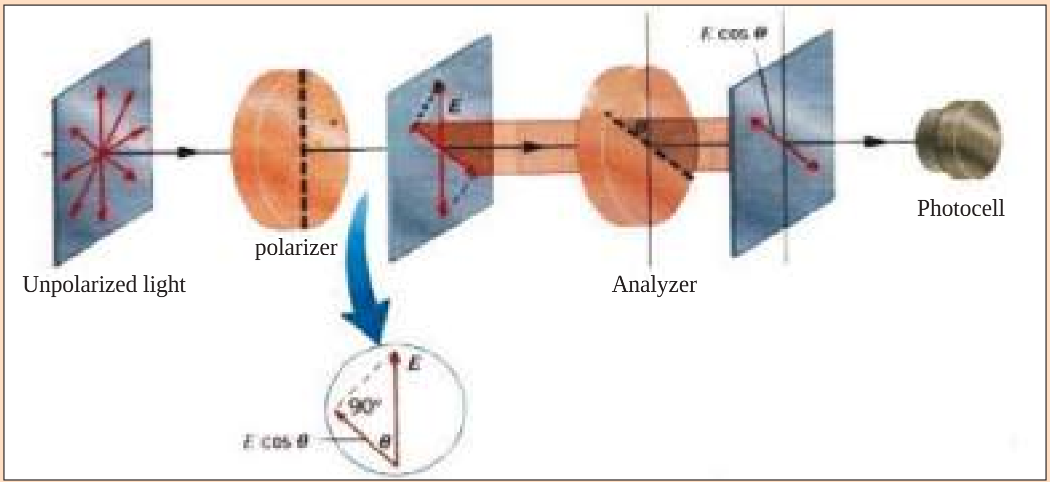



Figure (20) Illustrates the polarized material and the intensity of the polarized light

**Concludes from this:**

The unpolarized light passing through the polarizer plate has been plane polarized and its intensity decreased, when it passes through the analyzer plate, its intensity has decreased more.

When the analyzer plate is rotated at a certain position, we observe that the intensity of the light completely disappears by looking through it. This proves that the polarized light has been obstructed by the analyzer completely. See figure (20).

## Polarization methods in lights:

It is possible to obtain linearly polarized light beam (plane or total) from unpolarized light beam. The question here is, how? What are the methods used for this purpose?

That is possible by removing most of the waves from the light beam (unpolarized) except those which has the electrical field oscillates in one single plane. Most of the commonly used techniques in order to get polarized light by using material which transmit waves that has oscillating electric field in a plane parallel to a certain direction which is the optical axis and absorb waves that oscillate their electric fields in other directions. Some methods of the polarization light are:

### 1. Polarization By selective absorption

Some materials have been discovered called polarizer which polarize light by selective absorption, these material in the form of thin plate with long hydrocarbonic chain. These plates extend during its manufacturing where the molecules of the long chain line up in order to formulate optical axis allowing the light to pass through in which its electric field become perpendicular to its optical axis. It is worth mentioning that there are some materials called, optical active materials, such as, (quartz crystal, turpentine liquid, sugar solution in water).

These materials have the ability to rotate polarization plane of the polarized light when it passes through these materials with an angle called the angle of optical rotation. This angle depends on the type, the thickness of the material, the concentration of the solution and the wavelength of the light passing through it.

### 2. Polarization of light by reflection:

The scientist Malus discovered that when light incident on a reflected surfaces such as plane mirrors or the surface of water in a lake or glass, then the reflected light will be partially polarized and in a plane parallel to the reflected surface plane as in figure (21). While the refracted light in the second media will be at the plane of incident rays.

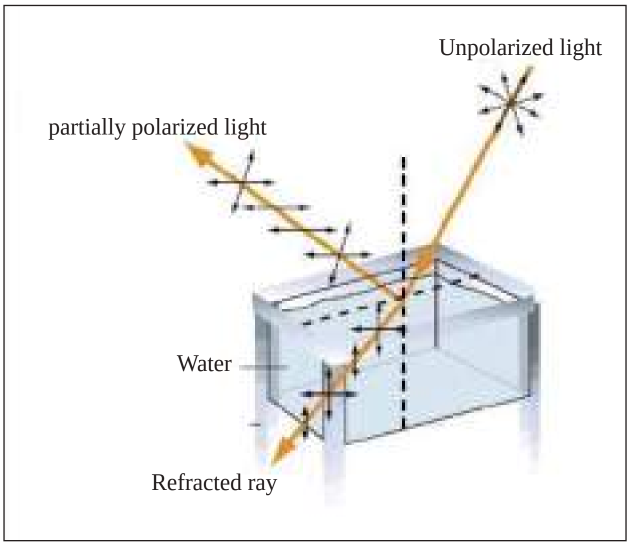



Figure (21)

The degree of polarization depends on the incidence angle. If the incidence angle is zero then there will be no polarization. At the same time the polarization will be increase by increase of the incidence angle until it reaches the total linear polarization at a certain angle called Brewster Angle, as in figure (22).

The refracted ray will be partially polarized and the angle between the reflected ray and the refracted ray equals $90^0$.

The scientist Brewster found a relationship between the angle of polarization ($\theta_p$) and the coefficient of refraction of the media (n) as follows:

$$\tan \theta_p = n$$

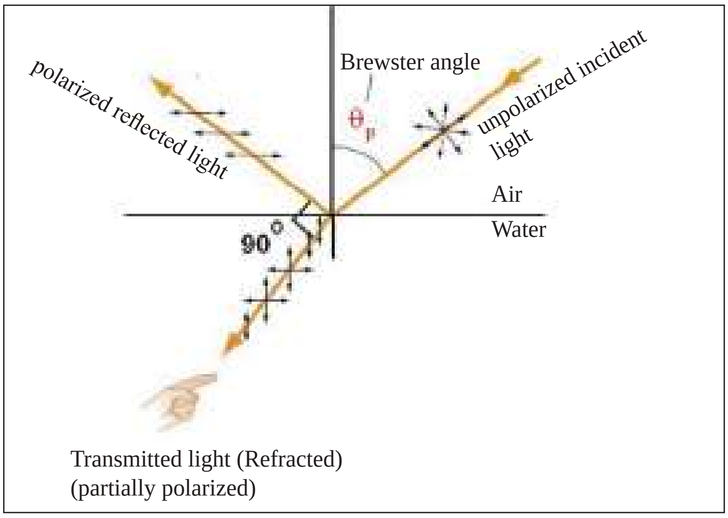



Figure (22)

## 5-8 Scattering of light

No doubt you have seen the sunrise and sunset and you have noticed the red colour of the horizon. You may be asked: What is the reason the predominant colour at the horizon? Why should the sky look pale blue when the sun is over the horizon during the day? Look at figure (23).

Figure (23)

The reason for this is due to the scattering of light phenomenon. When the sunlight is incident which has wavelength ($\lambda$) between (400 nm – 700 nm) on the air molecules and dust particles which has diameter (d) where $(d \leq \lambda)$, it has been found that the intensity of scattered light is inversely proportional to the fourth power of the wavelength, i.e $\left(\frac{1}{\lambda^4}\right)$.

According to this the wavelengths of the short waves from the sunlight (the blue light) scatter at the rate more than the long wavelengths (which is the red light ). Look at figure (24).

Therefore when we look up to the sky we see it is blue because of the scattering of the blue light.

If we look at the sky in the direction of west during the sunset (we look at the sky in the east direction at the sunrise), we see the red and orange light colouring the horizon at the sunset or the sunrising because of the its poor scattering.

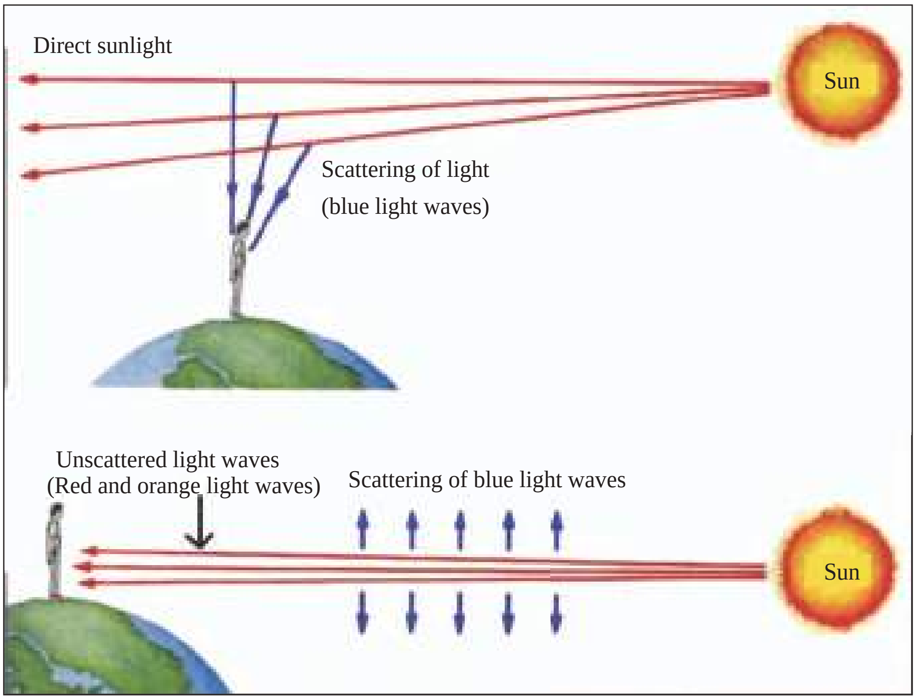



Figure (24) Blue light is more scattered than red light

The following table shows the extent of the light scattering by air molecules.

| Colour | Violet | Blue | Green | Yellow | Orange | Red |
|---|---|---|---|---|---|---|
| Wavelength | 0.40 | 0.48 | 0.52 | 0.58 | 0.60 | 0.70 |
| The relative number of the scattered waves | 10 | 5 | 4 | 3 | 2 | 1 |

**DO you know?**

This diagram shows that the feather of some birds are coloured in a very nice combination of colours as a result of the light scattering and their feather appears in this kind of combination.

# Questions of chapter 5

**Q1** Choose the correct statement for each of the following:

1. In light diffraction from one slit, the condition that the first bright fringe (non central), is that the width of the slit is equal:

   a. $\lambda$.

   b. $\frac{\lambda}{2\sin\theta}$ .

   c. $\frac{3\lambda}{2\sin\theta}$.

   d. $\frac{\lambda}{2}$.

2. The colours of the soap bubbles occurs because of:

   a. Interference.

   b Diffraction.

   c. Polarization.

   d. Scattering.

3. The reason of bright and dark fringes in Young's double slit experiment is:

   a. Diffraction and interference of light waves together

   b. Diffraction of light only

   c. Interference of light only

   d. Using two sources of light which are not coherent

4. When a green light is used in diffraction grating, the central fringe appears:

   a. Yellow.

   b. Red.

   c. Green.

   d. White.

5. Light diffraction angle increases with:
   a. Decrease of wavelength for the used light.
   b. Increase of wavelength for the used light.
   c. Constant wavelength for the used light.
   d. All of the above.
6. If the optical path difference between two optical waves which are coherent and overlapped equals odd numbers of half wavelength, then the following will happen:
   a. Constructive Interference.
   b. Scattering.
   c. Polarization.
   d. Destructive Interference.
7. To get permanent interference in light waves, their sources must be:
   a. Coherent.
   b. Incoherent.
   c.Two laser sources.
   d. All above the cases.
8. In Young's double slit experiment the first bright fringe occurs on both sides of bright central fringe which has been formed on the screen, when the difference of optical path equals:
   a. $\frac{1}{2}\lambda$.
   b. $\lambda$.
   c. $2\lambda$.
   d. $3\lambda$.
9. The pattren of interference is generated when the following happens:
   a. Reflection.
   b. Refraction.
   c. Diffraction.
   d. Polarization.
10. The thin oil films and the soap bubbles appear shiny coloured as a result of reflection and:
   a. Refraction.
   b. Interference.
   c. Diffraction.
   d. Polarization

11. The property of the generated spectrum by diffraction grating will be

a. Bright lines very clear.

b. Expanded bright lines.

c. Non-existence of bright lines.

d. Non-existence of dark lines.

12. The unpolarized light ray which electric fields oscillates:

a. In one plane.

b. In all direction.

c. which cannot transmitted through plorized plate.

d. In spacific direction.

13. The longitudinal waves cannot show:

a. Refraction.

b. Reflection.

c. Diffraction.

d. Polarization.

14. The sky is blue because;

a. Particle of air is blue.

b. The lens of eye is blue.

c. The light scattering would be more ideal for the short wavelength.

d. The light scattering would be more ideal for the long wavelength.

15. Young's double slits are lighted green, wavelength ($5 \times 10^{-7} m$), the distance between the slits is (1mm) and the distance of the screen from the slits is (2m). The distance between the centers of two bright fringe on the screen equals

a. 0.1 mm.

b. 0.25 mm.

c. 0.4 mm.

d. 1 mm

**Q2** Is it possible for the light from source which are incoherent to interfere? Is there any difference between coherent and incoherent sources?

**Q3** Two sources of light situated and they are side to side. The light waves are projected on a screen. Why dose not the interference pattern appear from the superposition of light waves from them on the screen?

**Q4** When Young's experiment is carried out under the surface of the water, how would interference pattern be affected?

**Q5** What is the condition applied in the difference in optical path between two interfered coherent waves in case of:

a. Constructive interference.

b. Destructive interference.

**Q6** An astronaut on surface of moon see sky as black and see star clear during the daylight. At the same time a man on the surface of earth see the sky blue and cannot see stars. Explain why?

**Q7** What happens to central bright fringe in one slit diffraction, if the width of the slit is reduced.

## Problems of chapter 5

**P.1.** A screen is placed at a distance of (4.5 m) from the barrier with two slits. The slits are lightened with monochromatic light with wavelength in the air ($\lambda = 490\text{nm}$). Fring spacing between the center of bright fringe and bright fringe with order (m=1) equals (4.5cm). Find the distance between two slits.

**P.2.** White light is distributed to its components by diffraction grating method. If grating has (2000 line/cm), find the angle of the first order for the red light with wavelength ($\lambda = 640$ nm). If you know $\sin 7.5^\circ = 0.128$.

**P.3.** A beam of light projected with different angles on reflective surface. Reflected ray becomes totally polarized when the angle of incidence is $48^\circ$. Calculate the refractive index of media. $\tan 48^\circ = 1.110$.

**P.4.** If the critical angle of the light rays for the blue agate meterial surrounded by air is ($34.4^\circ$). Calculate the polarization angle of the light rays for this material, note that $\sin 34.4^\circ = 0.565$ , $\tan 60.5^\circ = 1.77$.

CHAPTER

6

# Modern Physics

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6-1 Introduction.

6-2 Quantum theory (Blackbody radiation and Planck's hypothesis).

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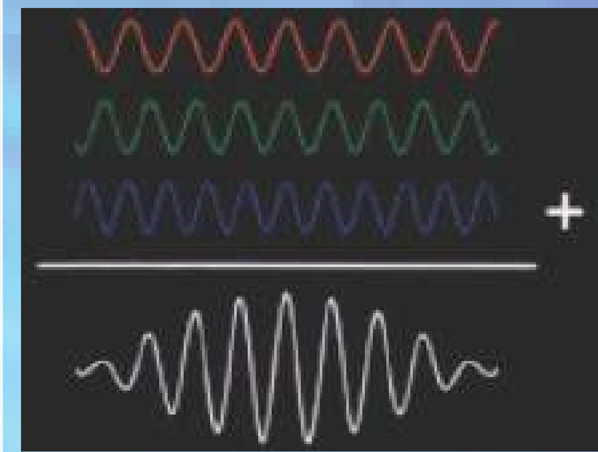
6-4 Particles and waves.

6-5 Matter waves.

6-6 An access to the understanding of quantum mechanics and wave function.

6-7 Heisenberg Uncertainty Principle.



## Behavioural targets

**After studying this chapter, the student should be able to:**

- Explain the concept of the blackbody.
- Mention Planck's proposition (hypothesis) for quantum energy.
- Outline the benefits of some photocell applications.
- Define the concept of the work function and the threshold frequency of the metal.
- Realize the behavior of the particles like waves.
- Realize the behavior of the waves as the particles.
- Mention the relation between the momentum of a photon and its wavelength.
- Explain de Broglie's hypothesis.
- Illustrate the wave function.
- Mention the uncertainty principle.
- Solve the problems by applying mathematical relations in this chapter.

| Scientific Terms | |
|---|---|
| modern physics | الفيزياء الحديثة |
| classical mechanics | الميكانيك الكلاسيكي (التقليدي) |
| quantum mechanics | الميكانيك الكمي |
| photoelectrons | الالكترونات الضوئية |
| stopping potential | جهد الايقاف (القطع) |
| threshold frequency | تردد العتبة |
| photocell | خلية كهروضوئية |
| quantized | مكماة |
| wave function | دالة الموجة |
| probability | احتمالية |
| matter waves | موجات مادية |
| wave properties | خواص موجية |
| particle properties | خواص جسيمية (دقائقية) |
| dual behavior | سلوك ثنائي |
| threshold wavelength | طول موجة العتبة |
| macroscopic world | العالم البصري (المرئي) |
| microscopic world | العالم المجهري (غير المرئي) |
| wave packet | رزمة (مجموعة) موجية |
| work function | دالة الشغل |

## 6-1 Introduction

At the beginning of the twentieth century, radical changes took place in physics science, as many new practical experiments led to results that do not obey the expectations of classical (traditional) laws. Among these experiments are the experiment of black-body radiation and the photoelectric effect. In order to explain the blackbody radiation, the scientist Planck presented the basic ideas that led to the formulation of the quantum theory, and the scientist Einstein assumed that light behaves like particles as well as like waves, and in order to explain the distinctive new observations, a new concept arose that we call modern physics.

## 6-2 Quantum theory (Blackbody radiation and planck's hypothesis)

It is known that all bodies emit thermal radiation in the form of electromagnetic waves to the surrounding medium, and they also absorb thermal radiation from this medium. At the end of the nineteenth century it became clear that the classical theory of thermal radiation had became inappropriate. Why?

The main and basic problem was in explaining or understanding the wavelengths distribution of radiation from the blackbody, so what is meant by the blackbody and how can we represent it practically? The blackbody is an ideal system that absorbs all the radiation falling on it (it is also a perfect radiator when it is a source of radiation) and as a good approximation we can represent the blackbody as a process with a narrow hole inside a gap (or a hollow body). Note Figure (1) that the nature of the rays emitted from the narrow aperture that Lead to the gap has been found to depend only on the absolute temperature of the walls of the gap. Here, the following question may come to your mind, how does the energy distribution of blackbody radiation change with wavelength and absolute temperature?

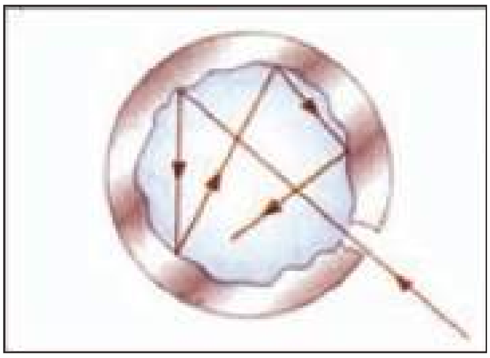


Figure (1)

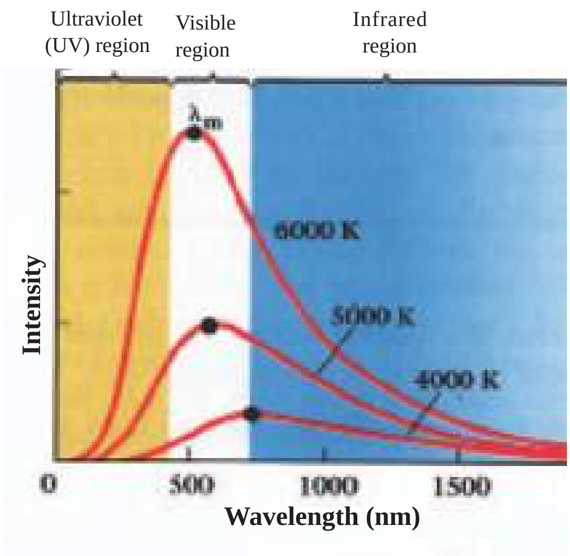



Figure (2)

Figure (2) shows the practical results of the distribution of blackbody radiation energy as a function of wavelength and for different absolute temperatures. We can notice from Figure (2) what follows:

1. The time rate of energy radiated by a blackbody per unit area (intensity) is directly proportional to the area under the curve, as it was found that this area is directly proportional to the fourth power of the absolute temperature (other than absolute zero) for black bodies and is expressed in the Stefan - Boltzmann law, which is given according to the following relation:

$$I = \sigma T^4$$

Since:

I: represents the intensity of radiation in unit ($\frac{W}{m^2}$).

T: represents the absolute temperature in kelvin units (K).

$\sigma$ : represents the Stefan - Boltzmann constant

$$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$$

**DO you know?**

Molten steel radiates energy at high rates, and it is an example of the Stefan-Boltzmann low of radiation.

2. The wavelength distribution peak of the radiation emitted from the blackbody shifts towards the shorter wavelength, when the absolute temperature rises (inverse proportion), it is called the Wein Displacement Law, and it is given according to the following relation:

$$\lambda_m T = 2.898 \times 10^{-3}$$

Since ($\lambda_m$) is the wavelength corresponding to the peak of the curve and is measured in meters unit (m), (T) the absolute temperature of the radiating body and is measured in kelvin unit (K).

Several attempts have been made according to the laws of classical physics to study and interpret the electromagnetic spectrum emitted from the blackbody as a function of length and at a certain temperature, but all failed, because classical physics assumed that the energy emitted was continuous quantities.

This failure led the scientist Max Planck in (1900) to propose (assumed) that a blackbody can radiate and absorb energy in specific and independent quanta of energy known as photons. This means that energy is quantized, giving the energy of the photon (E) according to the relation as:

$$E = hf$$

(f) is the frequency of the photon. (h) is Planck's constant and its value is ($6.63 \times 10^{-34}$ J.s).

**Example (1)**

Find the wavelength corresponding to the peak radiation emitted by the human body when the skin temperature is ($35^0$C). Suppose the human body radiates as a blackbody.

**The solution:** From the relation:

$$\lambda_m T = 2.898 \times 10^{-3}$$

$$\therefore \lambda_m = \frac{2.898 \times 10^{-3}}{T}$$

$$\therefore T = 35 + 273 = 308\,(K)$$

By substituting in the aforementioned relation, we obtain:

$$\therefore \lambda_m = \frac{2.898 \times 10^{-3}}{308}$$

$$\therefore \lambda_m = 9.409 \times 10^{-6}(m) = 9.409\,(\mu m)$$

the wavelength corresponding to the peak radiation emitted from the human body.

## 6-3 The photoelectric effect

In the last half of the nineteenth century, experiments showed that the incident light (with a certain effective frequency) the surfaces of certain metals causes the emission of electrons from those surfaces, note in figure (3). This is known as the photoelectric effect, and the emitted electrons are called photoelectrons. The scientist Hertz was the first to notice this phenomenon practically in (1887).

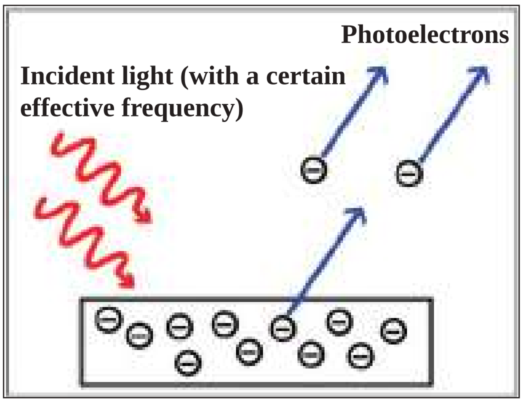


Figure (3)

To explain the photoelectric effect, a photocell is used note figure (4), which is a vacuum tube of air with a transparent window (or a cover) of glass , or quartz (so that ultraviolet rays passes in addition to visible light) and contain a metal plate (E) called the electron emitting plate or cathode, which is connected to the negative pole.

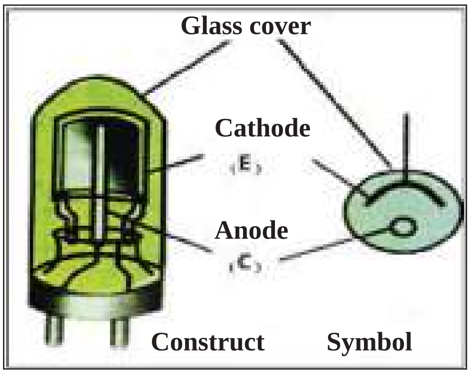


Figure (4)

For a direct voltage source (whose voltage can be changed) and another metal plate (C) called the collector plate or (anode) that receives the emitted photoelectrons and is connected to the positive pole of the voltage source. To study of the photoelectric effect practically we conduct the following activity:

## Activity

### The photoelectric effect

**Tools of activity:**

Photocell, Voltmeter (V), Ammeter (A), Continuous voltage source whose voltage can be changed, Conductor Wires, Light Source.

**Activity steps:**

- We connect the electrical circuit as in figure (5).
- When placing the tube in the dark, we notice that the ammeter reading is equal to zero, meaning that no current passes in the electrical circuit.
- When lighting the electron-emitting plate by light with an effective frequency, we notice the deviation of the ammeter pointer, indicating the passage of an electric current in the electrical circuit. This current appears as a result of the emission of photoelectrons from the emitter plate (negative) to be received by the collector plate (positive), so the photoelectric current flows into the electrical circuit.

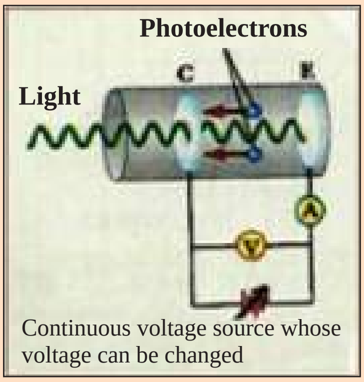


Figure (5)

- When increasing the positive voltage of the collector plate [that is, by increasing the potential difference ($\Delta V$) between the collector and emitter plates], we notice the increase in the photoelectric current until it reaches its maximum constant amount, and thus the time rate of the photoelectrons emitted from the emitter plate and coming to the collector plate is a constant amount, so the current flowing in the electric circuit in this case is called saturation current.

Here, you may ask:

First: What happens when the intensity of the incident light increases (for a certain effective frequency)?

Second: What happens if the polarity of the source voltage is reversed, that is, if the emitter plate is positive and the collector plate is negative and ($\Delta V$) is negative?

Third: What happens when you increase the Negativity voltage of the collector plate gradually?

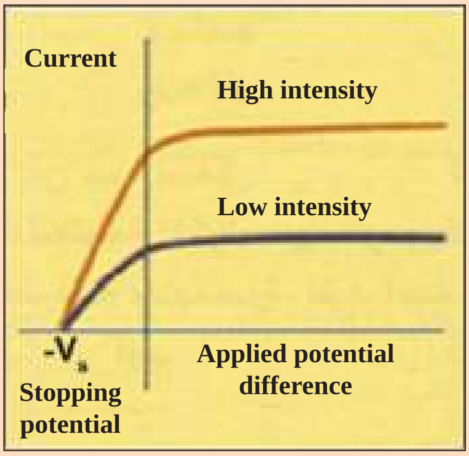


Figure (6)

To answer these questions, note figure (6).

First: When increasing the intensity of the incident light (for a certain effective frequency), we notice an increase in the saturation current, for example when the intensity of the incident light is doubled for a certain effective frequency, the saturation current doubles again.

Second: In the case of reversing the polarity of the voltage source, i.e. when the emitter plate is positive and the collector plate is negative and ($\Delta V$) negative, then in this case the current gradually drops to lower values because most of the photoelectrons will now repel the negative collector plate, and only the photoelectrons will arrive which has an energy greater than the value ($e\Delta V$) to the collector plate, since (e) is the charge of the electron.

Third: When increase the Negativity voltage of the collector plate gradually and at a certain voltage value ($V_s$), that is, when ($\Delta V = -V_s$) we notice that the circuit current is equal to zero. This voltage ($V_s$), is called the stopping potential. It can be seen experimentally that the stopping potential does not depend on the intensity of the incident light.

The stopping potential is a measurments of maximum kinetic energy of the emitted photoelectrons $(KE)_{max}$ so:

$$(KE)_{max} = \frac{1}{2} m v_{max}^2 = eV_s$$

Where (m) is the electron mass, (e) is the charge of the electron and ($v_{max}$) is the maximum speed of the emitted photoelectrons.The experience of the photoelectric effect revealed some facts that could not be explained by the classical physics (the wave theory of light) is:

1. Photoelectrons do not emit if the frequency of the incident light is less than a certain frequency called the threshold frequency ($f_0$), which is the minimum frequency that generates the photoelectric emission for that metal, and it is also a characteristic of the illuminated metal, as each metal has a threshold frequency of its own, this fact does not agree with the wave theory, which predicts that the photoelectric effect occurs at all frequencies, provided that the intensity of the incident light is high.
2. The maximum kinetic energy of the emitted photoelectrons $(KE)_{max}$, does not depend on the intensity of the incident light, but according to the wave theory, the light of high intensity carries more energy to the metal per second and therefore the photoelectrons emitted will have more kinetic energy.

**DO you know?**

The spacecraft can be affected by the photoelectric effect, as ultraviolet rays cause spacecraft to charge with a positive charge, and this positive charge is discharged when the spacecraft lands on the surface of the earth.

3. The maximum kinetic energy of the emitted photoelectrons increases with the increasing frequency of the incident light. While the wave theory Principle predicts that there is no relation between the energy of the emitted photoelectrons and the frequency of the incident light.
4. The photoelectrons are emitted from the metal surface instantaneously [in less than ($10^{-9}$s) after lighting the surface], even if the intensity of the incident light is low. But according to the wave theory, the photoelectrons need some time to absorb the incident light until they acquire sufficient kinetic energy to escape from the metal.

You may be wondering who is the scientist who was able to provide a successful interpretation of the photoelectric effect? In the year 1905, the scientist Einstein presented a successful interpretation of the photoelectric effect. He relied in his interpretation on Planck's principle, which is that electromagnetic waves are quantized. He suggested that light is a stream of photons, and each photon has energy (E), given according to the following relation:

$$E=hf$$

Since (h) is Planck's constant and (f) is the frequency of the incident light (the frequency of the photon), and the frequency of the photon is given according to the relation:

$$f = \frac{c}{\lambda}$$

Since (c) is the speed of light in a vacuum and ($\lambda$) is the wavelength of light, and according to Einstein's interpretation of the photoelectric effect, the maximum kinetic energy of the photoelectrons emitted by $(KE)_{max}$, note Figure (7), is given according to the following relation:

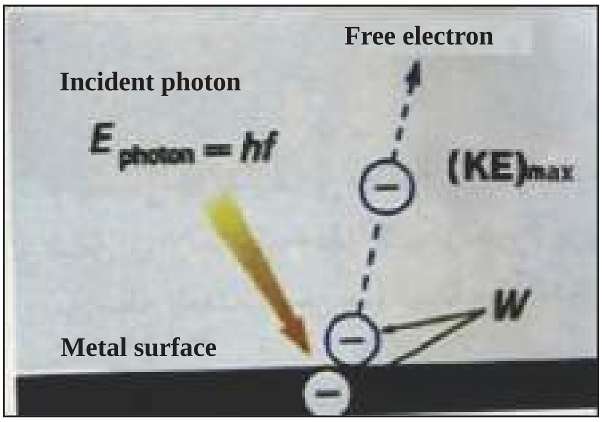


Figure (7)

$$(KE)_{max} = \frac{1}{2}mv^2_{max} = hf - w$$

Einstein's photoelectric equation

Since (hf) represents the energy of the incident light and (w) represents the work function of the metal, it is the lowest energy that electron bound with the metal and is given by the relation:

$$w = hf_o$$

and its value is within a few (eV) wheres ($1eV = 1.6 \times 10^{-19}$ J). Table (6-1) shows the work function of various metals

Table (6-1)
work functions for various metals

| Metal | Work function (eV) |
|---|---|
| Silver | 4.73 |
| Aluminum | 4.08 |
| Copper | 4.70 |
| Iron | 4.50 |
| Sodium | 2.46 |
| Lead | 4.14 |
| Platinum | 6.35 |
| Zinc | 4.31 |

And it may come to our minds how the scientist Einstein was able to explain the photoelectric effect, which classical physics could not explain? He was able to explain this according to the aforementioned photoelectric equation, based on Planck's quantum theory, as follows:

1. The photoelectric effect does not occur if the incident light's frequency is less than the threshold frequency ($f_0$). In order for this phenomenon to occur, the energy of the incident photon must be greater than or equal to the work function (w). The photoelectron is released or emitted by the absorption of one photon. If the energy of the incident photon does not satisfy this condition, the photoelectrons do not emit or completely liberate from the surface of the metal, regardless of the intensity of the incident light, this fact supports the existence of the threshold frequency, and in the case that the energy of the incident photon is equal to the work function of the metal (or the frequency of the incident light equals the threshold frequency of the metal), so only the photoelectrons are released from the metal surface without gaining kinetic energy.

2. From the relation:

$$(KE)_{max} = hf - w$$

it can be seen that maximum kinetic energy of the emitted photoelectrons $(KE)_{max}$ depends only on the incident light frequency and the work function (or threshold frequency) of the metal and does not depend on the incident light intensity because the absorption of one photon is responsible for the change in the kinetic energy of the electron.

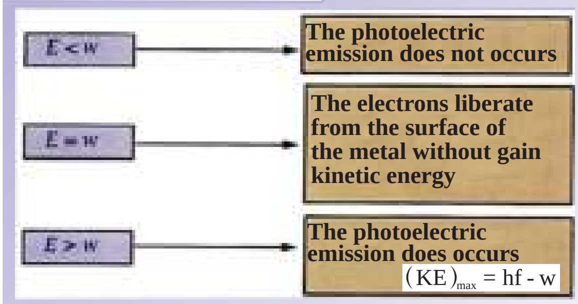
3. Since the relation between $(KE)_{max}$ and (f) is a linear relation according to the relation:

$$(KE)_{max} = hf - w$$

since it is noticed from the aforementioned relation that $(KE)_{max}$ is linearly proportional to the frequency of the incident light (f), thus Now you can easily understand why $(KE)_{max}$ increases with increase (f).

4. The photoelectrons are emitted from the surface of the metal instantaneously, regardless of the intensity of the incident light. From the practical results that showed the linear relation between the maximum kinetic energy of the emitted photoelectrons $(KE)_{max}$ and the frequency of the incident light (f) are shown in

**Remember:**




**E: Energy of the incident photon.**
**w: work function of the metal.**

**Think?**

Three different metals (a,b,c) projecting on each one a light of frequency ($0.85 \times 10^{15}$ Hz). If the threshold frequency for each of them, respectively, is:

a. $1.14 \times 10^{15}$ (Hz)
b. $0.59 \times 10^{15}$ (Hz)
c. $1.53 \times 10^{15}$ (Hz)

For which of the three metals do the photoelectric effect get? Why?

Figure (8). The intersection of the straight line in figure (8) with X-axis (that is, when $(KE)_{max} = 0$), it represents the value of the threshold frequency ($f_0$). At frequencies below ($f_0$), no photoelectrons are emitted, regardless of the intensity of the incident light, and the slope of the straight line represents the value of Planck's constant (h). If a straight line is extended and the Y-axis cut at a point like (z), then the negative section of the Y-axis represents the value of the work function of the metal, note Figure (8).

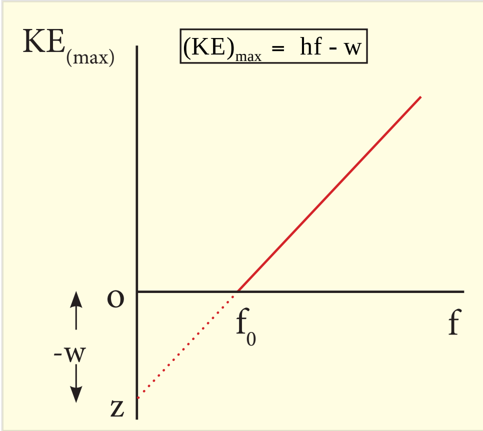


Figure (8)

The threshold wavelength ($\lambda_0$) can also be defined as the longest wavelength that can release photoelectrons from the surface of a particular metal, and it is given by the following relation:

$$\lambda_0 = \frac{c}{f_0} = \frac{hc}{w}$$

The wavelengths longer than ($\lambda_0$) and falling on a metal have a work function (w) that does not lead to the emission of photoelectrons.


Figure (9)

## Applications of the photoelectric effect:

There are many devices used in our daily life that depend on the photoelectric effect, for example the photocell, by means of which we can measure the intensity of light and convert light energy into electrical energy, as in the solar cells used for street lighting, for example, see figure (9). The photoelectric effect is also invested in digital imaging cameras, note figure (10), as well as in showing the recording of music accompanying the cartoon films and other practical applications.


Figure (10)

**Example (2)**

The light of wavelength (300nm) fell on the sodium metal. If the work function for sodium is equal to (2.46eV) find:

a. The maximum kinetic energy of the emitted photoelectrons in joules units (J) firstly then in electron-volts units, (eV) secondly.

b. Threshold wavelength of sodium.

knowing that Planck's constant is equal to $(6.63 \times 10^{-34}(J.s))$, $(1(eV) = 1.6 \times 10^{-19}(J))$ and the speed of light in a vacuum $(c) = 3 \times 10^{8}(m/s)$.

**The solution:**

a. From the relation:

$$(KE)_{max} = hf - w$$

We have the relation:

$$f = \frac{c}{\lambda}$$

From the two previous relations, we obtain:

$$(KE)_{max} = \frac{hc}{\lambda} - w$$

By substituting in the previous relation, we obtain:

$$(KE)_{max} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{300 \times 10^{-9}} - 2.46 \times 1.6 \times 10^{-19}$$

$$(KE)_{max} = 6.63 \times 10^{-19} - 3.936 \times 10^{-19}$$

$$\therefore (KE)_{max} = 2.694 \times 10^{-19}(J)$$

The maximum kinetic energy of the photoelectrons emitted in units of joules.

$$(KE)_{max} = \frac{2.694 \times 10^{-19}}{1.6 \times 10^{-19}} = 1.684(eV)$$

The maximum kinetic energy of the photoelectrons emitted in units of (eV).

b. From the relation:

$$\lambda_0 = \frac{hc}{w}$$

By substituting the previous relation we obtain:

$$\therefore \lambda_0 = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{2.46 \times 1.6 \times 10^{-19}}$$

$$\therefore \lambda_0 = 5.053 \times 10^{-7}(m) = 505.3(nm)$$

Threshold wavelength of sodium

## 6-4 Particles and waves

The photoelectric, the radiation and absorption phenomena are indicates that light behaves like particles (photons), and there are other phenomena such as interference, diffraction and polarization that show that light behaves like waves. Here, the following question arises: Which of the two behaviors is correct? Does light behave like particles or behave like waves? In fact, the answer to this question depends on the phenomenon that is being studied. Some experiments can be explained when the light behavior like particles, that is, the light shows a particle characteristic, and others can be explained when the light behavior like waves, meaning that the light shows a wave characteristic.

Light, which can eject electrons from metals, as in the photoelectric effect, meaning that light behaves like particles, the same light can diffract, meaning that light behaves like waves. On this basis, the modern view of the light nature takes the dual behavior, that is, the radiation energy is transmitted in the form of photons led by a wave field, from here it must be emphasized that in a particular case or circumstance the light appears either in the particle or the wave characteristic, but not both at the same time, that is, the particle theory of light and the wave theory of light complement each other.

Here the following question appears, how can mathematically explain the dual behavior of the photon?

The energy of the photon (E) is given according to the relation:

$$E=hf$$

According to Einstein's equation in mass (m) equivalent with energy (E) (which will be studied in a later). The energy (E) is given according to the relation:

$$E = mc^2$$

As (c) is the speed of light in a vacuum. From the two previous relations, we can get:

$$m = \frac{hf}{c^2}$$

The previous relation shows that the photon behaves as it had (a mass). The momentum of the photon (p) is given by the relation:

$$p = mc$$

The frequency of the photon (f) is related to the wavelength associated with the photon ($\lambda$) by the relation:

$$f = \frac{c}{\lambda}$$

By substituting the aforementioned relation of the photon as if it had mass (m), obtain:

$$\lambda = \frac{h}{mc}$$

or

$$\lambda = \frac{h}{p}$$

That is, the wavelength associated with a photon is inversely proportional to the momentum of the photon. It can also be demonstrated that the energy of the photon (E) is given according to the relation:

$$E = \frac{hc}{\lambda}$$

## 6-5 Matter waves

We previously observed that light have dual behaves as particle and wave. The question now is: Do particles also have dual behaves also? And the answer to this question was given by the scientist Louis de Broglie. In (1923) de Broglie proposed the idea of the dual nature of the particle (particle - wave). de Broglie assumed the following hypothesis:

(In every mechanical system that there must be waves that associated (accompanied) the motion of matter particles).

This idea that the scientist came up with is a colossal and unprecedented idea, and at that time there was no practical evidence or confirmation of it. According to de Broglie's hypothesis, particles matter such as electrons are like the light that have a duality or duality nature, that is, they behave like a particle and a wave behaviors. Thus, the electron is associated by a wave, this wave is not a mechanical wave or an electromagnetic wave, but what type of associated (accompanied) waves the movement of a particle such as an electron?

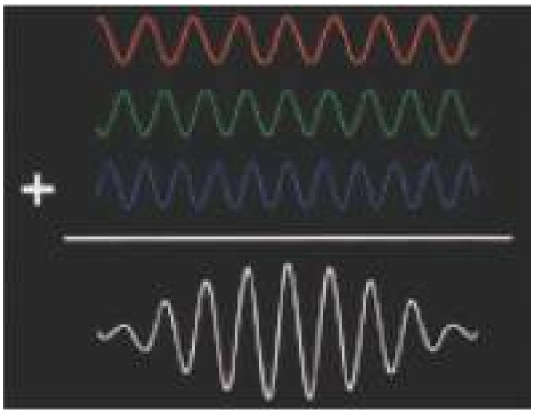


Figure (11)

The associated waves of a particle movement are another new type waves called matter waves, as the particle is represented by a wave packet, i.e a wave with a limited range in space, and the wave packet can be obtained by adding waves of slightly different wavelengths, see figure (11).

de Broglie assumed that the wavelength of the matter wave ( $\lambda$ ) is related to the momentum of the particle (p), as it is in the case of the photon, according to the relation:

$$\lambda = \frac{h}{p}$$

since (h) is Planck's constant, if a particle has mass (m) is moving with speed amounts (v) then the de Broglie wavelength associated with the particle is given according to the relation:

$$\lambda = \frac{h}{mv}$$

When looking closely at the aforementioned relation, the duality characteristic of matter becomes clear to us, as the right side of the relation contains the concept of particle [mass (m) or momentum (mv)] while the left side of the equation contains the concept of wave [wavelength ( $\lambda$ )]. In fact, the wavelength associated with normal objects in our daily life, that is ,visible , macroscopic world (such as moving football, moving cars, etc.) is so small that its wave behavior such as interference and diffraction cannot be noticed, because as well as the small value of Planck's constant, its mass is relatively large (or its momentum is relatively large) and thus the associated de Broglie wavelength is very small because the relation is inverse proportion, note Figure (12), since ( $\lambda = \frac{h}{mv}$ ) makes the wave properties of relatively large bodies neglected, But it becomes clear when studying the wave properties of atomic and nuclear particles (with very small masses and relatively small momentum) that is, in the (invisible) microscopic world, such as electrons, protons and neutrons, since the associated de Broglie wavelength these particles can be

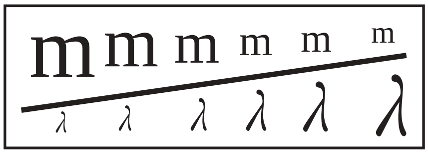


Figure (12)

**DO you know?**

The electron microscope is one of the practical devices that depends on the wave properties of the electrons, it is distinguished with greater resolving power from the regular light microscope , which can distinguish details about (1000) times smaller than those details that are distinguish by a light microscope because the wavelength of the used electron is shorter than the wavelength of visible light.

measure and study it. Figure (13) shows a model for the wave behavior of electrons (electron diffraction). It is worth noting that, as is the case with light, the two particle and wave behaviors of moving objects cannot be observed at the same time. It is useful to show here that de Broglie's equation applies to all objects in the universe, from the smallest, such as the electron, to the large, such as the planets.

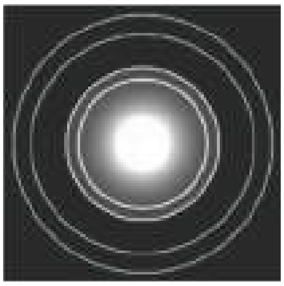


Figure (13)

**Example (3)**

Find the de Broglie wavelength associated with a ball of mass (0.221kg) moving with a speed amount of (3m/s), given that Planck's constant is equal to $(6.63 \times 10^{-34} (J.s))$

**The solution:**

According to the following relation: $\lambda = \frac{h}{mv}$

By substitution in the aforementioned relation we obtain:

$$\lambda = \frac{6.63 \times 10^{-34}}{0.221 \times 3} = 10^{-33} (m)$$

The de Broglie wavelength associated the ball.

**Example (4)**

Find the de Broglie wavelength associated with an electron moving by speed amount of $(6 \times 10^{6} m/s)$, knowing that the mass of the electron is equal to $(9.11 \times 10^{-31} kg)$ and Planck's constant is equal to $6.63 \times 10^{-34} (J.s)$.

**The solution:**

According to the following relation:

$$\lambda = \frac{h}{mv}$$

By substitution the previous relation we get:

$$\lambda = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 6 \times 10^{6}}$$

$$\therefore \lambda = 0.121 \times 10^{-9} (m)$$

which is the de Broglie wavelength associated the electron.

## 6-6 An access to the understanding of quantum mechanics and wave function

When using a computer, a digital camera, and personal laptop, did you know that all these devices and many more other work according to mechanical laws called quantum mechanics, what is the meaning of quantum mechanics?, in general "It is a branch of physics specified to studying the motion of objects they come in tiny bundles or quanta".

In fact, the involved quantities that studied by quantum mechanics are probabilities rather than the asserting as it is found in classical mechanics.

For example, according to classical mechanics, the Bohr radius of a hydrogen atom is equal to (0.0529nm). While this value, according to quantum mechanics, is represents by the most probable radius (probability). From experiments, it was found that Bohr radius is greater or less than this value, but the most probability value that found equal to (0.0529 nm).

Then, the shape of the atom according to classical mechanics, see figure (14) it differs from the shape of the atom according to quantum mechanics. see figure (15).

It is important to explain here that classical mechanics is only an approximate formula for quantum mechanics.

But what quantity is concerned with studying quantum mechanics? This quantity is called the wave function, which you will now know about.

**DO you know?**

The Schrodinger equation is the basic equation in quantum mechanics, as the equation of Newton's second law of motion is the basic equation in classical mechanics in the form of physics.

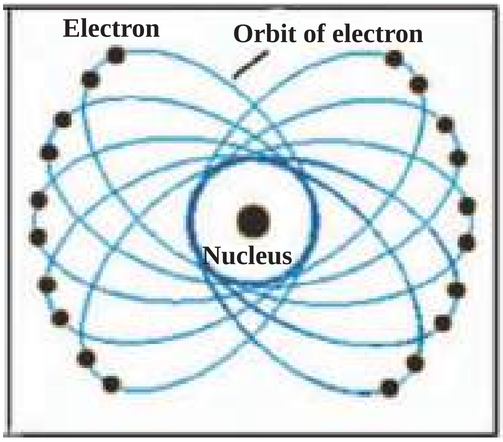



Figure (14): The shape of the atom according to classical mechanics

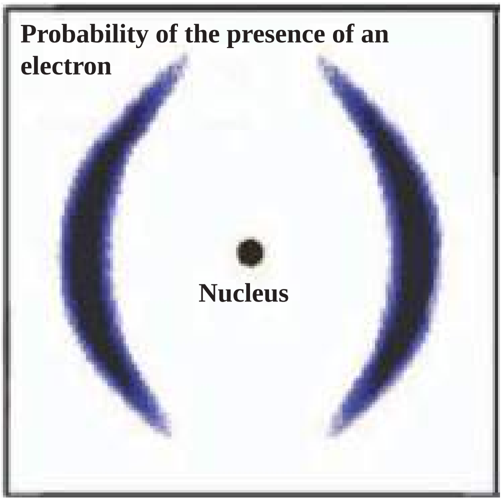



Figure (15): the shape of the atom according to quantum mechanics

### Wave function:

It is known that periodically varying quantity in water waves is the height of the water surface, in sound waves is its pressure, and in light waves is the electric field and magnetic field, but what is the varying quantity in the case of matter waves? Varying quantity from matter waves is called the wave function and is usually denoted by the symbol ($\psi$), read as (psi). Figure (16) illustrate an example of wave function ($\psi$) change with the X-axis. A wave function is a mathematical formula, as the value of the associated wave function of a moving particle in a certain position in space and for a certain time is related to the probability of finding the particle in that position and time. Since the probability density (i.e. the probability per unit volume) is to find the particle that is described by the wave function ($\psi$) in a specific position space and at a specific time. It is directly proportional to the value of $|\psi|^2$ at that particular position and time. Figure (17) shows an example of the wave function ($\psi$) and the probability density $|\psi|^2$ of a particle.

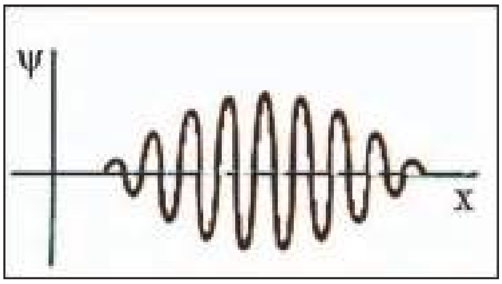


Figure (16)

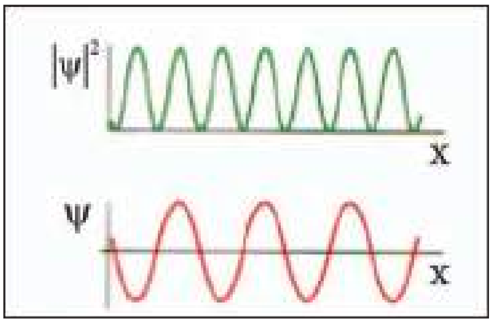


Figure (17)

If the amount of $|\Psi|^2$ is great, probability of particle's existence at same position and the same time is great. In fact, $|\Psi|^2$ is small, probability of particle's existence at same position and the same time is weak. However, the value of $|\Psi|^2$ can not be zero at anywhere, that means there is probability for particle's existence at same position and same time. This is firstly expalined by Born in 1927.

## 6-7 Heisenberg uncertainty principle

If you were to measure the position and speed of a particle at any instant, you would always be faced with experimental uncertainties in your measurements. According to classical mechanics, it's possible, in principle, to make such measurements with arbitrarily small uncertainty. However this is not possible. In 1927 Heisenberg introduced this notion, which is now known as the uncertainty principle.

**DO you know?**

There is another formula for the uncertainty principle, which links the uncertainty of particle energy ($\Delta E$) and the uncertainty of time taken to measure the energy ($\Delta t$), which is expressed in the relation:

$$\Delta E \, \Delta t \geq \frac{h}{4\pi}$$

Which can be defined as "It is impossible to measure instantaneously (at the same time) the exact position and linear momentum of a particle". If the uncertainty in measuring the particle's position is ($\Delta x$) and the uncertainty in measuring the particle's momentum is ($\Delta p$), then the principle of uncertainty is given by the following relation:

$$\Delta x \, \Delta p \geq \frac{h}{4\pi}$$

Since (h) represents Planck's constant. In our study, it is meant by ($\Delta x$) is the uncertainty of position component in the x-axis direction and ($\Delta p$) is the uncertainty of linear momentum component in the x-axis direction.

As can be seen from uncertainty principle, the smaller value of ($\Delta x$), the greater value of ($\Delta p$), and vice versa, that is, whenever the value of ($\Delta x$) is large, value of ($\Delta p$) is small. The higher measuring accuracy of either of these two quantities, the less we know about the other quantity, see figure (18). Also the uncertainty of ($\Delta x$) can be considered as the error in the position of the particle and the uncertainty of ($\Delta p$) considered as the error in the linear momentum of the particle.

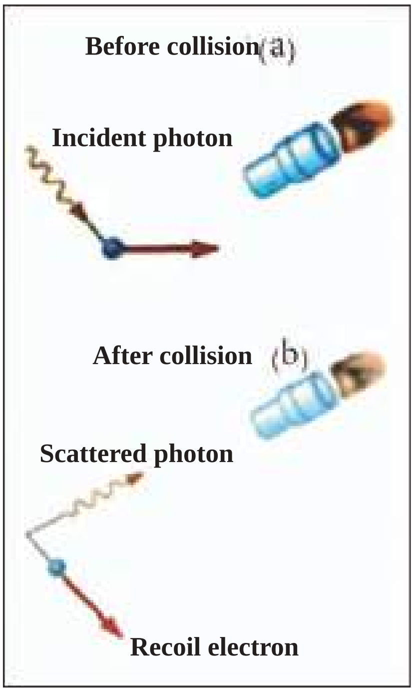



Figure (18) An idea of an experiment to see an electron using a powerful optical microscope. (a) The electron moves to the right before the collision with the photon. (b) A recoil of electron (changes its momentum) is as a result of the collision with the photon.

As you known, the momentum of a particle (p) is given by the relation:

$$p = mv$$

since (m) is the mass of the particle and (v) is the speed of the particle. The uncertainty momentum of a particle ($\Delta p$) is given by the relation:

$$\Delta p = m \, \Delta v$$

since ($\Delta v$) is the uncertainty in the particle's speed (or the error in the particle's speed).

so when we can get the lowest (minimum) uncertainty for either one of the two quantities ($\Delta x$) or ($\Delta p$) in the uncertainty principle relation?

The answer is that by Multiplying these two quantities which equal to ($\frac{h}{4\pi}$) i.e.

$$\Delta x \, \Delta p = \frac{h}{4\pi}$$

It is worth noting that the uncertainty principle , which sets limits for the accuracy of measuring the position and momentum of a particle in the same time, which are limits resulting from the devices used or methods of measurement, these limits are basic limits imposed by nature, and there is no way to overcome them. Finally we must show that it is because of the very small value of Planck's constant, this explains why we do not observe the uncertainty principle in our daily life and our everyday observations, that is, in the macroscopic world.

**Example (5)**

If the uncertainty in momentum of a ball is ($2 \times 10^{-3} kg\frac{m}{s}$). Calculate uncertainty in its position, Planck's constant is ($6.63 \times 10^{-34} J.s$).

**The solution:**

From the relation:

$$\triangle x \triangle p \geq \frac{h}{4\pi}$$

$$\therefore \triangle x \geq \frac{h}{4\pi \triangle p}$$

By substituting in the previous relation, we obtain:

$$\triangle x \geq \frac{6.63 \times 10^{-34}}{4 \times 3.14 \times 2 \times 10^{-3}}$$

$$\therefore \triangle x \geq 2.639 \times 10^{-32} m$$

The uncertainty in position of a ball

This value is very small and in fact cannot be measured experimentally.

**Example (6)**

The speed of an electron is measured $(6 \times 10^{3} \frac{m}{s})$ .If the error is (0.003%) from its original speed, find minimum uncertainty in the position of this electron. Knowing that the mass of the electron is equal to $(9.11 \times 10^{-31} kg)$ and the Planck's constant is equal to $(6.63 \times 10^{-34} J.s)$.

**The solution:**

The minimum uncertainty is given by the relation:

$$\Delta x \, \Delta p = \frac{h}{4\pi}$$

$$\therefore \Delta x = \frac{h}{4\pi \, \Delta p} .....(1)$$

The uncertainty of momentum is given by the relation:

$$\Delta p = m \, \Delta v.....(2)$$

From the operative of the question, (Δv) is equal to:

$$\Delta v = \frac{0.003}{100} \times 6 \times 10^{3}$$

$$\therefore \Delta v = 0.18 \frac{m}{s}$$

By substitution In relation (2) we get:

$$\Delta p = 9.11 \times 10^{-31} \times 0.18$$

$$\therefore \Delta p = 1.64 \times 10^{-31} kg \frac{m}{s}$$

By substitution In relation (1) we get:

$$\Delta x = \frac{6.63 \times 10^{-34}}{4 \times 3.14 \times 1.64 \times 10^{-31}}$$

$$\therefore \Delta x = 3.219 \times 10^{-4} m$$

The minimum uncertainty in the position of this electron.

**Example (7)**

If the uncertainty of momentum of an electron is $(3.5 \times 10^{-24} \text{kg} \frac{\text{m}}{\text{s}})$. Calculate uncertainty of its position. Given that Planck's constant is equal to $(6.63 \times 10^{-34} \text{J.s})$.

**The solution:**

According to the following relation:

$$\triangle x \triangle p \geq \frac{h}{4\pi}$$

$$\therefore \triangle x \geq \frac{h}{4\pi \triangle p}$$

By substitution in the aforementioned relation, we get:

$$\triangle x \geq \frac{6.63 \times 10^{-34}}{4 \times 3.14 \times 3.5 \times 10^{-24}}$$

$$\therefore \triangle x \geq 1.508 \times 10^{-11} \text{m}$$

the uncertainty of electron position.

# Questions of chapter 6

**Q1** Choose the correct phrase for each of the following:

1. At high absolute temperature, the peak wavelength distribution for the radiation emitted from the blackbody shifts towards:

a. The longest wavelength.
b. The shortest wavelength.
c. The shortest frequency.
d. None of them.

2. The phrase (In every mechanical system that there must be waves that associated (accompanied) the motion of matter particles). This is an expression of:

a. The uncertainty principle of Heisenberg.
b. Blanck's suggestion.
c. Lenz's law.
d. de Broglie hypothesis.

3. Photoelectric effect can be understood on the basis of:

a. Electromagnetic Theory.
b. Light waves Interference.
c. Light waves diffraction.
d. None of them.

4. One of the following phenomena is regarded as one of signs which confirms that the light has a particle behavior:

a. Diffraction.
b. Photoelectric effect.
c. Polarization.
d. Interference.

5. Suppose that the location of a particle is accurately measured, i.e ($\Delta x=0$). Then the smallest inaccuracy in this particle's momentum is given by:

a. $\frac{h}{4\pi}$.
b. $\frac{h}{2\pi}$.
c. Infinity.
d. Zero.

Since (h) is Planck's constant.

6. If de Broglie wavelength associated to a particle with mass (m) is ($\lambda$), then the kinetic energy for the particle equals:

a. $\frac{2mh^2}{\lambda^2}$.
b. $\frac{\lambda^2}{2mh^2}$.
c. $\frac{h}{2m\lambda}$
d. $\frac{h^2}{2m\lambda^2}$.

(h) is Planck's constant.

7. When the intensity of the incident light is doubled with a certain effective frequency in a certain surface metal, one of the following amounts will be doubled:

a. The maximum kinetic energy of the emitted photoelectrons. b. Stopping potential.

c. Photon momentum. d. Saturation current

8. Probability density to find the particle in a certain point and moment is:

a. Directly proportional with $|\Psi|^2$. b. Inversely proportional with $|\Psi|^2$.

c. Directly proportional with $|\Psi|$. d. Inversely proportional with $|\Psi|$.

[Where ($\Psi$) represents the wave function for the particle].

9. If de Broglie wavelength associated with the electron mass (m) moving with the speed of (v) equals ($\lambda$). If the speed is reduced to ($\frac{v}{2}$), the associated de Broglie wavelength will be:

a. $4\lambda$. b. $2\lambda$.

c. $\frac{\lambda}{4}$. d. $\frac{\lambda}{2}$.

10. The phrase (It is impossible to measure instantaneously (at the same time) the exact position and linear momentum of a particle) is an expression for:

a. Faraday's law. b. Wien's displacement law.

c. Stefan-Boltzman law. d. Heisenberg's uncertainty principle.

11. The associated waves for a particle's movement like an electron is:

a. Longitudinal mechanical waves. b. Transverse mechanical waves.

c. Electromagnetic waves. d. Matter waves.

**Q2** What is meant by the blackbody and how we represent it practically?

**Q3** Why did many attempts failed in order to study and explain the electromagnetic spectrum emitted from the blackbody as a wavelength function at a given temperature, according to the laws of classical physics?

**Q4** What is the Planck's proposal concerning the radiation and absorption energy with respect to the blackbody?

**Q5** What is meant by each of the following:

Quantum mechanics, threshold frequency of metal, Work function for the metal.

**Q6** What do the following refer to:

a. High value to $|\Psi|^2$ for a particle in certain place and time.

b. Low value to $|\Psi|^2$ for a particle in certain place and time.

[Where ($\Psi$) the wave function for the particl].

**Q7** Justify: Usually it is preferable to use photocell with its window from made of quartz instead of glass in photoelectric effect experiments.

**Q8** Does light behave like particles or as waves?

**Q9** What is the modern view of the light nature?

**Q10** It is impossible to observe the wave nature of moving ordinary particles in our daily life of the macroscopic world, such as a moving car, why?

**Q11** A light of energy equal to (5eV) fell on an aluminum metal. Photoelectrons light were emitted. When the same light fall on the platinum metal, no photoelectrons are emitted. Explain that if you are given that the work function for the aluminum metal is (4.08eV) and the work function for the Platinum metal is (6.35eV).

**Q12** What is the quantitaty that the quantum mechanics is interested in its studying and what does it mean?

**Q13** Explain why we do not notice the uncertainty principle in our daily life and our normal daily observations in the macroscopic world, for example, football feet moving?

**Q14** When the ultra-violet rays falls on the metal disk of the electroscope with negative charge, we see that the two leaves not saperated first. And as these rays continue to fall on the metal disk the leaves will saperated this time. Explain the reason for that, if you know that the energy for ultra-violet rays which is falls on the disc is greater than the work function for the metal part of the disc.

## Problems of chapter 6

**Hint:**

Planck's constant = $6.63 \times 10^{-34}$ J.s

Electron Mass = $9.11 \times 10^{-31}$ kg

Electron charge = $1.6 \times 10^{-19}$ C

1(eV) = $1.6 \times 10^{-19}$ J

The speed of light in vacuum (c) = $3 \times 10^{8} \frac{m}{s}$

**P.1.** If you know that the wavelength corresponding to the peak emitted radiation by the distant star is (480nm), what is the Temperature of its surface? Consider the star radiates as a blackbody.

**P.2.** Assume that the Planck's constant is now equals to (66 J.s). What will de Broglie wavelength associated with a person has (80kg) mass and running with speed of (1.1m/s)?

**P.3.** A photon wavelength (3nm). Calculate the amount of its momentum?

**P.4.** Light with wavelength of (300nm) falls on a metal surface. If the threshold wavelength for this metal is equal to (500nm). Find the stopping potential in order to stop emitted photoelectron with maximum kinetic energy?

**P.5.** The emitted photoelectrons from a metal surface stops when increases the wavelength of light falling on it with (600nm). If the surface of the metal is lightened by light with wave length of (300nm). What is the maximum kinetic energy in the photoelectrons emit from the surface of the metal measured by the units joules (J) first and the units of the electron – volts (eV) second?

**P.6.** Light of wavelength ($10^{-7}$m) falls on the surface of metal with work function equal to ($1.67 \times 10^{-19}$ J). Then photoelectrons emitted from the surface. Find:

a. The maximum speed for the photoelectrons emitted from the surface of the metal.

b. De Broglie's wavelength associated to the photoelectrons emitted with maximum speed.

**P.7.** A light with frequency of ($0.6 \times 10^{15}$ Hz) falls on the surface of a metal. It is found that The stopping potential of the emitted photoelectrons with maximum kinetic energy is equal to (0.18 V). While another light fell on the surface of the same metal which has ($1.6 \times 10^{15}$ Hz) frequancy, it is found that the stopping potential is equal to (4.324V). Find the value of Planck's constant.

**P.8.** Find the de Broglie's wavelength associated with an electron that is accelerated through potential difference of (100V)?

**P.9.** An electron moves at the speed of (663m/s). Find:

a. De Broglie's wavelength associated to the electron

b. Minimum error in the electron position, if the error in its speed is (0.05% ) of its original speed.

**P.10.** A proton with kinetic energy ($1.6 \times 10^{-13}$ J). If the uncertainty in its momentum is (5%) of its original momentum, what is the minimum uncertainty in its position? Where the mass of the proton is ($1.67 \times 10^{-27}$ kg).

**P.11.** Find the speed of an electron which enables the associated de Broglie's wavelength equals the X- ray wavelength with frequency ($3.25 \times 10^{17}$ Hz).

**P.12.** Suppose the uncertainty in a particles position of mass (m) and its speed (v) is equal to the de Broglie's wavelength associated to it. Prove that:

$$\frac{\Delta v}{v} \geq \frac{1}{4\pi}$$

Where ($\Delta$v) is the uncertainty in the particle's speed.

# CHAPTER 7

# Solid-State Electronics

Contents


7-1 Introduction.

7-2 Electronic orbits and energy levels.

7-3 Conductors, insulators and semiconductors.

7-4 Energy bands in solid materials.

7-5 Intrinsic semiconductors.

7-6 Extrinsic semiconductors.

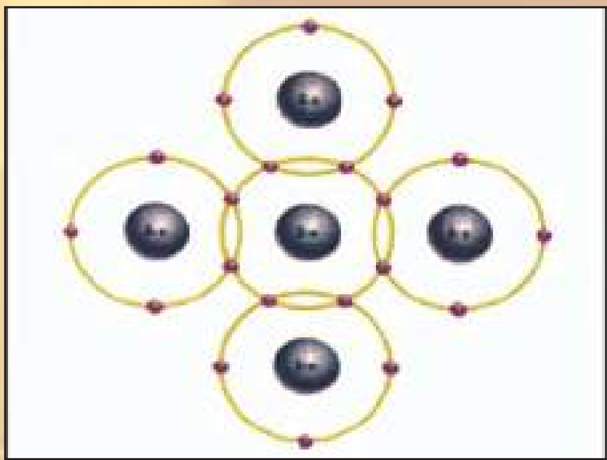
7-7 PN diode.

7-8 Biasing potential for PN-diode.

7-9 Some types of diodes.

7-10 Transistor.

7-11 Integrated circuits.

## Behavioural targets

**After studying this chapter, the student should be able to:**

- Explain the concept of electronic orbits and energy levels.
- Mention the concept of the valence shell and valence electrons.
- Compare between conductors and semiconductors.
- Explain the concept of energy bands in solids.
- Define the intrinsic semiconductors.
- Compare between the electron current and the hole current.
- Demonstrate extrinsic semiconductors (impurity).
- Mention PN-diode.
- Define the concept of biasing potential for a diode.
- list some types of the diode.
- Define the concept of the transistor.
- List some uses of the transistor.
- Illustrate the concept of integrated circuits.

| Scientific Terms | |
| --- | --- |
| Energy Levels | مستويات الطاقة |
| Conductors | الموصلات |
| Insulators | العوازل |
| Semiconductors | أشباه الموصلات |
| Energy Bands | حزم الطاقة |
| Conduction Band | حزمة التوصيل |
| Valence Band | حزمة التكافؤ |
| Forbidden Energy Gap | ثغرة الطاقة المحظورة |
| Covalent Bond | الأصرة التساهمية |
| Valence Electron | الكترون التكافؤ |
| Donor Atom | الذرة المانحة |
| Acceptor Atom | الذرة القابلة |
| Electron-Hole Pair | الزوج الكترون- فجوة |
| Doping | التشويب |
| Depletion Region | منطقة الاستنزاف |
| pn diode | الثنائي |
| Junction | المفرق (الملتقى) |
| Forward Bias | الانحياز الامامي |
| Reverse Bias | الانحياز العكسي |
| rectifier | المقوّم |
| Light-Emitting Diode | الثنائي الباعث للضوء |
| The Photodiode | الثنائي الضوئي |
| Transistor | الترانزستور |
| Integrated circuits | الدوائر المتكاملة |

## 7-1 Introduction

Figure (1)

Electronics are used in all fields of science years ago, and it has been developing growing so fast. Many electronic devices are made like radio, Television, loud speakers, electric power supplies, electronic detectors, electric signal devices, electronic voltmeter, cathode –ray oscilloscopes, broadcasting and receiving devices, Radar and so many electronic devices used in medicine , engineering, astronomy, chemistry, biology and remote sensing devices.

All of these devices depend on crystal diodes, transistors and integrated circuits to operate. See figure (1).

## 7-2 Electronic orbits and energy levels

You might ask? What shells whose electrons participates in chemical reactions and determines electrical properties of matter?

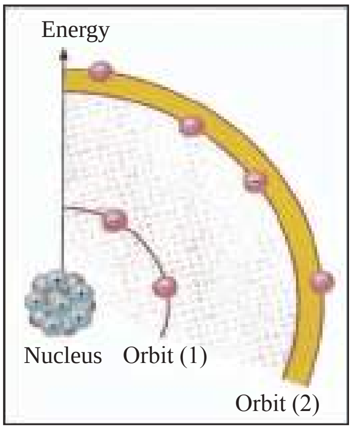



Figure (2)

The electron which revolve in the outer shells farthest from the nucleus has greater energy, and bound to nucleus with minimum attractive force (the nucleus is positive charge and electrons are negative) compared to electrons in the inner shells close to the nucleus.

Electrons with higher energy occupy the outer shells far from the nucleus of that atom. The outer shell is called Valence shell, see figure (2). Electron in this shell is called valence electron. This means that valence electrons are the ones that participate in chemical reactions and determine electronic properties of matter.

**Remember:**

- The secondary outer shell that is far from the nuclens is called the valence shell, and the electrous that occupy this shell are called the valence electrons.
- Valence electrons have more energy and are very weakly bound with the nucleus of their atom compared to the electrons closest to the nucleus.
- Valence electrons participate in chemical reaction that determine the electronic properties of matter.

To illustrate the process of releasing an electron from an atom and it from attraction force of the nucleus. See figure (3), which shows a one-dimensional diagram of energy levels in hydrogen atom. The vertical axis (y) represents energy (E) measured in (eV) on negative scale compared to zero level (E=0) which is the highest level of atom energy, because the electron is bind to the nucleus by attractive force.

The lowest amount of energy that an electron can have in hydrogen atom is (-13.6eV), this means when this electron gains (+13.6eV) energy, it escape from the hydrogen atom (at the ground state). This applies only to single atom.

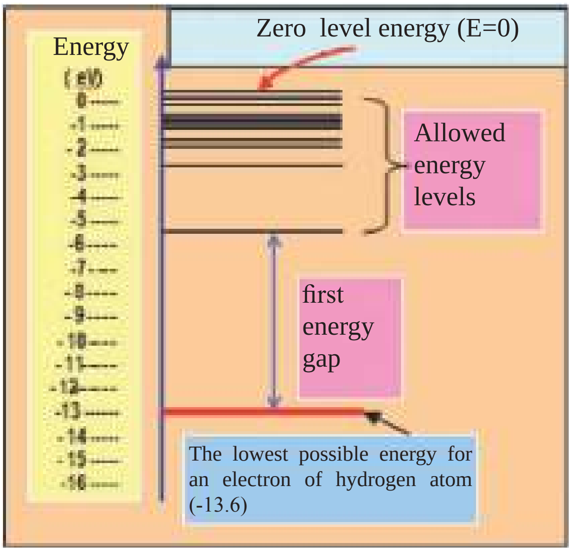



Figure (3) [For reference only (not required)]

## 7-3 Conductors, insulators and semiconductors

What are the characteristics of conductors, insulators and semiconductors materials?

A conductor is a material that allows flow of electric current through it, electric charges move freely in conductors like (copper, silver, gold and aluminum). Conductors have one valence electron very weakly bound to the nucleus. These electrons are easily escape from the nucleus and becomes free moving (free electrons). Therefore, conductors have plenty of free electrons, an electronic current arises through the conductor by placing appropriate potential difference on its sides due to the movement of these electrons in one direction. Specific resistance of conductors is about ($10^{-8}$ -$10^{-5}$ Ωm).

Insulators is a material that do not allow electric current to flow through it in normal conditions. Valence electrons of insulators are strongly bound to the nucleus. Specific resistance of insulators is about ($10^{10}$-$10^{16}$Ωm).

As for semiconductors material, that electric charges move less freely than conductors. The specific electrical resistance of semiconductors ranges between that of the specific resistance of conductors and insulators in electric conductivity, which is around ($10^{-5}$-$10^{8}$Ωm).

## 7-4 Energy bands in solid materials

If electrons of a single atom revolve around the nucleus in specific orbits, each orbit has a specific energy level, then, how energy levels would be in solid materials, which are made of massive numbers of atoms?

Looking closely at figure (4), which illustrates effect of overlapping energy levels in conductors. Electrons of any atom are affected by electrons of neighboring atom in same material. As a result of this interaction between neighboring atoms in the same material, the energy levels are divided to allowed external secondary shells, which are very close to each other in form of bands. Each band has secondary energy levels that are very close to each other, forming what are called Energy bands.

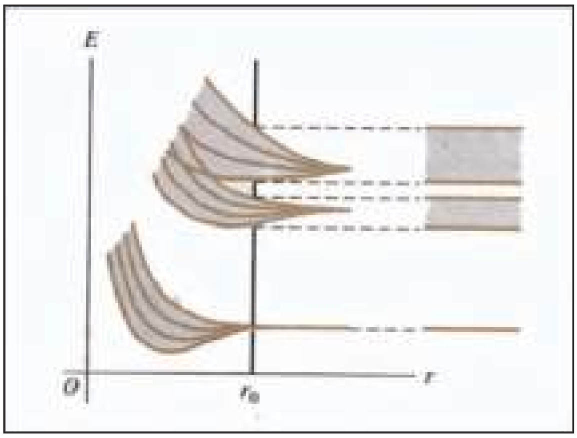


Figure (4) The energy bands [For reference only (not required)]

There are two types of energy bands, which determine electronic properties of the material: See figure (5).

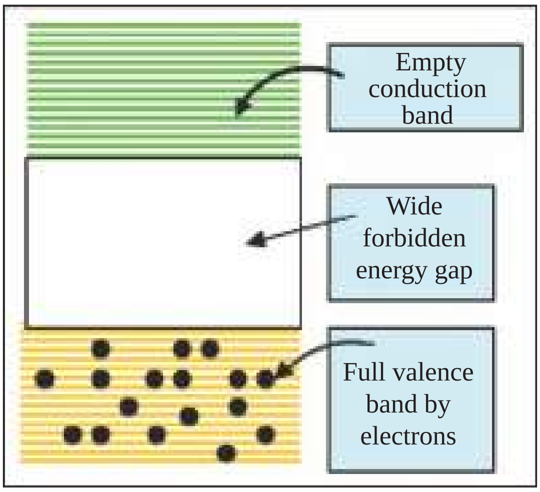


Figure (5) Energy bands

- First band, called Valence Band It contains low allowed energy levels, partially or completely full of electrons and cannot be empty. Its electrons are called valence electrons, they cannot move among neighboring atoms because they are so close to the nucleus and bound to the nucleus with relatively large forces.

- Second band called Conduction band, it contains high allowed energy levels, higher than allowed energy levels of valence band. Its electrons are called conduction electrons, these conduction electrons can move freely to participate in electric conduction.

- Forbidden energy gap This gap neither has allowed energy levels (nor it allowed electrons to occupied it). Each electron must gain energy form outer source in order to move from valence band to conduction band through forbidden energy gap. This outer energy source (thermal, light or effect of an electric field), this amount must be not less than the amount of forbidden energy gap.

You might ask, What are the characteristics of energy bands in insulators, conductors and semiconductors?

To answer this question, see figure (6) which shows typical diagram of energy bands in insulators, conductors and semiconductors, see figure (6):

a. Energy bands in Conductors (metals for example):

1. Valence bands overlap with conduction bands.
2. No forbidden energy gap between valence bands and conduction bands.

Consequently, valence electrons are free to move through conductors, thus, these metals have high electrical conductivity.

3. Electrical conductivity of metal decreases when their temperature increases due to increase in their electrical resistance (due to increase time rate of vibrational energy of atoms and molecules).

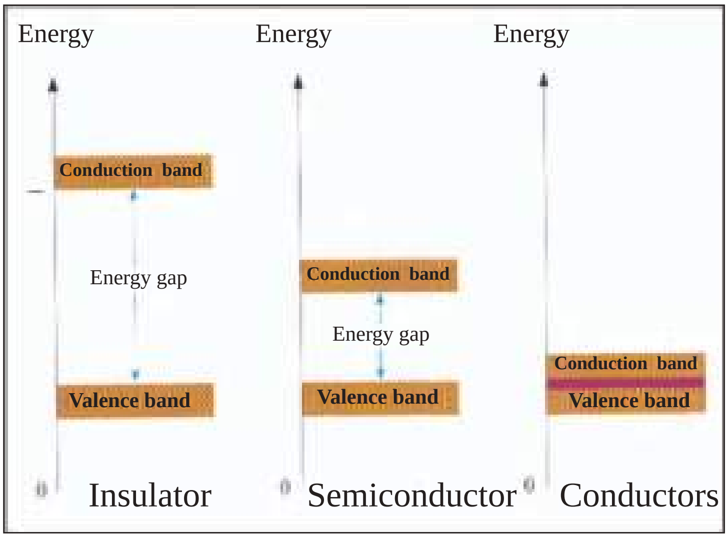



Figure (6)

b. Energy bands in insulators: see figure (6).

1. Valence band is full of valence electrons.
2. Conduction band is empty of electrons.
3. Forbidden energy gap is relatively wide.

It appears that the insulator has no electrical conductivity because the forbidden energy gap in the insulator is relatively wide (around 5eV) or more, electrons in valence band cannot pass forbidden energy gap and move to conduction band when the supplied energy is less than forbidden energy gap. As a result, valence band remains full of valence electrons while conduction band is empty.

It is worth noting that placing a huge electric field or heat onto the insulator might lead to collapse of the insulator and flow of a very little current through insulator.

c. Energy bands in semiconductors: see figure (6).

At very low temperature (at zero Kelvin 0k), and absence of light, intrinsic semiconductors behave like insulators, therefore, at these conditions:

1. Valence band are full of valence electrons.
2. Conduction band is empty of electrons.
3. Forbidden energy gap is narrow relative to insulators.

## 7-5 Intrinsic semiconductors

Germanium (Ge) and Silicon (Si) are the most commonly used semiconductors in electronics applications. Each atom contains four valence electrons, therefore each silicon atom (Si) bind by four valence electrons with four neighboring silicon atoms, see figure (7).Thus, we have eight valence electrons, each pair of which constitute covalent bond between each two neighboring atoms in silicon crystal. This makes the crystal chemically balanced.

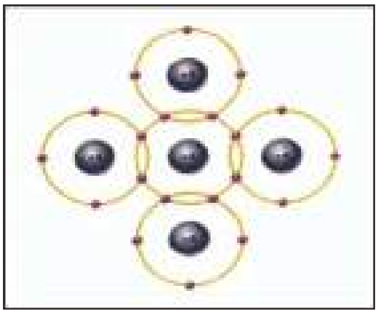


Figure (7)

Figure (8) shows energy bands of intrinsic silicon atoms at zero Kelvin (0K).

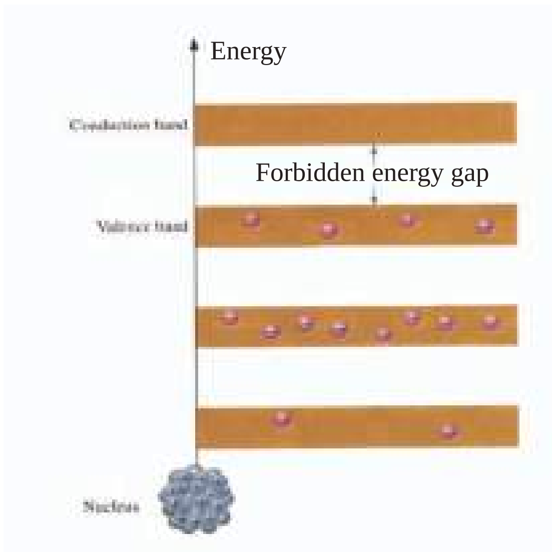



Figure (8) Energy bands of intrinsic silicon at zero Kelvin.

How can make intrinsic semiconductor (like silicon) have electric conductivity by thermal effect?

To answer this question, when the temperature of the intrinsic semiconductor increases to room temperature (300K), valence electrons gain sufficient energy to break some of covalent bonds from the source of (thermal energy) that enables them to move from valence band to conduction band through forbidden energy gap. Then these electrons are free in movement through conduction band. See figure (9).

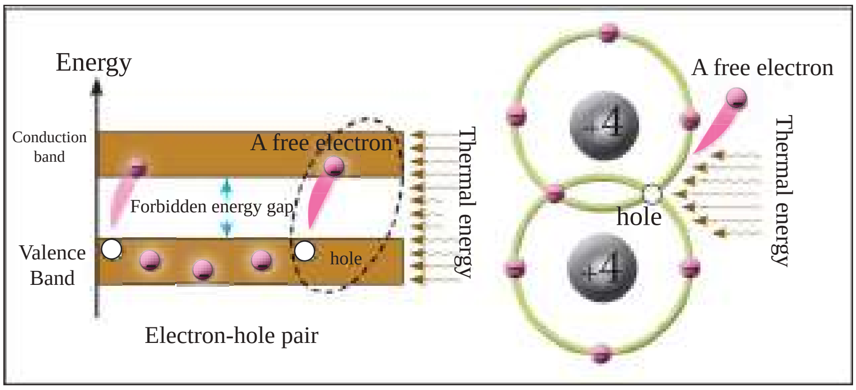



Figure (9)

When these electrons move from valence to conduction band, each moving electron leaves behind an empty space in valence band, this spot is called (hole) which acts as a positive charge. At this point, free electrons generated in conduction band and equal numbers of holes in valence band, and with this process is generated the so-called electron-hole pair.

With continuation of thermal, more electron-hole pair is generated. Thus, time rate for generating the electron-hole pair increases when the intrinsic semiconductor temperature increases. As the number of free electrons moving from valence band to conduction band increase the number of positive holes increases. What that means?

It mean, there is a decrease in specific resistance of semiconductor when its temperature increases.

Time rate of generating (electron-hole) pairs in intrinsic semiconductor depends on:

1. Temperature of semiconductor. 2. Type of semiconductor material.

The forbidden energy gap decreases in intrinsic silicon when temperature increases above zero Kelvin to room temperature (300K), the amount will be (1.1eV for intrinsic silicon) and (0.72 eV for intrinsic Germanium).

It is worth noting that, at room temperature (300K), for the intrinsic semiconductor: the concentration of positive holes generated in valence band is equal to free electrons in conduction bond.

## Electrons-holes current:

Figure (10) shows effect of imposing an electric field on the sides of intrinsic semiconductor crystal like silicon at room temperature (300K). Look at the figure (10) and answer the following:

- Does the electric current flow through the intrinsic semiconductor (Si)?
- If yes, then what is the type of this current?

When an electric field is imposed on the sides of intrinsic silicon crystal at room temperature, free electrons are attracted easily to the positive side. As a result of free electron movement in the intrinsic semiconductor material it creates a current is called electron current.

Another current is created in valence band, it is called holes current, the direction of positive holes inside the crystal is toward the direction of the electric field while the electrons move in

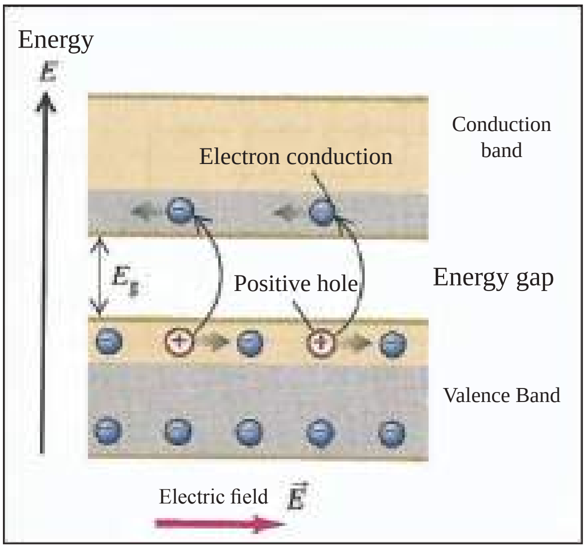


Figure (10)

the opposite direction of the electric field applied, this means that holes move in the opposite direction of the electrons. See figure (11).

The total current flowing through the intrinsic semiconductor is the sum of electrons currents and holes current. Both electrons and holes are called Charge carriers.

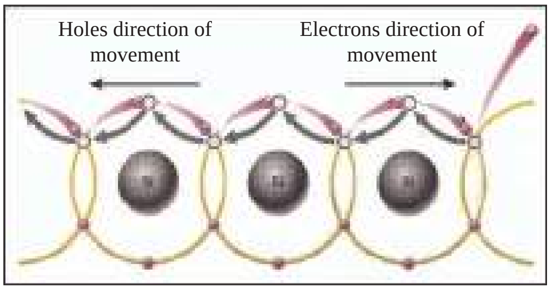



Figure (11)

You may wonder, what determines occupancy of electrons at a given level of allowed energy of their electrons?

Occupying electrons at an allowed energy level is compared to a particular level called Fermi Level. Fermi level is the highest allowed energy level that an electron can occupy at absolute zero (0K).

In conductors, at zero Kelvin, Fermi level is lies above the region which full of electrons in conduction band. The energy level occupied by these electrons is below Fermi level.

As for intrinsic semiconductors, Fermi level lies in the middle of the forbidden energy gap between conduction band and valence band, see figure (12).

When the intrinsic semiconductor is doped with impurities, Fermi level shifts either above or below, and this shift depends on the type of impurity added (we will deal with that later).

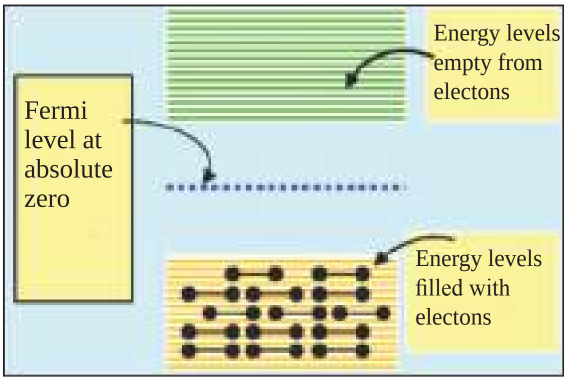



Figure (12) Illustrate the position of fermi level for interinsic semiconductors

## 7-6 Extrinsic semiconductors

If the thermal effect on semiconductors increases electrical conductivity, why resort to doping with trivalent or pentavalent?

To answer this question, controlling electrical conductivity of the intrinsic semiconductor is not possible by thermal effect method, therefore, it requires a better way to control its electrical conductivity by adding atoms of pentavalent or trivalent elements called impurities. Impurities are added carefully and accurately (with rate of one to $10^8$ approximately) at room temperature and at very low rates in an intrinsic semiconductor crystal. This process is called doping.

Doping can control electrical conductivity of semiconductors and increase it significantly due to increase in charge carriers (electrons and holes) in the crystal compared to thermal effect.

## (N-type) Semiconductor:

To get an N-type semiconductor crystal, an intrinsic semiconductor crystal (silicon or Germanium) should be doped by a pentavalent atom (Antimony Sb for example). It should be carefully and controllably doped at room temperature.

Consequently, each atom an impurity displaces a silicon atom from the crystalline structure and binds with four neighboring silicon atoms. This binding process is done by four valence electrons out of the five electrons of the impurity, as for the fifth valence electron, it is left free in the crystalline structure. See figure (13).

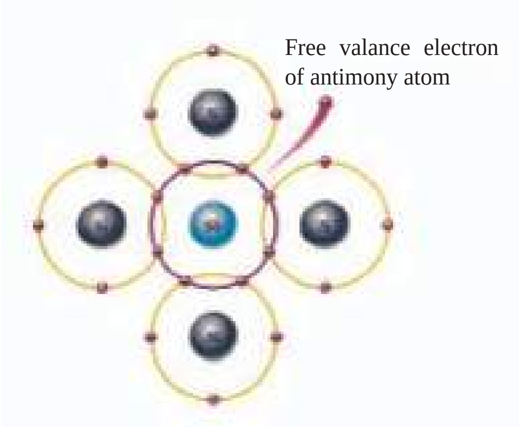



Figure (13) N - type semiconductor crystal.

Free electrons participate in the electrical conductivity process of the doped semiconductor, this type of pentavalent impurity is called Donor atom. It becomes a positive ion that binds strongly with the crystalline structure. It is not a charge carrier because it does not participate in the electrical conductivity of the doped semiconductor.

These donor atoms increase concentration of free electrons in conduction band, and decrease concentration of positive holes in valence bond (originally generated by thermal effect). Therefore, donor atoms add a new energy level called donor level, which lies within forbidden energy gap and exactly below conduction band. See figure (14).

Donor level is occupied by electrons released by donor atoms and gives its electrons to conduction band.

As a result, Fermi level rises and becomes close to conduction band.

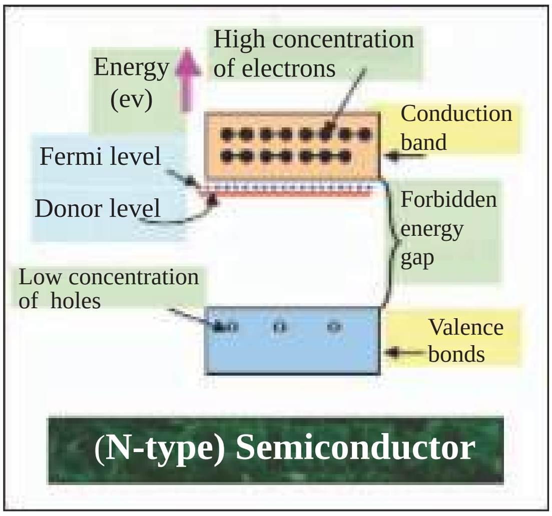



Figure (14)

* It is worth noting that electrons released by pentavalent impurities leave no holes in valence band when move to conduction bond,(as in thermal effect). Therefore, the concentration of electrons in conduction band is larger than concentration of holes is valence bond. Thus, electrons are called Majority Carriers, because they are generated from doping and thermal effect processes. As for positive holes, they are called Minority carriers because they are generated by thermal effect.

In conclusion, we get a (N-type) semiconductor crystal.

But, why a semiconductor crystal after doped by pentavalent impurities, is called N-type semiconductor? Or a negative crystal? Is this crystal charge negative?

They are called (N-type) because Majority Carriers of the charge are the electrons, while the minority carriers are the positive holes.

It is worth noting that net total charge of (N-type) crystal is zero, i.e. electrically neutral, because it has an equal number of negative charges to that of the positive charges.

## (P-type) Semiconductor

To get a (P-type) semiconductor crystal, it requires doping (carefully and controllably) of an intrinsic semiconductor (silicon or germanium) with trivalent impurities (like Boron B) atoms at room temperature. Therefore, each impurity atom displaces a silicon atom of the crystalline structure and bind with three neighboring silicon atoms.

But, the trivalent impurity leaves a covalent bond lacking one electron, see figure (15). Therefore, a hole is generated in the silicon crystal, which is doped by trivalent impurity and each atom of trivalent impurity accepts an electron from the valance electrons to bind four covalent bond with four silicon atom and for this reson trivalent impurity called Acceptor atom, like trivalent impurity (Boron, aluminum and Indium).

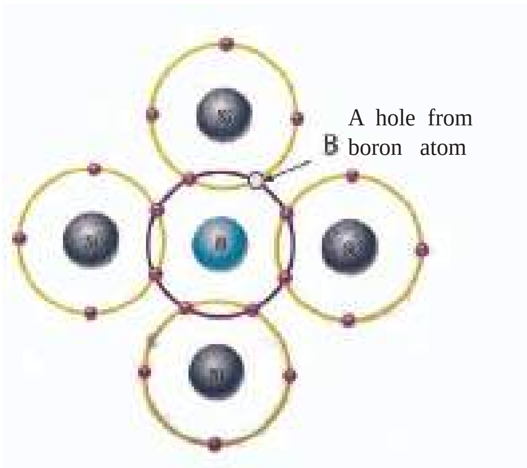



Figure (15) P - type semiconductor crystal

In doping silicon with trivalent impurities (like Boron), the impurity becomes a negative ion, after accepting one electron from the silicon atom in the crystalline structure, it will be negative ion. The negative ion is not a charge carrier because it binds with the crystalline structure strongly by (covalent bonds). It does not participate in electrical conductivity of the doped semiconductor.

These acceptor atoms add a new energy level called Acceptor level, which lies within the forbidden energy gap and directly above valence band, therefore, Fermi level drops and becomes close to valence band. See figure (16).

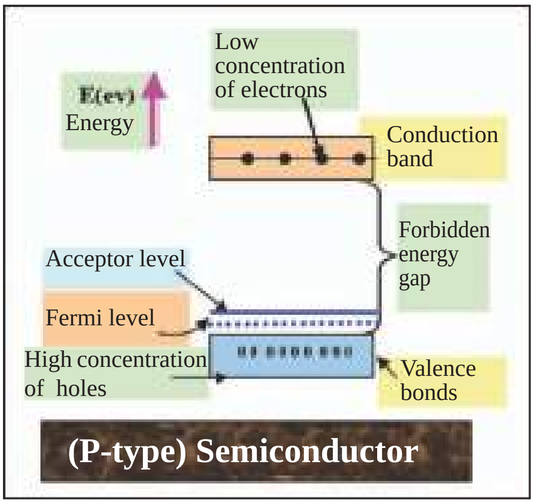



Figure (16)

It is worth noting that the trivalent impurity causes a hole in valence band when accepts one electron of valence electrons, (no transfer of extra electrons into conduction band as in thermal effect). As a result, holes will be concentrated in valence band more than concentration of electrons in conduction band, so, the holes in valence band are called majority carriers while electrons in conduction band are called Minority carriers. Hence, we have (P-type) semiconductor crystal.

But, why a semiconductor crystal after doped by trivalent impurities (like Boron), is called (P-type)? or the positive crystal? is this crystal charge positive?

They are called (P-type) because Majority Carriers of the charge are the positive holes in valence band, while the minority carriers of the charge are the electrons in conduction band.

The total charge of (P-type) crystal is zero, i.e. electrically neutral, because it has an equal number of negative charges (free electrons in conduction band and negative ions of trivalent impurities) equals to positive charges (holes in valence band).

**Remember:**

The energy gap of intrinsic semiconductor:

- At zero absolute degree is (1.2eV) for silicon and (0.78eV) for germanium.
- At the laboratory temperature of (300K) (1.1eV) for silicon and (0.72eV) for germanium.

## 7-7 PN diode

In electrical and electronic circuits, we need a means to control direction of the current or to change or to improve output signals shape, thus, the (PN diode) crystal is used. Figure (17) shows different types of crystalline diodes use in electronics devices. The crystal (PN- diode) is obtained by doping a semiconductor crystal (silicon or germanium) with two types of impurities, one is trivalent (like boron), so we get a semiconductor region of the (P-type), the other is pentavalent (antimony).

Figure (17)

So we get a semiconductor region of (N-type), the connection region is coated with a metal material so that conductive wires can be connected to the (PN) crystal diode and the external circuit, see figure (18). The surface that separates the two regions is called junction.

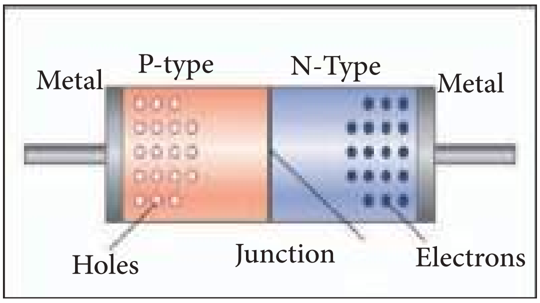


Figure (18) PN-diode crystalline

We know that the majority charge carriers in the (N-type) material are electrons, and the minority charge carriers in the (N-type) material are the positive holes.

By observing figure (19), we find that the free electrons in (N) region close the (PN) junction spread (osmosis) to (PN) region, generating positive ions in (N) region, holes move from (P) region to (N) region through the junction, generating negative ions in (P) region. Then, electrons combine with holes near the junction.

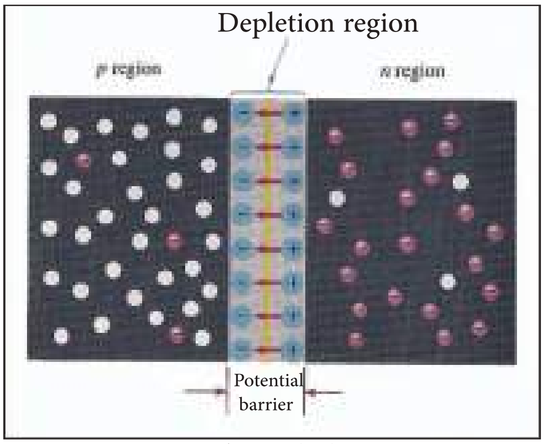


Figure (19)

This process causes a thin region on the two sides of the junction containing positive ions in (N) region and negative ions in (P) region, and is devoid of charge carriers, this region is called Depletion region.

Electrons spread through the (PN) junction stops when there is an equilibrium state.

What is the explanation for this?

The continous electrons spread through (PN) junction generate more positive ions and negative ions on both sides of the (PN) junction at depletion region. This creates an electric field (represented by red arrows) in figure (19), the electric potential difference resulting from this filed prevents additional electrons from passing the (PN) junction, so, electrons stop spreading process, this is called potential barrier.

The potential barrier in the (PN-diode) depends on the type of semiconductor, rate of doped impurities, and temperature of the material.

Potential barrier in (PN-diode) at room temperature (300K) is (0.7V) for silicon, and (0.3V) for germanium.

## 7-8 Biasing potential for PN-diode

We know that spread of electrons through the (PN) junction stops when there is an equilibrium state. This requires a certain electrical potential difference called Biasing potential. To provide practical conditions for the electronic device used, there are two ways of (PN)junction bias: forward bias method and reverse bias method.

## a. Forward bias method:

The end of (PN-diode) is connected to the two terminals of a battery (conductive wires and a resistance R) to determine the amount current flow through the diode and to avoid diode damage, see figure (20) and (21). The positive terminal of the battery is connected to (P) region of the diode, the negative terminal of the battery is connected to (N) region of the diode, the potential difference on the ends of diode should be greater than that on the (PN) junction.

What happens to the (PN) diode when in forward bias?

Free electrons in (N) region (majority carrier of the charge in N region), repulse with the negative terminal of the battery heading toward the junction, gaining enough energy from the battery to pass the electric potential barrier and cross the (PN) junction to (P) region. At the same time, holes in (P) region (majority carriers of the charge in P region) repulse with the positive terminal of the battery toward the junction, gaining enough energy to pass the potential barrier and cross the (PN) junction to (N) region. Thus, depletion region narrows and potential barrier on (PN) junction decreases, see figure (22), because the direction of the electric field on the diode is opposite to direction of the electric field on the potential barrier and even greater than it. The (PN) junction resistance decrease and huge current flows through it, this current is called Forward Current.

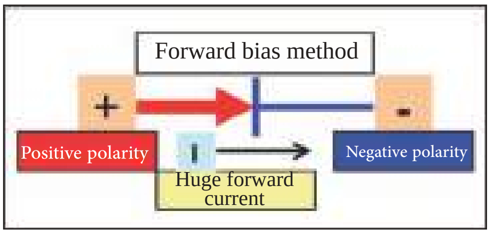


Figure (20)

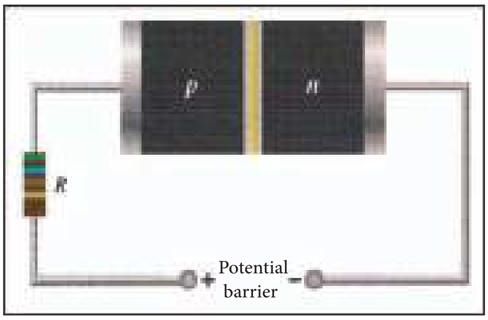


Figure (21) Forwaed Bias

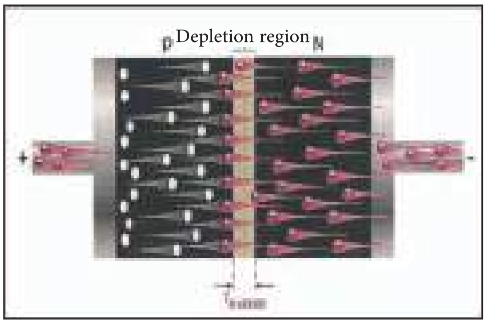


Figure (22)

## b. Reverse bias method:

The end of (PN-diode) are connected to the two terminals of a battery (through conductive wires and a resistance R) see figure (23) and (24). The negative terminal of the battery is connected to (P) region of the diode and the positive terminal of the battery is connected to (N) region of the diode. What happens to the (PN-diode) when reversely biased?

Free electrons in (N) region are attracted to the positive terminal of the battery moving away from the (PN) junction and at the same time,

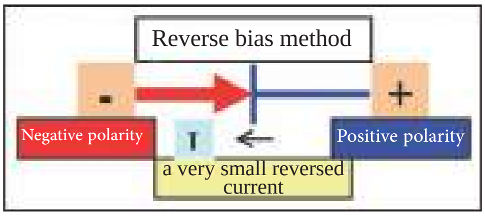


Figure (23)

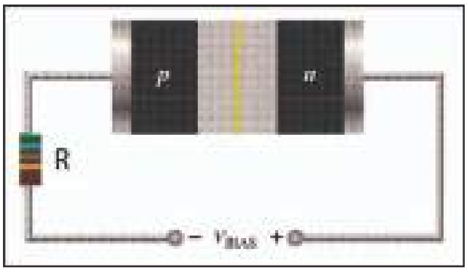


Figure (24) Reverse bias

holes in (P) region are attracted to the negative terminal of the battery moving away from (PN) junction, see figure (25).

Thus, depletion region increases as well as the potential barrier on (PN) junction, because the direction of the applied electric field on the diode is toward the direction of the electric field on the (PN) junction, hence, the resistance of the diode increases. For this reason, a very small current flows (can be neglected) through the (PN-diode), this current is called Reverse Current. The (PN-diode) is expressed in figure (26)

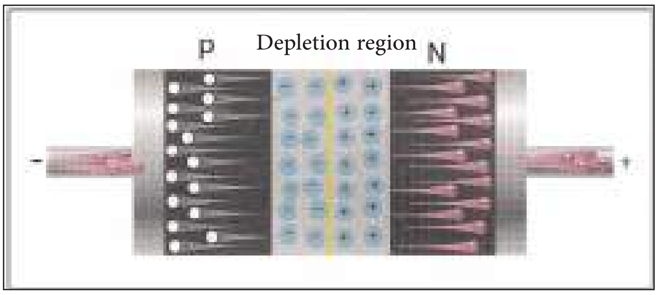


Figure (25)

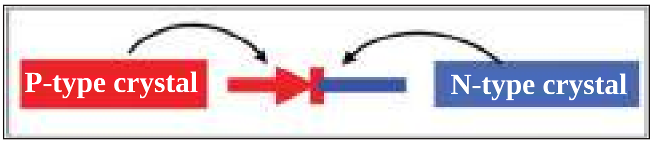


Figure (26)

Figure (27) illustrates a diagram of an electric circuit with (PN-diode) connected in two methods.

Figure (27-a) illustrates a diagram of an electric circuit with (PN-diode) connected in forward bias method (notice the flow of an electric carrent in the circut).

Figure (27-b) illustrates a diagram of an electric circuit with (PN-diode) connected in reverse bias method (notice there is no electric current flow in the circut).

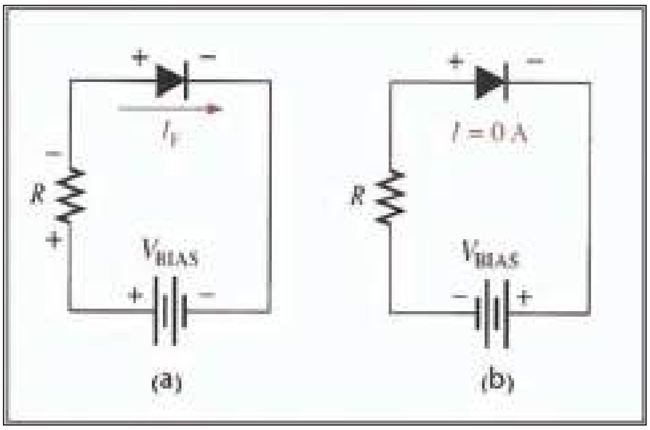


Figure (27)

Change in the amount of current flow in the crystal diode with voltage of the diode in forward and reverse bias can be represented coordinately. When voltage is increased in forward bias the amount of forward current increases, see figure (28). If polarity of applied voltage is reversed (reverse bias voltage), the flowing current through the crystal diode is almost zero.

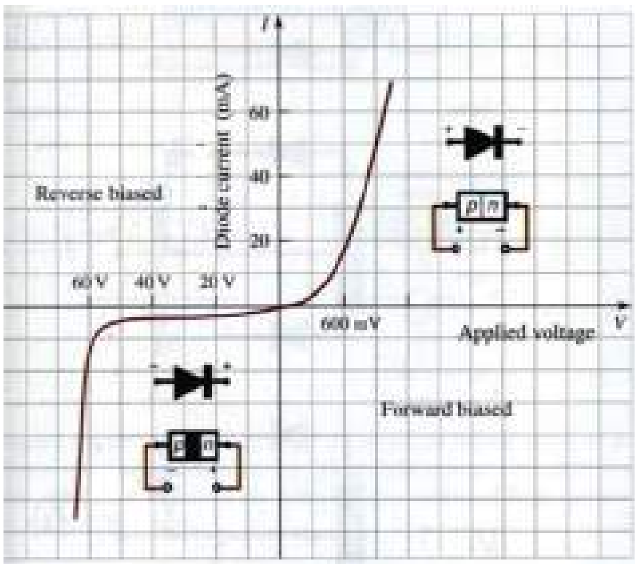


Figure (28) [For reference only (not required)]

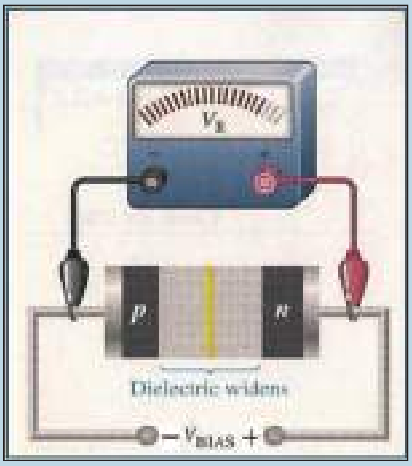
**DO you know?**

Depletion region (between P region and N region) in the crystalline (PN-diode) is considered a dielectric between the ends of a capacitor.

- When the crystalline (PN-diode) is connected in forward bias method, depletion region narrows, the thickness of dielectric will be thin and thus increases in the amount of capacitance of the capacitor between the two region due to decrease in distance between the plates according to the relation: $C = \in_0 \frac{A}{d}$


The capacitive reactance decreases and thus potential difference on the sides of the junction also decreases. This can be observed when connected a voltmeter between the ends of a diode, the voltmeter indicates a small potential difference on the ends of the forward biased diode. See figure on the right.

- When the crystalline (PN-diode) is connected in reverse bias method, depletion region widens, the dielectric becomes thicker, and this decreases in amount of capacitance of capacitor between the two regions.




The capacitive reactance increases and, also the potential difference on the sides of the junction increases. This can also be observed by connecting a voltmeter to the diode, the voltmeter indicates a huge potential difference on the ends of the reversely biased diode. See figure on the right.

## 7-9 Some types of diodes

We have already known that the energy source needed to generate (electron-hole) pairs in semiconductors is thermal energy, mostly provided through room temperature. However, is it possible use light energy or electromagnetic radiation for the same purposes? can light control electric conductivity of semiconductors and (PN-diode)?

Light energy (photon energy) falling on the (PN-diode) can be converted into electrical energy. Diodes which used for this purposes are of two types, the first is photosensitive diode and the second photovoltaic diode (solar cell).

## • Photosensitive diode:

This diode is connected in reverse bias method before exposed the light on it. See figure (29), so the current will be very weak and neglected (which is the electrons and holes current generated by thermal effect), this means that current in the diode circuit is zero when there is no light effect in the diode.

This diode converts light energy into electrical energy. When the (PN-diode) is exposed to light, see figure (30).

New charge carriers are generated depending on the intensity of incident light. It has been practically proven that amount of current in the photosensitive diode circuit is directly proportional with the intensity of incident light.

This type of diodes is used in light detectors and light intensity meter.

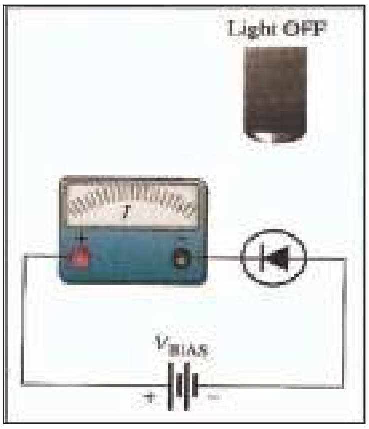



Figure (29) The photosensitive (PN) diode before the light is incident on it.
The current is not flow in its circuit, notice the ammeter (The current is zero).

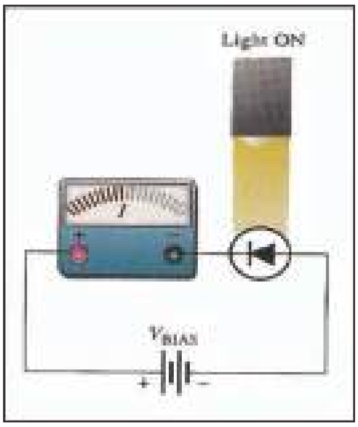



Figure (30) The photosensitive (PN) diode when the light is incident on it.
The current is flow in its circuit, notice the ammeter (indicating the current flow)

## • Photovoltaic diode or solar cell

This diode converts light energy into electric energy. It symbolized as in the figure (31).

This diode is connected in reverse bias method before exposed light on the PN-junction region. The photon, which has energy equal to or greater than (1.1eV), can generate electron-hole pair in silicon and the photon which has energy equal to or greater than (0.72eV) can generate electron-hole pair in germanium. This diode generates electromotive force between its ends when exposed to incident light, it amounts is (0.5V) in silicon and (0.1V) in germanium.

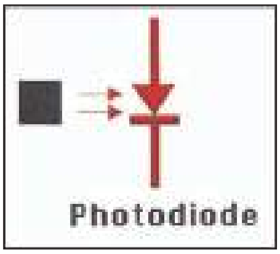



Figure (31) Symbol of PN-diode solar cell

This diode is used artificial satellites as a power source, these cells can be connected in series combination to increase potential, while connected in parallel combination to increase power.

## ● Light Emitting Diode (LED)

This diode converts electrical energy into light energy; it is connected in forward bias method, see figure (32). When an external electric potential difference is applied between its two ends, a current flows in its circuit because of recombination between electrons and holes, energy is released when electrons fall in the holes; this energy is manifested as heat in the crystalline structure. If the diode was made of gallium arsenide (GaAs), energy will be released when electrons fall in the holes as light energy.

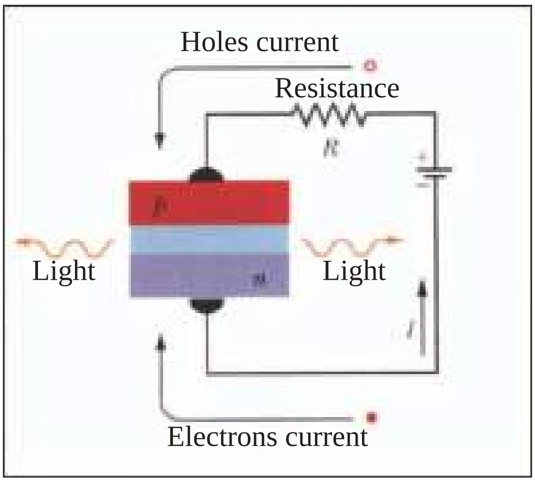



Figure (32)

These diodes emit light in different colors (red, yellow and green) according to the material it is made of. There are other diodes, which emit infrared ray.

Intensity of light from light emitting diode increases when the amount of flowing forward current of the crystalline diode in its circuit increases. Light emitting diodes are used in digital calculators and clocks to show the numbers clearly. Digital screens use the concept of diodes in the form of seven segment. The illuminated number can be shown from (0-9) by distributing the electric current on the designated diode, see figure (33).

Figure (33)

## ● Current rectifier diode:

This diode rectifies the alternating current into rectifier current in one direction, when the diode is connected to an alternating voltage source; one-half of the waves (the positive polarity) makes it in forward bias, allowing the current to pass through the circuit. See figure (34).

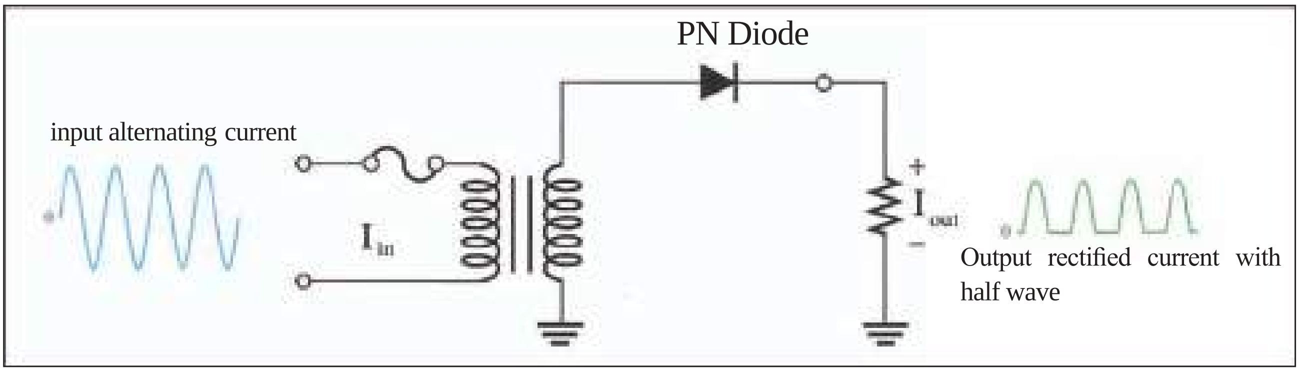


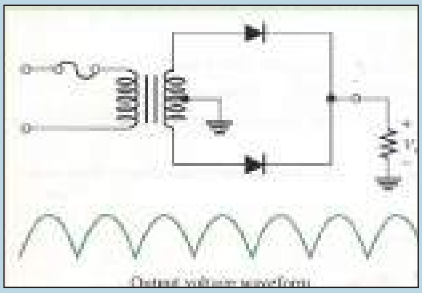

Figure (34)

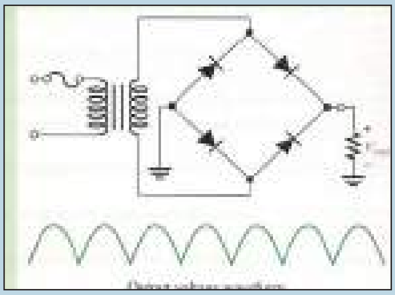
For the other half –wave, it makes the diode bias in reverse, then, it does not allow current flow in the circuit.

We conclude that this diode converts the alternate current into a rectified half-wave current.

**DO you know?**

You can get a rectified full-wave current by using more (PN- diodes), see adjacent figure.





## 7-10 Transistor

It is a device consisting of three regions made of a semiconductor (silicon or germanium) separated by two junctions. The three regions are symbolized by: Emitter (E), Base (B), and Collector (C) .the emitter is doped with a high rate of impurities, the base is doped with a low rate of impurities, as for the collector regions, it has medium amount of impurities. There are two types of transistors, the first type PNP- transistor, see figure (35), the second is NPN-transistor, see figure (36).

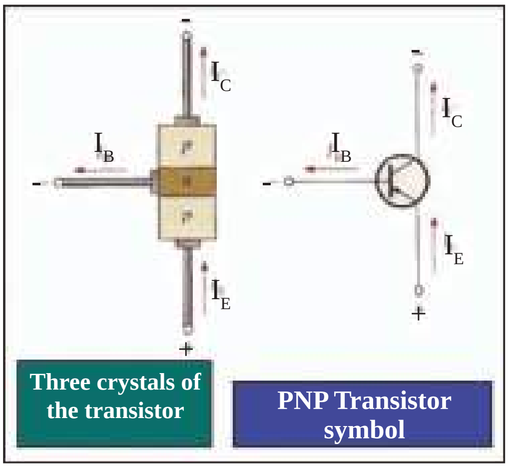



Figure (35)

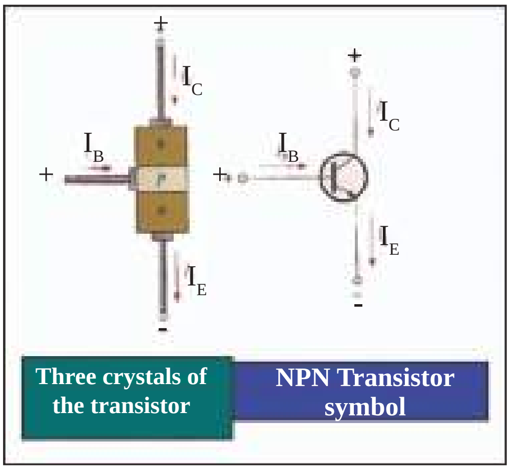



Figure (36)

Since the emitter supplies the charge carriers, thus, it is always in forward bias.

While the collector attracts these carriers through the base, thus, it is always in reverse biased.

## PNP-transistor

It consists of two region of a semiconductor type (P), one is the emitter, the other is the collector, separated by a relatively thin region of (N–type) called the base, and the three region are the poles of the transistor, see figure (37).

Do you want to know type of charge carriers, which perform the electrical conduction in the (PNP) transistor? What is the relation between emitting current and collector current?

The answer is, the holes move from the emitter to the collector through the (PNP) transistor (they are majority carriers).

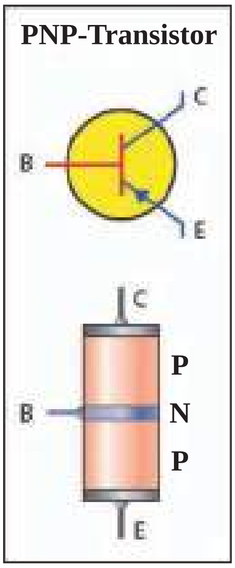


Figure (37)

## NPN-Transistor

It consists of two region (N-type) semiconductor, one is called the emitter and the other is called the collector, separated by a relatively thin region of (P-type) called the base, the three regions are the poles of the transistor, see figure (38).

.

Do you want to know type of charge carriers, which perform the electrical conduction in the (NPN) transistor?

What is the relation between emitting current and collector current?

The answer is, the electrons are move from the emitter to the collector through the (NPN) transistor (they are majority carriers).

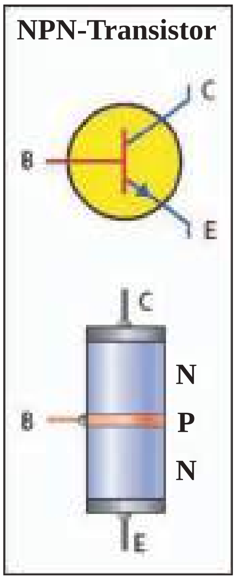


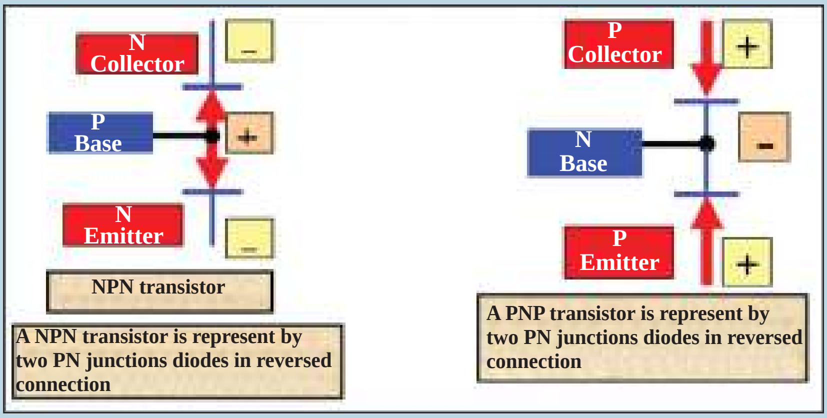
Figure (38)

**Remember:**

- The collector current ($I_C$) is always less than the emitter current ($I_E$) as much as base current ($I_B$), because of the recombination at the base region between the holes and electrons. Thus: ($I_C = I_E - I_B$).
- Base current is very small compared to emitter current ($I_E$), because the base region is thin and has less percentage by impurity doping.
- If the base current ($I_B$) for example equals (1%) of the emitter current ($I_E$), then the collector current ($I_C$) is about (99%) of the emitter current.

**DO you know?**

PNP transistor can represent connecting two (PN-diodes) in reverse directions, as well as the case of NPN transistor, as in the adjacent figure.



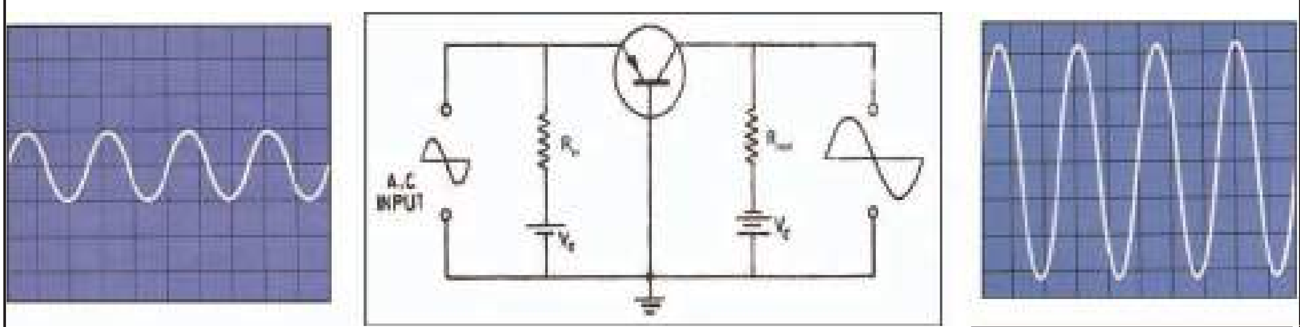

## Using the transistor as an amplifier

The basic function of the transistor is amplifying the siguals entering, these amplifiers are: Common base (grounded base) – PNP amplifier, common-emitter pnp amplifier. Choosing type and shape of transistor for a particular application depend on input impedance and output impedance.

## Common –base pnp-amplifier (grounded base):

Amplification in a transistor depends on low-power input circuit control over the high-energy output circuit.

Figure (39) represents a diagram of an amplifier circuit using common-base PNP-transistor (grounded base), we find that the (emitter base) junction is in forward bias, while (base-collector) junction is in reverse bias.




The input signal of the emitter circuit

Amplifier circuit using common base PNP trasister (grounded base)

The output signal form the collector circuit is amplified in the same phase with the input signal in the emitter circuit (phase diffrent between them=zero).

Figure (39) Common-base PNP amplifier [For reference only (not required)]

It is characterized by:

- Input circuit (emitter-base circuit) with a small impedance (because the emitter –base junction is in forward bias), and an output circuit (collector base circuit) with a very large impedance (because collector-base junction is in reverse bias).
- Bias Voltage a very small input circuit, while output circuit bias voltage is high. Thus voltage gain is very high:

$$\text{Voltage gain}(A_V) = \frac{\text{output voltage}(V_{out})}{\text{input voltage}(V_{in})}$$

- Current gain is less than integer one.

  Current gain is the ratio of output current (collector circuit current $I_C$) to input current (emitter current $I_E$):

$$\text{Current gain}(\alpha) = \frac{I_C}{I_E}$$

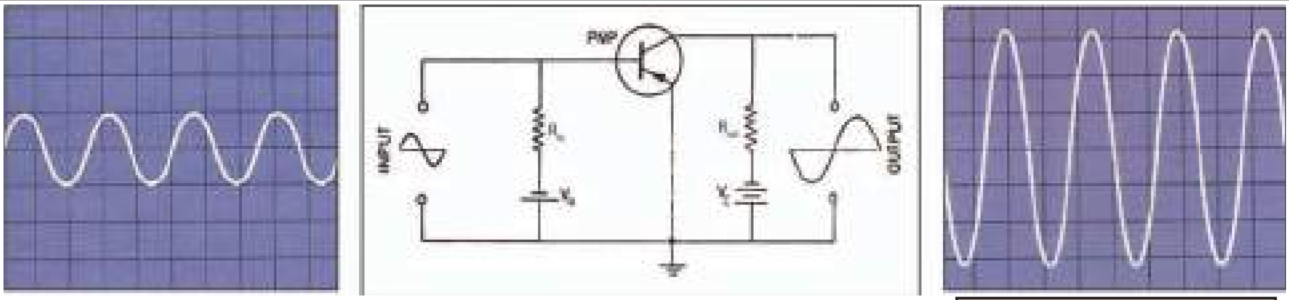
- Power gain:

$$\text{Power gain}(G) = \frac{P_{out}}{P_{in}}$$

$$\text{Power gain}(G) = \text{Current gain}(\alpha) \times \text{Voltage gain}(A_V)$$

- The output signal has the same phase of the input signal. What is the explanation for this? The reason for this is that collector current changes in the direction of the emitter current itself.

## Common-emitter (ground emitter) PNP amplifier:




The input signal of the emitter circuit

Amplifier circuit using common emitter (grounded emitter) PNP transister

The output signal form the collector circuit is amplified and opposite phase of the input signal of the emitter circuit (phase differnt between them=180°)

Figure (40) Common-emitter PNP amplifier [For reference only (not required)]

From the observation figure (40), which shows a diagram of an amplifier circuit using the Common- emitter pnp transistor (grounded emitter), we find:

The base has negative potential relative to the emitter, while the collector has a negative potential relative to both emitter and base. When an alternating signal voltage between the two ends of input circuit, it will change potential of the base. It is found that any small change in base potential will significantly change (collector-base) current circuit. Since this current flows through a load of high resistance ($R_L$), it generates a high potential difference through the load resistance, which represents the potential difference of the output signal.

The figure (40) also shows that output signal from the collector circuit is out of phase with the input signal in the emitter signal (phase difference=$180^0$). What is the explanation for this?

The answer is:

The positive half of the input voltage signal decreases forward bias voltage of (emitter-base) junction, thus, the flowing current in the (collector-base) circuit decreases, which flows in the load ($R_L$). Consequently, the potential difference decreases through the load, this makes the output signal negative. As for the negative half of the input signal, it causes increase in forward bias voltage of the (emitter-base) junction, which renders the signal potential positive.

Common-emitter (grounded emitter) PNP-amplifier circuit is characterized by:

- The current gain is the high output current (collector circuit current $I_C$) is greater than the input current (base current $I_B$), because:

Current gain is the ratio of output current (collector current circuit $I_C$) to input current (base current $I_B$).

$$\text{Current gain}(\alpha) = \frac{I_C}{I_B}$$

- Voltage gain ($A_V$) is high (output voltage is greater than input voltage).

$$\text{Voltage gain}(A_V) = \frac{\text{output voltage}(V_{out})}{\text{input voltage}(V_{in})}$$

- Power gain (G) is very high (power gain equals voltage gain ($A_V$) $\times$ current gain ($\alpha$).

$$\text{Power gain}(G) = \text{Current gain}(\alpha) \times \text{Voltage gain}(A_V)$$

$$\text{Power gain}(G) = \frac{P_{out}}{P_{in}}$$

- The output signal is out of phase with input signal phase diffrence ($180^0$), the reason is that collector current changes in reverse direction to that of the base current.

**Example (1)**

In a common-base (grounded-base) amplifier transistor circuit, if the emitter current is ($I_E$=3mA), collector current ($I_C$= 2.94mA), input resistance ($R_{in}$ =500Ω) and output resistance ($R_{out}$=400KΩ), then calculate:

1. Current gain ( $\alpha$ ) 2. Voltage gain ($A_V$)

**The solution:**

$$\alpha = \frac{I_C}{I_E} = \frac{2.94 \times 10^{-3} A}{3 \times 10^{-3} A} = 0.98 \text{ Current gain}$$

$$V_{in} = I_E R_{in} = (3 \times 10^{-3} A)(500\Omega) = 1.5V$$

$$V_{out} = I_c R_{out} = (2.94 \times 10^{-3} A)(400000\Omega)$$

$$V_{out} = 1176V$$

$$A_V = \frac{V_{out}}{V_{in}} = \frac{1176V}{1.5V} = 784 \quad \text{Voltage gain}$$

**Example (2)**

In a common-base (grounded-base) amplifier transistor circuit, if power gain is (G = 768), voltage gain is ($A_V$=784) and emitter current ( $I_E = 3 \times 10^{-3} A$ ), find base current ($I_B$).

**The solution:**

$$\text{power gain } (G) = \alpha \times A_V$$

$$768 = \alpha \times 784$$

$$\therefore \alpha = \frac{768}{784} = 0.98$$

$$\alpha = \frac{I_c}{I_E}$$

$$0.98 = \frac{I_c}{3 \times 10^{-3} A}$$

$$\therefore I_c = 2.94 \times 10^{-3} A \quad \text{Collector current}$$

$$I_B = I_E - I_c$$

$$= 3 \times 10^{-3} A - 2.94 \times 10^{-3} A$$

$$I_B = 0.06 \times 10^{-3} A \quad \text{Base current}$$

## 7-11 Integrated circuits

It is a small device used to control electric signals in many electronic devices like computer, televisions, cell phone, some parts of cars, CD's, and spaceships. See figure (41)

Figure (41)

The integrated circuits contain thousands of complex elements, which are manufactured in a single process. It is made of a small chip of silicon wafer; these elements include crystal diodes, transistors, resistors, and capacitors to form electronic systems for a particular function.

Manufacturing integrated circuits depend on what is called diffused planar process, where all the manufacturing steps are performed on one surface of silicon chip. Manufacturing an integrated circuit is basically done by producing three major layers, see figure (42):

1. Substrate layer (P-type): it is the process of growing a cylindrical silicon crystal then cut it into wafers, called substrate. This layer is a (P-type) semiconductor. It represents the body of the integrated circuit.
2. Epitaxial layer (N-type): this layer is made by placing silicon chips in a thermal oven and exposed to gas (it is a mixture of silicon atoms, and pentavalent donor atoms on the chips). This mixture forms a thin layer of semiconductor of (N-type), called epitaxial layer.

(Insulating layer)

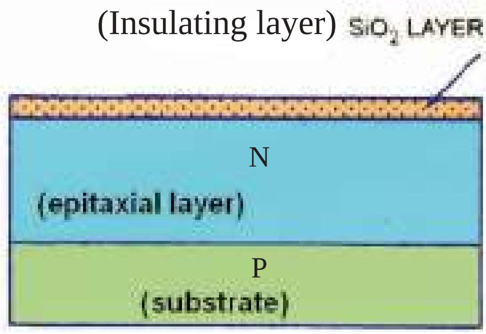



Figure (42)

3. The insulating layer: after growing the epitaxial layer (N) on the substrate (P), the chips are placed in a special thermal oven containing oxygen, water vapor at a given temperature, thus, silicon dioxide ($SiO_2$) is formed as the insulting layer.

After manufacturing these three layers, the wafer is ready to be processed in manufacturing the components of the integrated circuit.

Integrated circuits differ from regular electric circuits (separated circuits). The integrated circuits are small, consumes power are little, fast, light weight and cheap. Furthermore, the integrated circuits do many functions usually done by regular electric circuits.

**DO you know?**

This chip of initegrated circuits is very small and contain millions of transistors.

# Questions and problems of chapter 7

**Q1** Choose the correct statement for each of the following:

1. A crystalline PN-diode is forward bias, if the forward voltage is increased, then the forward current:

   a. Increases. b. Decreases. c. Remains stable. d.Increases then decreases.

2. When potential barrier is increased in crystalline PN-diode is forward biased, the amount of the forward current:

   a. Increases. b. Decreases. c. Remains stable. d. Increases then decreases.

3. Free electrons in intrinsic semiconductor at room temperature occupy:

   a. Valence band. b. Forbidden energy gap. c. Conduction band d. Acceptor level.

4. Electron-hole pairs are generated in intrinsic semiconductor by:

   a. Recombination. b. Ionization. c. Doping. d. Thermal effect.

5. Flowing current in intrinsic semiconductor is the result of:

   a. Free electrons only. b. Holes only.

   c. Negative ions. d. Both electrons and holes.

6. In (N-type) semiconductor and at room temperature:

   a. Number of free electrons in conduction band equals number of holes in valence band.

   b. Number of free electrons in conduction band is greater than number of holes in valence band.

   c. Number of free electrons in conduction band is less than number of holes in valence band.

   d. All of the above, depending on type of impurity.

7. Depletion region is generated in (PN-diode) by:

   a. Recombination. b. osmosis. c. ionization. d. All previous possibilties (a ,b and c)

8. The PN-diode of light emitting diode (LED), emits light when:

   a. Forward biased b. Reverse biased.

   c. The potential barrier across the junction is large. d. It is at room temperature.

9. Emitting current ($I_E$) in transistor circuit is always:

   a. Greater than base current. b. Less than base current.

   c. More than collector current. d. Answers (c & a)

10. Depletion in crystal diode at (N) region contains only:

a. Free electrons. b. Holes. c. Positive ions. d. Negative ions.

11. Silicon acts as insulator when:

a. Pure. b- In the dark. c. At absolute zero. d. All of the three choices (a, b, c).

12. Time rate for generating electron-hole pair increases in semiconductor by:

a. Adding pentavalent impurities. b. Adding trivalent impurities.

c. Increase in temperature. d. None of the above.

13. Base region in the transistor is:

a. Wide and less impurities. b. Wide and many impurities.

c. Thin and less impurities. d. Thin and many impurities.

14. Current gain ( $\alpha$ ) in PNP-common emitter amplifier is :

a. $\frac{I_E}{I_C}$ b. $\frac{I_B}{I_C}$ c. $\frac{I_C}{I_B}$ d. $\frac{I_C}{I_E}$

15. Phase difference between output signal and input signal of common –base PNP amplifier is:

a. Zero b. $90^0$ c. $180^0$ d. $270^0$

16. Current gain ( $\alpha$ ) in the common base amplifier PNP transistor circuit is:

a. $\frac{I_E}{I_B}$ b. $\frac{I_c}{I_E}$ c. $\frac{I_C}{I_B}$ d. $\frac{I_B}{I_E}$

17. In semiconductor N-type and at (0K), Fermi level lies at:

a. Below donor level.

b. Middle distance between bottom of conduction band and donor level.

c. In the middle of energy gap.

d. Middle distance between valence band and donor level.

18. Fermi level is:

a. Average of all energy levels. b. Energy level at the top valence band.

c. Higher energy level occupied at $(0^0)$ C. d. Higher energy level occupied at 0K.

**Q2** Write True or false, correct the false without changing underlined:

1. <u>(N-type) silicon crystal has</u> negative <u>charge</u>.
2. <u>Depletion region in PN-diode contains</u> positive ions <u>in P region</u> and negative ions <u>in N region.</u>
3. <u>Electric conductivity in intrinsic semiconductor</u> increases <u>when temperture rises</u>.
4. <u>Light emitting diode is biased in</u> forward method.

5. Forbidden energy gap in germanium is (1.1eV) at (300K).

6. Potential barrier in crystal diode increases when biased in forward mehod.

7. The emitter in transistor is always in forward bias

8. In conductors at 0K the energy levels below Fermi level are occupied by electrons.

9. Power gain in common-base PNP amplifier is very large.

10. Electron-hole pairs are generated in semiconductor because of recombination between electrons and holes.

11. Base region in transistor is always thin and low impurities.

12. In NPN-transistor of the common base, the emitter current is larger than the collector current.

13. In NPN-transistor of the common emitter, input and output signals have the same phase.

14. P-Type germanium crystal, the holes are the majority charge carriers.

**Q3** What is the difference between the following:

1. Positive ions and hole in semiconductors.
2. Light emitting diode and photosensitive diode.
3. N-type semiconductor and P-Type semiconductor in terms of:
   a. Type of doped impurity. b. Majority charge carriers and minority charge carriers.
   c. The level generated by each impurity and its position.
4. Emitter and collector in transistor in terms of :
   a. Collecting current carriers or transmitting. b. Bias method.
   c. Junction impedance. d. Rate of impurities.

**Q4** Explain the reasons of the followings.

a. Generating of depletion region in PN crystalline diode?

b. Junction impedance (collector-base) in transistor is high, while emitter-base junction impedance is low?

c. At absolute zero and in the dark, the conduction band in intrinsic semiconductor is empty of electrons?

d. Huge current flows in crystalline PN-diode circuit when forward bias voltage increases?

e. Photosensitive PN-diode is reverse biased before exposed to light?

f. The positive ion, which is generated when a donor impurity is added to intrinsic semiconductor, is not a charge carrier?

**Q5** Define the followings:

1. Fermi level.
2. Donor level and how it generates.
3. Depletion region in PN-diode, and how it generates.
4. Hole in semiconductor, and how it generates.
5. Electron-hole pair and how it generates.

**Q6** What does the amount of the followings depend on?

a. Potential barrier in PN-diode crystalline.

b. The rate of creating electron-hole pair in an intrinsic semiconductor?

c. Number of free electrons moving from valence band to conduction band in n-type semiconductor at constant temperature.

d. Flowing current in photosensitive PN-diode.

**Q7** What happens to the alternating current if it is connected to a PN-diode?

**Q8** After doping a semiconductor (like silicon) by trivalent impurities (like Boron), what is the resultant crystal. Does it have positive charge? or negative? or electrically neutral?

**Q9** In common emitter transistor circuit, if the emitter current is ($I_E$=0.4mA) and base current is ($I_B$=40μA), input resistance ($R_{in}$=100Ω), output resistance ($R_{out}$=50kΩ). Calculate:

1. Current gain ($\alpha$). 2. Voltage gain ($A_V$). 3. Power gain (G).

**Q10** In common emitter transistor circuit; calculate the current gain ($\alpha$), emitter current ($I_E$), if the base current is ($I_B$=50μA) and collector current ($I_C$=3.65mA).

# CHAPTER 8

# Atomic spectra and laser

Contents

8-1 Introduction
8-2 Energy levels and Bohr's model for atom.
8-3 Hydrogen atom spectrum.
8-4 Spectra.
8-5 Types of spectra.
8-6 X - rays.
8-7 Compton effect.
8-8 Laser and maser.
8-9 Properties of laser.
8-10 Mechanism of laser action.
8-11 Boltzmann distribution and population inversion.
8-12 Construction of laser.
8-13 Laser levels systems.
8-14 Types of laser.
8-15 Some application of laser.

## Behavioural targets

**After studying this chapter, the student should be able to:**

- Explain the development of an atomic model.
- Define Bohr's model of the atom.
- Mention the items of Bohr’s model.
- Give a reason for the failure of the Rutherford model of the atom.
- Know the spectrum of the hydrogen atom.
- Know energy levels.
- List the types of spectra.
- Demonstrate how to generate X-rays.
- Demonstrate the Compton Effect.
- Solve mathematical problems.
- Know what the laser and the maser.
- Mention Boltzmann’s law.
- Define the inversion population.
- know the mechanism of laser action.
- List the types of lasers.

## Scientific Terms

| | |
|---|---|
| Bohr's model of the atom | انموذج بور للذرة |
| Energy Levels | مستويات الطاقة |
| Excited state | مستوى متهيج |
| Ground state | مستوى ارضي |
| Spectrum of Hydrogen Atom | طيف ذرة الهيدروجين |
| Spectra | الأطياف |
| Continuous Spectrum | الطيف المستمر |
| Line Spectrum | الطيف الخطي |
| X-rays | الأشعة السينية |
| Compton Effect | تأثير كومبتن |
| Maser | الميزر |
| Laser | الليزر |
| Induced Absorption | الامتصاص المحتث |
| Spontaneous emission | الانبعاث التلقائي |
| Stimulated emission | الانبعاث المحفز |
| Pumping | الضخ |
| Excimer Laser | ليزر الاكسايمر |
| Solid-state Laser | ليزر الحالة الصلبة |
| Boltzmann Distribution | توزيع بولتزمان |
| Population inversion | التوزيع المعكوس |
| Gas Lasers | الليزرات الغازية |
| Ruby Laser | ليزر الياقوت |
| Four-Level system | منظومة رباعية المستوى |
| Three-Level system | منظومة ثلاثية المستوى |

## 8-1 Introduction

Scientists were interested in studying the atomic structure of matter; Thompson proposed a model describing the atom as a tiny ball with a positive charge and negative electrons are distributed inside in such a way that it becomes electrically neutral. Then, other models were proposed based on more observations and information on nature and structure of matter, and nature of electric charge. Rutherford, Dalton and Bohr proposed these models. By the end of ninteenth century, most spectral studies were focused on Hydrogen atom as the simplest atom in structure. Thus, any model placed at the atom should explain all the facts and information about the behavior of the atom.

## 8-2 Energy levels and Bohr's model

In 1911 Rutherford proposed a model of atom. He assumed that the atom is a positive nucleus at the center of the atom with electrons revolving around it, see figure (1). This model failed for the following reasons:

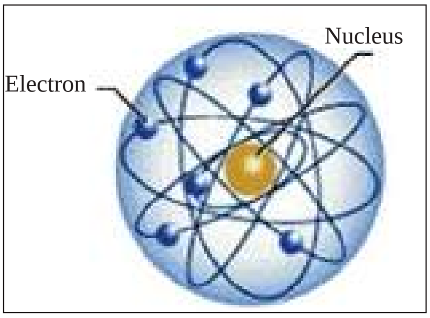


Figure (1) Rutherford a model of atom

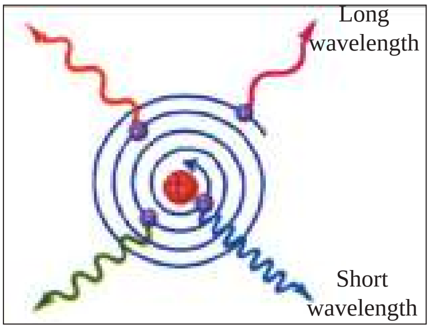


Figure (2)

1. When electrons revolve around the nucleus in the atom, it always changes its direction; therefore, it is an accelerated particle. According to classical electromagnetic theory; any charge moving with certain acceleration emits electromagnetic radiation, so, the electron moving around the nucleus must lose some of its energy while circling, i.e. it is losing energy continuously as long as it is moving. Then, it ends in a spiral movement approaching the nucleus in a short time, and then the atomic structure collapses, see figure (2).
2. When electron energy decreases gradually, a continuous spectrum is generated, while experiments show that Hydrogen atom spectrum is line spectrum.

In fact, none of these things happens, because atoms still exist and can still emit radiation with a special and a unique wavelengths. Besides, at Standard Temperature and Pressure (STP), atom is a stable structure and does not emit radiation unless heated or exposed electric potential difference in vacuum tubes.

The stable status of electrons in atom remained a clue; scientists kept searching and investigating on non-collapse of atom. Then, light spectra emitting from excited atoms were studied, quantum theory is discovered too, so, Bohr proposed 1913 a new model of the atomic structure. He hypothesizes:

1. Negative-charge electrons revolve around nucleus in a certain allowed orbits representing energy levels without radiating energy, see figure (3). An electron has lowest energy if it is in closer level to the nucleus, then, the atom is stable. An electron must have proper energy and momentum to remain at this level.

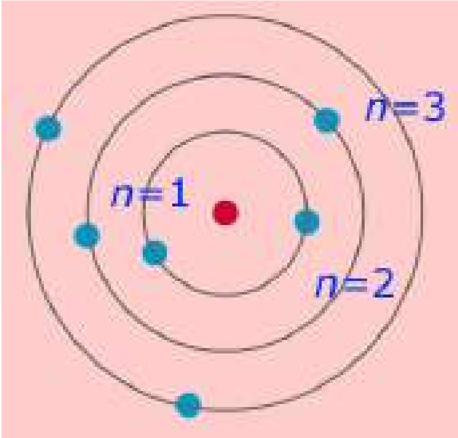


Figure (3)

2. The atom is electrically neutral when the charge of the electrons equal the positive charge of nucleus.
3. The atom does not radiate energy because of electron revolving in stationary orbits, and the atom is stable.
4. When an electron gains energy, it jumps from its stability level ($E_i$) into higher energy level ($E_f$), then the atom is excited and it moves back to its stability when the electron goes back to stability level, emitting photons with frequency (f). See figures (4, 5)….it is expressed as follows:

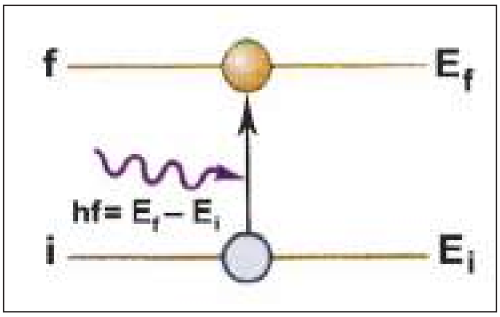


Figure (4) Atom moved from a lower energy level to a higher energy level

i.e. $hf = E_f - E_i$

h: Planck constant= $6.63 \times 10^{-34}$ J.s

f: frequency.

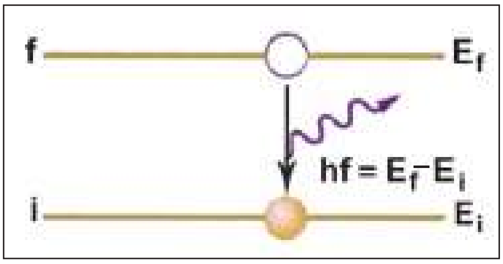


Figure (5) Atom is excited emitting photons goes back to stability level

5. Coulomb's law of electric charges and Newton's second law of mechanics are applied in atomic structure. See figure (6).
6. An electron has angular momentum (L= mvr) in its stationary orbit that equals integers from (h/2π)

$$L_n = n\left(\frac{h}{2\pi}\right)$$

$$m\nu_n r_n = n\left(\frac{h}{2\pi}\right)$$

n =1, 2, 3, 4, 5, .......... it is represent principal quantum number.

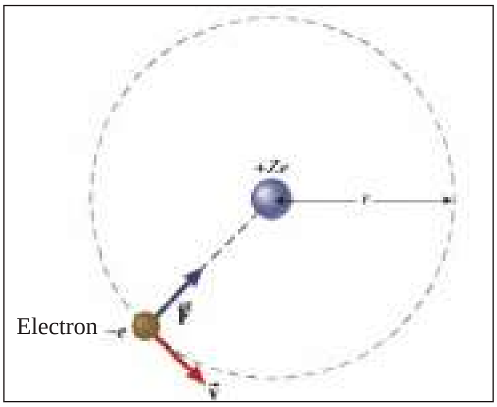


Figure (6)

## 8-3 Hydrogen atom spectrum

Bohr studied spectrum of hydrogen atom because it is the simplest form, it has one electron only. Bohr came with many observations and conclusions, which were the foundations of his theory of hydrogen atom.

When Hydrogen atom is excited, its electron moves from low-energy level to a higher energy level. It does not remain at the high energy level only for a small period, about ($10^{-8}$s), then it moves down to low-energy level.

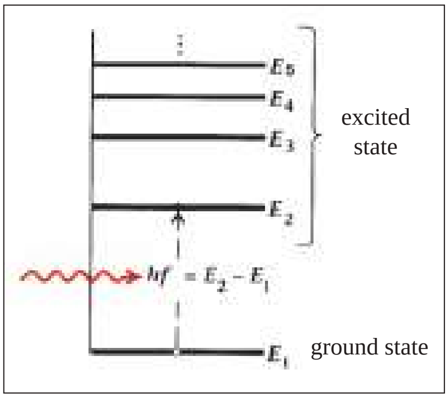


Figure (7) Energy levels

The lowest energy level ($E_1$) is called ground state, while higher levels $E_2$, $E_3$, $E_4$....... are called excited states. See figure (7).

All energies of these levels are negative; therefore, the electron has no sufficient energy to escape from the atom.

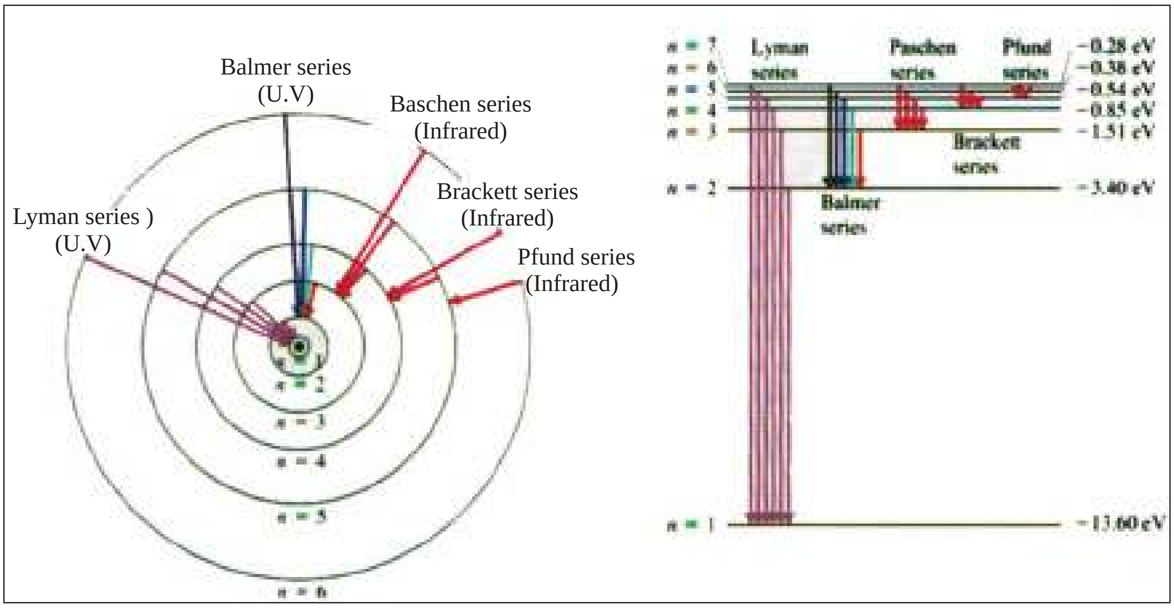


Figure (8) Energy levels of hydrogen atom

1. When the electron of hydrogen atom moves from high-energy levels to first energy level ($E_1$), where n=1, it produces lyman series, it is frequancies range lies in the ultraviolet region (UV-region). It is an invisible series, see figure (8).
2. When the electron of hydrogen atom moves from high-energy levels to second energy level, ($E_2$) where n=2, , it produces Balmer series, it is frequencies lies in the visible region and extends to ultraviolet region.

3. When the electron of hydrogen atom moves from high-energy levels to third energy level, ($E_3$) where n=3, it produces Paschen series, its frequencies range lies in the infrared region It is an invisible series.

4. When the electron of hydrogen atom moves from high-energy levels to fourth energy level, ($E_4$) where n=4, it produces Brackett series, its frequencies range lies in the infrared region It is an invisible series.

5. When the electron of hydrogen atom returns from high-energy levels to fifth energy level, ($E_5$) where n=5, it produces Pfund series, its frequencies range lies in the infrared region It is an invisible series.

## 8-4 Spectra

When sunlight is incident on a glass prism for example, it analysis into seven components, which are called Spectrum. This phenomenon is observed by Newton in late seventeenth Century. The series of light frequencies resulting from the white light when analyzed by a prism is called (spectrum). Study and explanation of atomic spectrum of matter, structure of atoms and molecules are the most important studies that led to discovery of atomic and molecular structure, by analyzing light emitting from these matters and their spectra using the spectroscope. See figure (9).

Figure (9)

The most light sources used in studying spectra are:

1. Thermal sources: which are sources that radiate light as a result of their of increasing temperature like sun, Tungsten lamps and electrical arches.

2. Sources which depend on electrical discharge through in gases, like electrical discharge tubes at low pressure.

# 8-5 Types of spectra

One might wonder, what are the types of Spectra?

What is the difference between a spectrum and others, and how to get both?

To answer this question, let us do the following activity:

## Activity

### Types of spectra

**Tools of activity:**

A glass prism, a barrier with a slit to obtain the parallel light falls on the prism, a white screen, discharge tubes (like neon, hydrogen, or mercury vapor), electric capillary lamp and an electric source.

**Activity steps:**

- The hydrogen tube is connected to the electric circuit to glow, see figure (10).
- The glass prism is placed in the path of the light emitting band from the hydrogen gas tube. Then change the position and incident angle of the emitted beam to obtain the best spectrum on the screen.
- Note shape and color of spectrum on the screen.
- Repeat the previous steps using other gas tubes, electric capillary lamp.
- Note the shape and color of the different spectra on the screen.

We conclude that spectrum resulting from analyzing radiations emitting from other gases differ according to the type of gas.

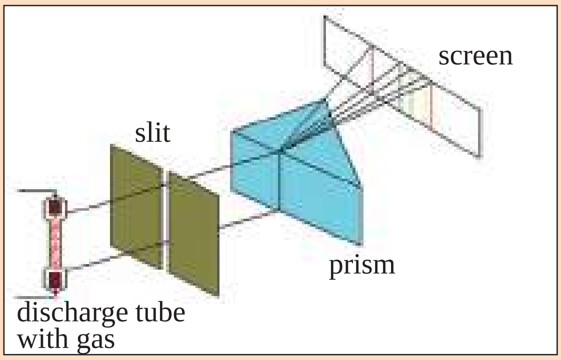


Figure (10)

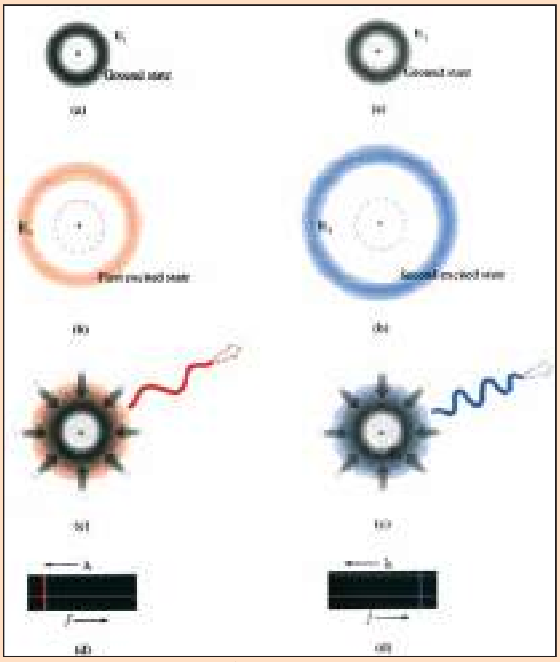


Figure (11) [For refrence only (not required)]

There are two types of Spectra:

1. Emission Spectra.
2. Absorption Spectra. See figure (11).

1. Emission Spectra: they are spectra of incandescent materials, which are:

a. Continuous spectrum: this spectrum is obtained from incandescent solid and liquid incandescent material or incandescent gas under high pressure. Figure (12) illustrates a continuous spectrum with a wide range of frequencies.

Spectrum emitting from white tungsten capillary lamp is a continuous spectrum; it consists of a wide range of a continuous wavelengths within visible range.

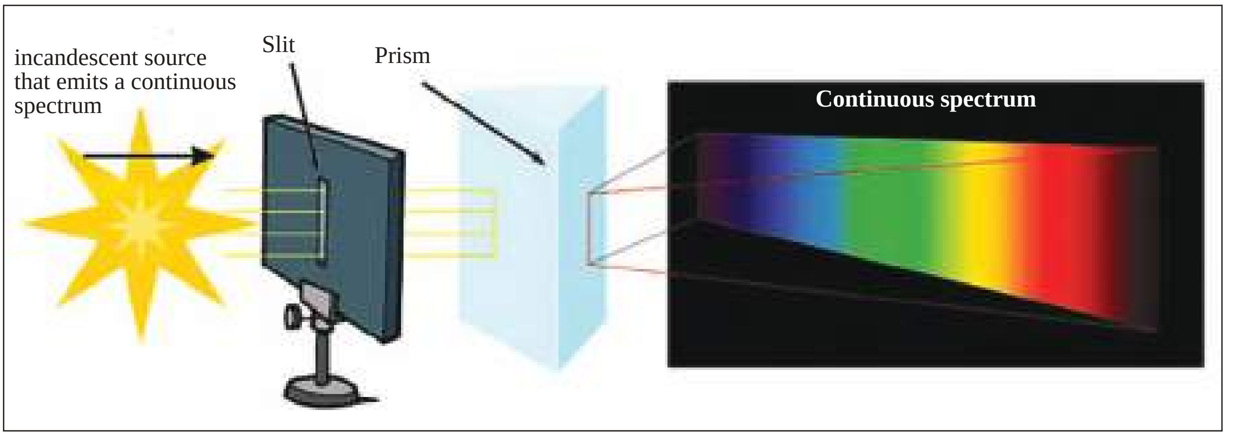



Figure (12) Continuous spectrum

b. Line spectrum: this spectrum is obtained from incandescent gases and vapors under normal or low pressure, see figure (13).which illustrates a set of bright colorful lines on a black background, each of which represents particular wavelength.

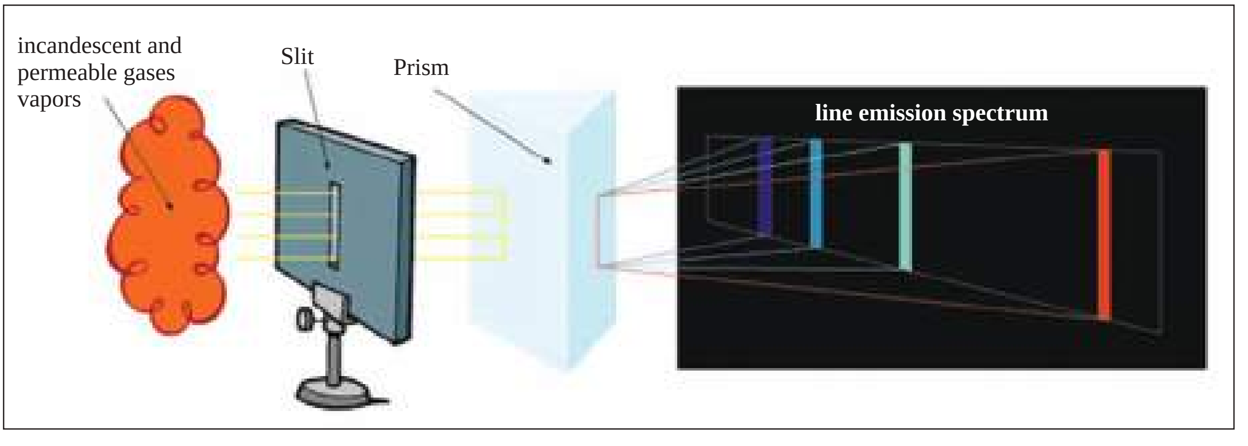



Figure (13) Line spectrum

The bright line spectrum of Sodium consists of two bright yellow lines very close to each other, at the yellow region of the visible spectrum. If the spectroscope is not accurate, the yellow lines might appear as one line. As for line spectrum of hydrogen; it consists of four bright lines (red, green, dark blue and purple). See figure (14).

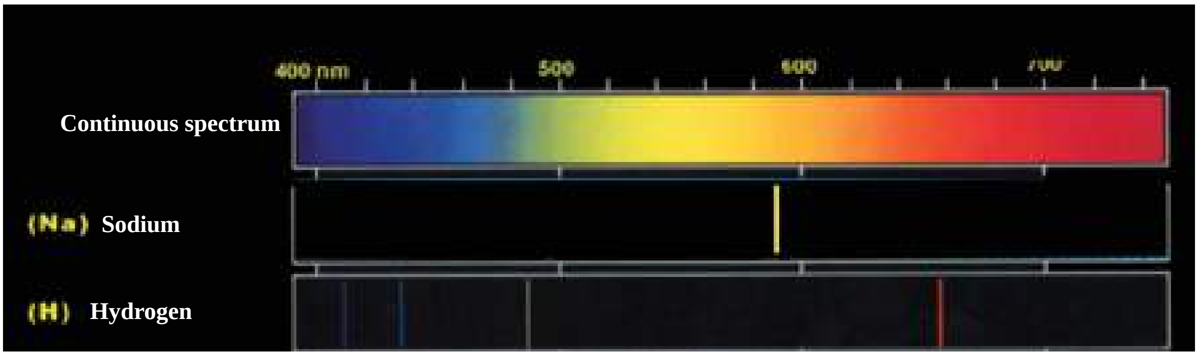



Figure (14) [For refrence only (not required)]

It is found that each element has its own line spectrum, i.e. line spectrum is a basic and distinctive characteristic of atoms. The study of spectra has led to developing detection methods of an unknown element in a certain material or the components of alloys. This can be done taking a sample of that material and vaporize it in a carbon arch to make it glow, then its line spectrum is recorded by the spectroscope and compared with standard spectra of each element.

c. Band spectrum: it is a spectrum, which contains a band or a number of bands on a black background. Each band consists of convergent lines; it is a characteristic feature of molecular structure materials. It can be obtained from glowing molecular materials like Carbon dioxide gas in a discharge tube, which contains Barium salts, or Calcium salts that are glowing by Carbonic arch.

2. Absorption Spectra: it is a continuous spectrum punctuated by lines or dark bands. When light passes through non-incandescent vapor (or permeable material) it absorbs from the continuous spectrum wavelengths it emits if it was incandescent. Then we get the absorption spectrum. see Figure (15).

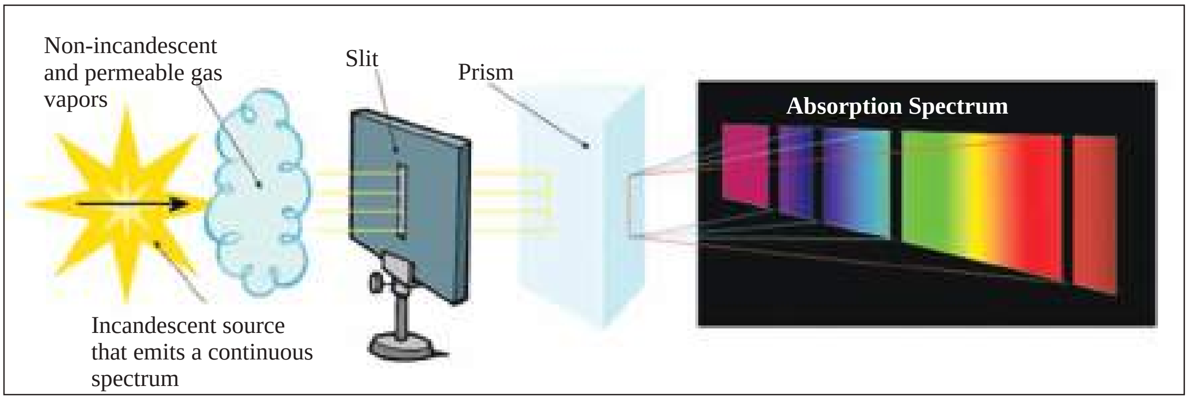



Figure (15) Absorption Spectrum

It is noted that the gaseous atmosphere, which surrounds the sun absorbs a portion of its continuous spectrum (it absorbs wavelengths emits if it were it incandescent). Fraunhofer noticed black lines in the continuous spectrum of the sun, called Fraunhofer lines, named after the scientist Fraunhofer who discovered about (600) lines of it.

The reason behind the black lines in the sun is that the gases around the sun and in the atmosphere of the earth that are less incandescent than the gases of the interior of the sun absorb from the continuous spectrum of the sun the wavelengths that these gases emit if they were incandescent, this is called line absorption spectrum of the sun, and from these lines it is possible to know the gases that absorb this light. See figure (16).

**DO you know?**

The helium element was discovered from the linear absorption spectrum of the sun before it was discoverd on the surface of the earth.

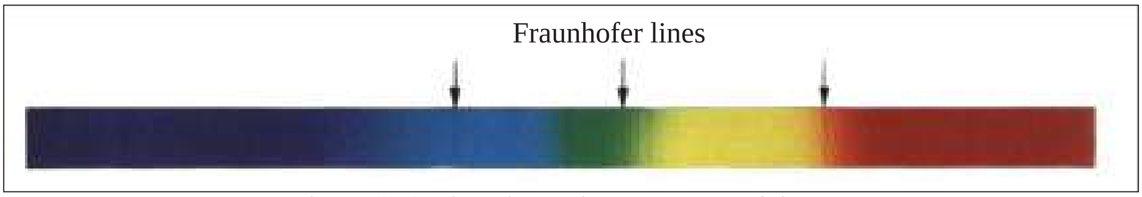



Figure (16) Line absorption spectrum of the sun

## 8-6 X - rays

X-ray was accidentally discovered in 1895 by Roentgen while working on electricity of gases and electric conduction of electrons inside partially discharged tubes.

X-ray are invisible electromagnetic waves with a very short wavelength (0.001-10) nm. They are not affected by electric or magnetic fields because they are not charged particles. The X-ray can be obtained by using a vacuum glass tube, see figure (17).

This tube has two poles, one is negative (Cathode); a filament which emits electrons when heated. The other pole is positive (Anode); it is a metal target, which inclines by a certain angle toward the movement of accelerated electrons. This collision causes high heat; therefore, the anode target is made of a material of high melting point like Tungsten and Molybdenum. It is also made of a material of large atomic number to increase efficiency of X-ray. Some techniques are used to cool down the anode due to high heat.

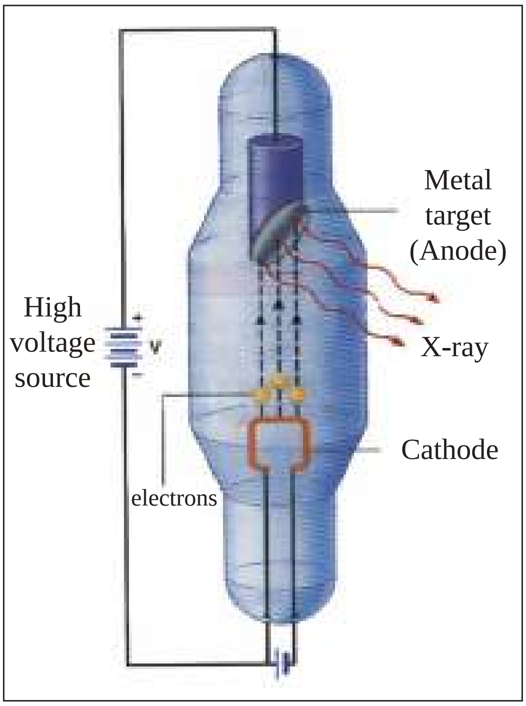



Figure (17) X-ray generator

**DO you know?**

Wilhelm Roentgen professor discovered X-rays and because he was ignorant of their nature, he called these rays an (X-ray).

### Types of X-ray Spectrum

X-ray is a reverse of photoelectric effect because it is generated to transform energy of accelerated electrons emitting from cathode and falling on the target into X-ray photons. Figure (18) illustrates typical X-ray spectrum, which results from collision of electrons with target, hence, intensity of X-ray is directly proportional with number of emitted photons at a given wavelength. X-ray spectrum consists of two types: Continuous spectrum and line spectrum.

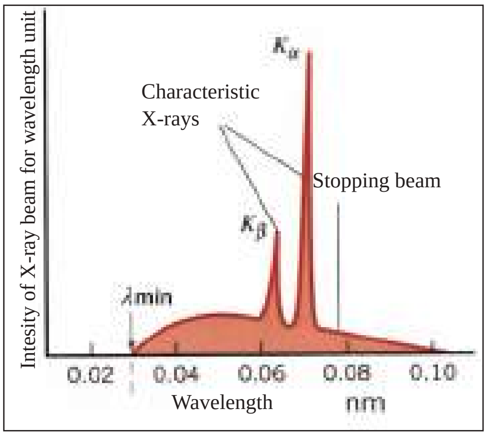


Figure (18)

1. A sharp line spectrum X-ray: also called (Characteristic X-ray spectrum). When accelerated electrons are fall on the atom of the target material, these electrons extract one of the electrons from inner levels of the target material and leave the atom permanently and ionization state occurs. This electron might go up into a higher energy level, and becomes excited. In both cases; the atom becomes anxiety (excited) and attempts to return to stability. When an electron falls from a high-energy level (with high energy) to the energy level from which the electron was extracted, energy is emitted in the form of an X-ray photons. Its energy is the energy difference between levels $E_1$, $E_2$ that is:

$$hf = E_2 - E_1$$

This spectrum is a characteristic feature of target atom material.

2. Continuous spectrum X-ray: This spectrum results from the collision of accelerated electrons with the atom of target material. This collision slows down their movement because of the electric field nuclei of target material. Because of this slowdown, electrons lose their energy and appear as X-ray photons with different frequencies.

Maximum frequency of an X-ray photons depends on potential difference (V) applied at the sides of X-ray tube, which accelerates the electron and gives it maximum kinetic energy ($KE_{max}$) according to the following relation:

$$KE_{max} = eV$$

$KE_{max}$: Maximum kinetic energy of electron.

e: Electron charge.

V: Potential difference.

When electrons collide with target, this energy is transformed into radiation energy of X-ray photon (X-ray quantum).

Then we have this relation: $(KE)_{max} = Ve$

Form previous relation we have the following:

$$hf_{max} = Ve \Longrightarrow f_{max} = \frac{Ve}{h}$$

$f_{max}$: Maximum frequency of photon.

$\lambda_{min}$: Minimum wavelength, see figure (18).

$$f_{max} = \frac{c}{\lambda_{min}}$$

From both relations above, we have the following:

$$\therefore \frac{c}{\lambda_{min}} = \frac{Ve}{h}$$

$$\therefore \lambda_{min} = \frac{hc}{Ve}$$

Applications of X-ray is used in the following fields:

1. Medical field: X-ray gives a clear image of bones, which appear as light color, and tissues appear as dark color in radiographs. It is used to diagnose tooth decay, fractures, specify location shrapnel and bullets in the body, as well as detection and treatment of some tumors in the body. See figure (19).

X-ray is also used to sterile Medical equipments like plastic surgical gloves and syringes. These equipments damage when exposed to excessive heat, therefore, they cannot be sterilized by heat.


Figure (19) Some application of X-ray [For refrence only (not required)]

2. Industrial field: it is used to detect dents and cracks in metal molds and wood used in building boats. Studies on absorption spectrum helped in making X-ray one of the ways of detecting and analyzing component elements of various materials. It is also used in study of solids and crystalline structures.

3. Security Field: X-ray is used in checking passengers' luggage in airports, see figure (20).

It is also used in identifying the methods of painters and distinguishing between real paintings and fake paintings, because colors used in old paintings contain many metalic compounds, which absorb X-ray while modern paintings are organic compounds, which absorb less X-ray.

Figure (20)

## 8-7 Compton effect

Compton concluded that when a band of X-rays (photons) of a given wavelength (λ) is incident on a target metal of pure graphite, rays will scatter with different angles. Scattered ray has a longer wavelength (λ') than that of the original ray (λ) for the incident ray. Change in wavelength (λ' -λ) increases with the increase in scattering angle (θ) and an electron emit on the other side of the target, see figure (21).

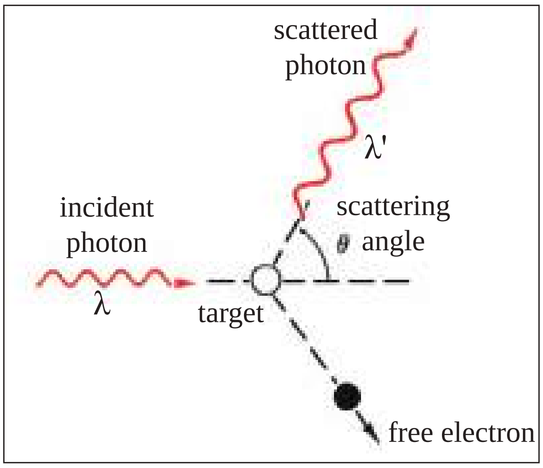



Figure (21) Compton effect

Compton explained this phenomenon saying that the incident photon on graphite target collides with a free electron from the target material, losing some of its energy. After collision, this electron gains an amount of kinetic energy, enabling it to travel and leave target material (The photon acts as particles).

He assumed that the collision between the photon and the free electron is elastic scattering, it follows laws of momentum conservation and energy conservation.

According to Compton Effect:

Increase in wavelength of scattered X-ray photons by free electrons of target atom, compared to wavelength of incident photons depends on scattering angle (θ) only according to the following relation:

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

Since:

λ': wavelength of scattered photon.

λ: wavelength of incident photon.

h: Planck's constant= $6.63 \times 10^{-34}$ J.s.

$m_e$: Electron mass= $9.11 \times 10^{-31}$ kg.

c: Speed of light in vacuum= $3 \times 10^{8}$ m/s.

θ: photon scattering angle.

$h/m_e c$ Represents Compton wavelength which equals $(0.24 \times 10^{-11}\,m)$.

It is worth noting that Compton Effect is an important proof particle behavior of electromagnetic waves, which Maxwell theory failed to explain.

**Example (1)**

What is the amount of increase in wavelength of a scattered photon (in Compton Effect) if scattered at ($60^0$) angle? If:

Planck's constant= $6.63 \times 10^{-34}$ J.s

Speed of light in vacuum= $3 \times 10^{8}$ m/s.

Electron mass= $9.11 \times 10^{-31}$ kg.

**The solution:**

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

$$\Delta\lambda = \lambda' - \lambda = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 3 \times 10^{8}}(1 - \cos 60^\circ)$$

$$\Delta\lambda = \lambda' - \lambda = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 3 \times 10^{8}}\left(1 - \frac{1}{2}\right)$$

$\Delta\lambda = \lambda' - \lambda = 1.2 \times 10^{-3}\,nm$ the amount of increase in wavelength of photon.

**Example (2)**

If the potential difference between poles of X-ray tube is $(1.24\times10^{4}V)$, to generate the shortest wavelength on a graphite target in (Compton Effect), if X-ray scattering angle is ($90^0$). What is the wavelength of scattered X-ray?

**The solution:**

$$hf_{max} = (KE)_{max} = eV$$

$$f_{max} = \frac{eV}{h} = \frac{1.6\times10^{-19}\times(1.24\times10^{4})}{6.63\times10^{-34}J.s}$$

$$f_{max} = 2.99\times10^{18}Hz \simeq 3\times10^{18}Hz$$

$$\lambda_{min} = \frac{c}{f_{max}} = \frac{3\times10^{8}}{3\times10^{18}} = 1\times10^{-10}m$$

$$\lambda_{min} = 0.1\times10^{-9}m \quad \text{incident X-ray wavelength}$$

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

$$\lambda' - 0.1\times10^{-9}m = (0.24\times10^{-11}m)(1-\cos90^\circ)$$

$$\lambda' - 0.1\times10^{-9}m = (0.24\times10^{-11}m)(1-0)$$

$$\lambda' = 0.24\times10^{-11}m + 0.1\times10^{-9}m$$

$$\lambda' = 0.0024\times10^{-9}m + 0.1\times10^{-9}m$$

$$= 0.1024\times10^{-9}m$$

$$\lambda' = 0.1024nm \quad \text{Scattered X-ray wavelength.}$$

## 8-8 Laser and maser

Laser has become an important element in many technological products like Compact disks, electronics, and accurate distance measurements, especially celestial objects, and communications. Dentists' machines and welding machines also use laser. but what is laser? Why it is different from other light sources?

laser is named as the first letter of the words that give the idea of the mechanism of action laser as an acronym for

Light Amplification by Stimulated Emission of Radiation

It means the amplifaction of light by stimulated emission of radiation

Albert Einstein was the first in 1917 set the theoretical foundation of stimulated emission. T.H. Maiman designed the first Laser device in 1960 using ruby crystal. It is called ruby laser.

As for Maser, it is named of: Microwave Amplification by Stimulated Emission of Radiation.

**DO you know?**

Scientist Towns was able to design the first device to amplify microwaves using stimulated emission technology, which is an ammouia maser in 1954.

## 8-9 Properties of laser

### Laser enjoys the following features:

1. Monochromatic wavelength (monochromaticity): It has one wavelength. Laser beam has the purest spectrum of all light sources light emitting from other sources has a wide of wavelengths. See figure (22).

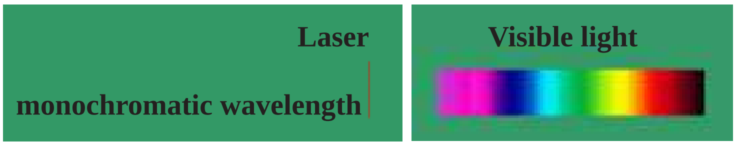



Figure (22)

2. Coherency: The waves of a laser beam have the same phase, direction and energy. Thus, two waves can constructive interference. See figure (23).

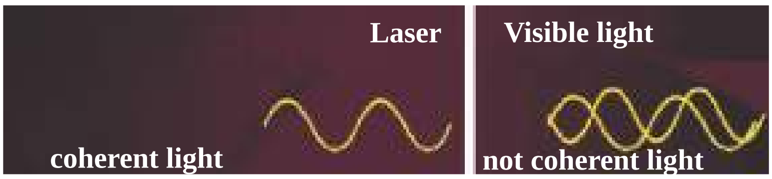



Figure (23)

This can be observed when laser ray is directed onto a barrier, it appears as small speckle dot, see figure (24).

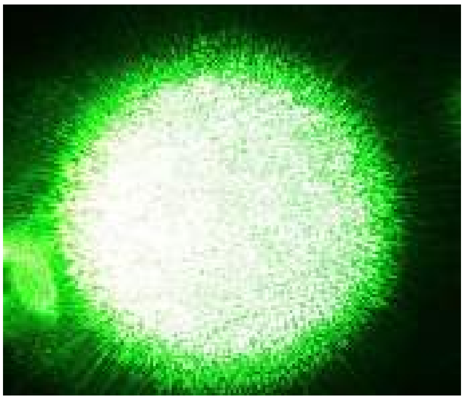


Figure (24) represents the interference of the laser beams.

3. Directionality: laser waves remain parallel for a long distance with a little divergence from each other. This means that laser beams relatively maintain intensity while normal light waves propagate randomly in all directions, see figure (25). If a laser beam wave is sent to the moon (384000 km) from earth, with sufficient intensity, it spreads a spot of light on the surface of the moon around (1 Km). while normal light, if sent to the moon , hypothetically, the diameter of spreads light on the moon's surface around (4376 km).


Figure (25)

4. Brightness: Energy of laser beam waves concentrate in a small space because they do not diverge, therefore, laser beam has a very high brightness, see figure (26). Laser beam can be million times brighter than sunlight. For example, intensity of emitted rays from normal tungsten lamp with power (100 watt) equals (2000watt/cm$^2$) while intensity of laser with the same amount is ($2\times10^9$watt/cm$^2$), i.e. million times higher than Tungsten lamp.

Figure (26) laser brightness

## 8-10 Mechanism of laser action

One might ask:

- What are conditions for generating laser?
- What are transmission, which happen between excited energy level and ground level?
- What are the transmission, which generate laser? and under what conditions?
- Are these transmission necessary to emission laser beam?

To answer these questions. See figure (27-a-b-c)

Assume an atomic system of two- energy levels, and three types of electron transmission:

## 1. Induced Absorption:

It is the transmission of the atom from low-energy level ($E_1$) to an excited -energy level ($E_2$) by absorbing a photon whose energy is equal to the difference between these two levels, see figure (27-a).

i.e. $E_2 - E_1 = hf$


an excited atom in the energy level ($E_2$) after absorbing a photon whose energy

$hf = E_2 - E_1$

Figure (27-a) Induced Absorption

## 2. Spontaneous emission:

When the atom reaches higher-energy level (excited state), it tends to back to stability. So it spontaneously goes back to stability after a short period of time (period of excited state) to the ground state. this process is accompanied by photon emission whose energy is equal to the difference between levels ( $E_2 - E_1 = hf$ ) this transmission is called Spontaneous emission, see figure (27-b).

Spontaneously emitted photons are different in terms of phase, direction and energy. See figure (28).


Figure (27-b) Spontaneous emission

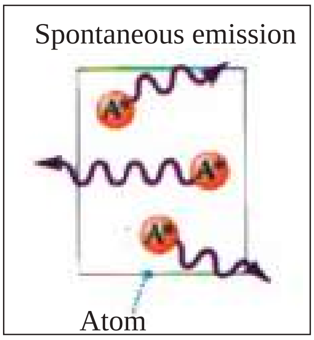



Figure (28) Spontaneously emitted photons are different in phase and direction.

## 3. Stimulated Emission:

When a photon affects an excited atom at energy level ($E_2$), the Photon energy is equal to energy difference between $E_2$ and lower energy level $E_1$. The Photon stimulates the unstable electron to decline (descent) to level $E_1$. An identical photon is emitted, it has the same energy, frequency, phase and direction. i.e. two coherent photons are obtained, See figures (27-c), (29).

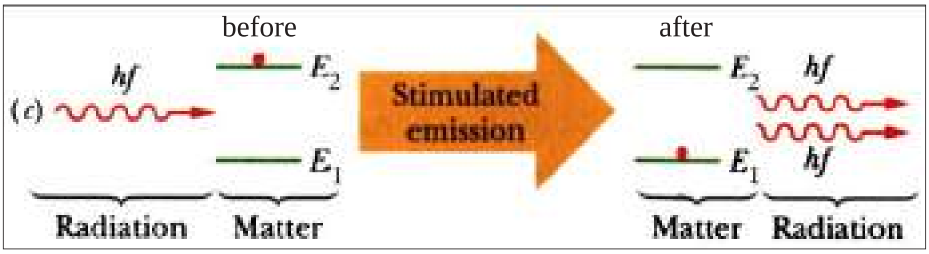



Figure (27-c) Stimulated Emission

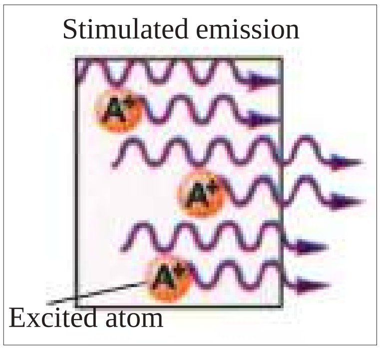



Figure (29) Two coherent photons in stimulated emission

## 8-11 Boltzmann distribution and population inversion

If we have a system of (molecules atoms or ions) in a state of thermal equilibrium, most atoms will be in low-energy levels, few of them will be excited at higher energy levels, see figure (30).

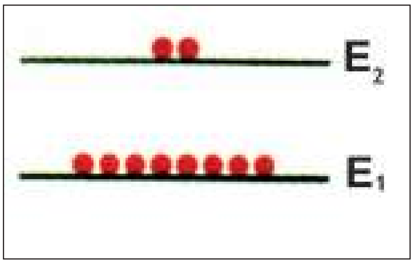



Figure (30)

This means that population or number of atoms and molecules in the ground state ($N_1$) is larger than the number of atoms and molecules in higher energy level ($N_2$), see figure (31).

i.e. $N_1 > N_2$

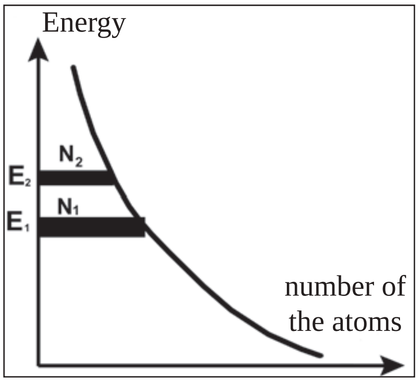



Figure (31)

Boltzmann found a mathematical relation illustrates the distribution of atoms or molecules in energy levels, this equation is named after him and called Boltzmann law according to the following relation:

$$\frac{N_2}{N_1} = \exp\left[\frac{-(E_2 - E_1)}{kT}\right]$$

Since

k: Boltzmann's constant.

T: temperature (Kelvin).

$N_2$: number of atoms in higher energy level.

$N_1$: number of atoms in ground state of energy level.

$E_2$: high energy level.

$E_1$: lowest energy level.

For example, suppose an atomic system of 100 atoms, the normal distribution of atoms can be illustrated according to Boltzmann distribution of this system, as in figure (32).

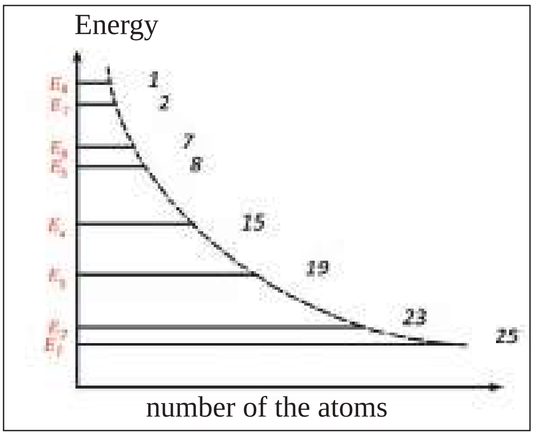



Figure (32)

The figure shows that lower levels ($E_1$) have greater number of atoms (25 atoms), while higher levels ($E_8$) have less number of atoms (1 atom).

## Population Inversion:

If the atomic system is not thermal equilabrium, the number of atoms in higher levels is greater than those in low-energy levels. This is contrary to Boltzmann distribution, see figure (33), meaning that the distribution of atoms in this case is inversed, it is called Population Inversion, see figure (34). This process increases probability of stimulated emission, it is the basis of producing laser. It happens when there is sufficient pump intensity,it is achieved by the presence of an energy level with a relatively longer lifetime and this level is called the Metastable state.

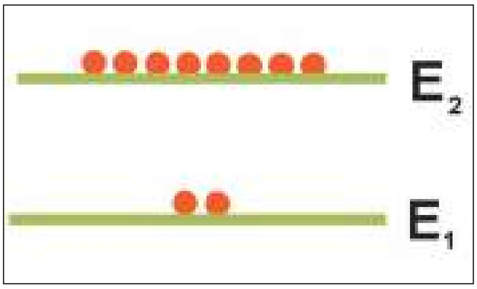


Figure (33)

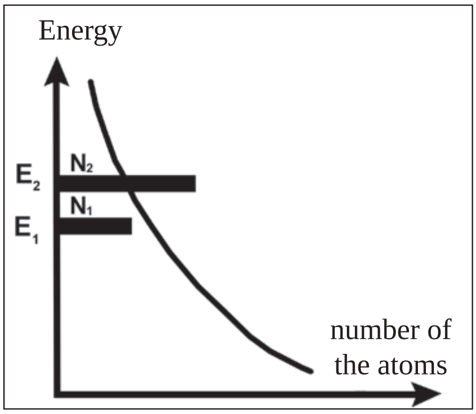


Figure (34) Population Inversion

### Example (3)

If energy difference between the two levels is equal to (KT) at room temperature, calculate the number of atoms ($N_2$) by significance of ($N_1$)?

### The solution:

$$\frac{N_2}{N_1} = \exp\left[\frac{-(E_2 - E_1)}{kT}\right]$$

$$\frac{N_2}{N_1} = \exp - \left[\frac{kT}{kT}\right]$$

$$\frac{N_2}{N_1} = \exp(-1)$$

$$\frac{N_2}{N_1} = e^{-1} \Longrightarrow N_2 = 0.37N_1$$

This means that, in normal conditions, the number of atoms ($N_1$) in level ($E_1$) is greater than number of atoms ($N_2$) in level ($E_2$) ($N_1 > N_2$) .

**Example (4)**

Prove mathematically that population inversion is not achieved when thermal energy (kT) is equal to incident photon energy.

**The solution:**

$$\frac{N_2}{N_1} = \exp\left[\frac{-(E_2 - E_1)}{kT}\right] \quad \text{..................1}$$

$$E_2 - E_1 = hf \quad \text{..................2}$$

$$kT = hf \quad \text{..................3}$$

$$\frac{N_2}{N_1} = \exp - \left[\frac{hf}{hf}\right]$$

$$\frac{N_2}{N_1} = \exp(-1)$$

$$\frac{N_2}{N_1} = 0.37 \Longrightarrow N_2 = 0.37N_1$$

$\therefore N_2 < N_1$ Thus, population inversion is not achieved.

**Remember:**

1. To generate laser, the number of atoms at excited state must be greater than in the low energy levels, this process is called population inversion.
2. stimulated emission cannot be reached without spontaneous emission occuring first.
3. Photons which are obtained from spontaneous emission that emits parallel to the optical axis within the active medium that stimulate the excited atoms and produce stimulate emission (laser production).

## 8-12 Construction of laser

The diagram shown in figure (35), shows the most important components required in laser devices:

1. Active medium.
2. Optical resonator.
3. Pumping technique.

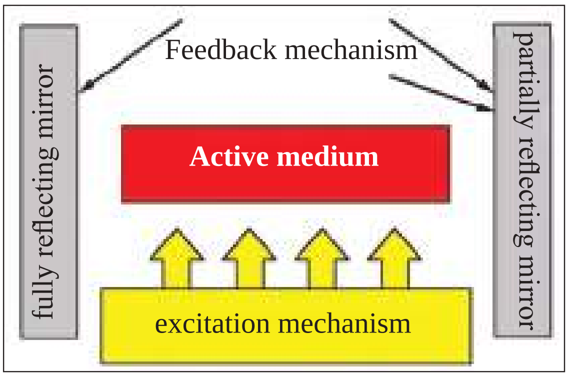



Figure (35) Laser construction diagram

**1. Active medium:** It is atoms, molecules or ions of matter whether its gaseous, liquid or solid state at which population inversion can takes place when the active medium is excited enough.

**2. Optical resonator:** A cavity with particular design consisting of two mirrors, the active medium is placed between them. The mirrors are facing each other; one of them reflects light totally, while the second is partially reflecting light (reflection depends on wavelength of generated laser), the incident ray on one of the mirrors reflects parallel to the optical axis of the two mirrors then incidents on the other mirror, then it reflects back and forth inside the optical resonator. In each reflection, stimulated emission happens, thus number of photons generated by stimulated emission increase enormously which causes amplification. Partial reflection mirror allows permeability of some incident light outside the optical resonator, as for the remaining light, it is reflected back again to perpetuating amplification process. See figure (36)

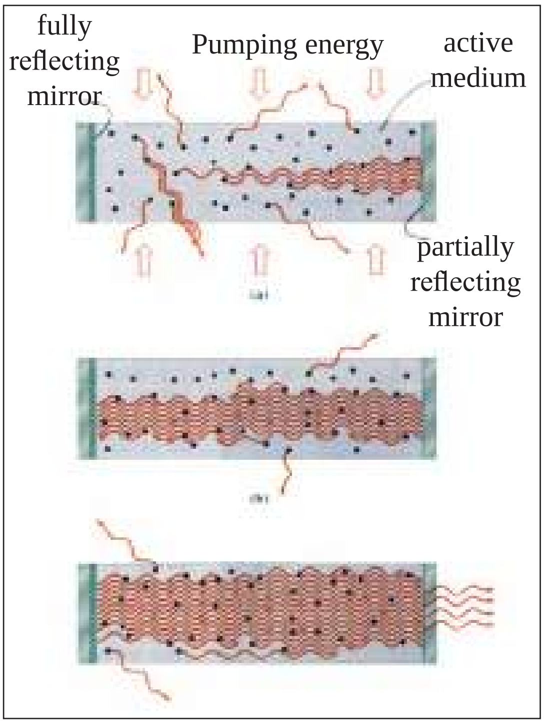


Figure (36)

**3. Pumping technique:** It is a technique by which atom energy is prepared for use in the active medium by transforming it from stability state to excitation state. Pumping energy is obtained to excite the stable atoms in medium so that proper population inversion is achieved. This population inversion ensures generating laser.

There are three types of Pumping techniques:

**a. Optical Pumping:** it is used to generate lasers, which work within the visible or infrared region close to visible spectrum, like ruby laser and Neodymium laser.

As flashing or continuous lights are used with high illumination power to excite the active medium, the walls of flashing lamps are made of quartz material and filled with different gases depending on the type of active medium, and they are in different shapes, spiral or straight, see figure (37).


Figure (37)

There is another technique for optical pumping in which a specific laser beam is used to make this beam excited the active medium to achieve population inversion and obtain a wavelength laser that differs from the pumping laser beam.

**b. Electrical pumping technique:** this technique uses electrical discharge the gas placed inside the electric discharge tube. A high potential difference is applied between its sides of the tube, accelerated electrons collide with gas atoms or molecules. This process excites the electrons and transition them into higher energy level. This technique is often used in gas lasers. This technique is also used in producing semiconductor laser.

**c. Chemical pumping technique:** in this technique, the chemical reaction between components of active medium is the source of providing energy to generate laser. This technique does not require an external power source.

## 8-13 Laser levels systems

Laser levels systems can be classified according to energy levels, which participate to achieve population inversion of the active medium in to two types:

1. Three- level system.
2. Four-level system.

**1. Three-level System:** In this system, three energy levels are involved. These levels are: ground state of energy ($E_1$), intermediate state of energy ($E_2$) (metastable state), and excited state of energy ($E_3$), see figure (38).

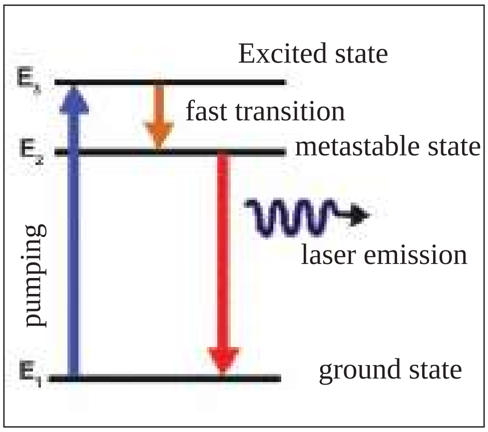


Figure (38) Three-level System

When most atoms or molecules are in the ground state of energy ($E_1$), this means that the active medium is in a stable state. But, when the active medium is excited by any of the pumping techniques, these atoms or molecules will be excited to ($E_3$). The lifetime of this process is short, around ($10^{-8}$s). To generate laser, there should be sufficient pumping energy to achieve population inversion.

These atoms soon descend spontaneously from ($E_3$) level to metastable state ($E_2$) by thermal emission. The lifetime of this process is longer, around ($10^{-6}$s), which gathers atoms in level ($E_2$) larger than level ($E_1$), thus population inversion is achieved between these levels. stimulated emission of laser happens. These systems require high pumping energy so that the number of excited atoms increases and becomes larger then ground state. Consequently, population inversion is achieved.

### 2. Four-level systems:

In this system, four levels are involved ($E_1$, $E_2$, $E_3$, $E_4$). In this process, ground state atoms ($E_1$) are pumped into excited state ($E_4$) of energy. See figure (39), then, these atoms soon fall to energy level ($E_3$). Thus, atoms gather at energy level ($E_3$) (Metastate state in this system). Then, population inversion is achieved between levels ($E_3$) and ($E_2$), with a minimum number of atoms at level ($E_3$), while level ($E_2$) is almost empty because of the fast fall of atoms. This system requires less pumping energy to achieve population inversion compared to three-level system.

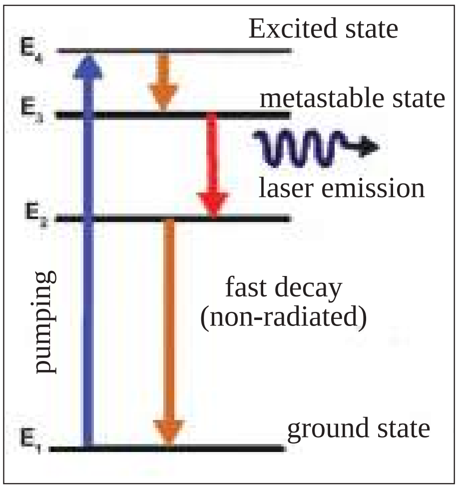


Figure (39) Four-level systems

**Question:**

Which is better for generating a laser the three-level system or the four-level system? why?

## 8-14 Types of laser

Laser has different types according to active medium, for example, Helium Neon laser (He-Ne leaser) means that the active medium is a mix of helium and neon, while ruby laser means the resulting material is ruby laser and so on. Let us consider laser types:

1. Solid –state laser: like ruby laser and neodymium laser.
2. Gas laser: like Helium-Neon laser and carbon dioxide laser, see figure (40).
3. Excimer laser: are useful and important type of molecular lasers which utilize transfers between two different electrons states. Lasers from noble gases like xenon, Krypton,


Figure (40) gas laser

argon with Halogen atom to form halide gas like (ArF, KrF, XeCI), these gases produce laser with ultra-violet wavelengths.

4. Dye laser: they are lasers in which the active medium is liquid state from solution compounds of organic dye like dissolved Rhodamine 6G in a liquid such as methyl alcohol of ethyl alcohol. It produces laser of controllable wavelength.

5. Semiconductor laser: like Gallium arsenide laser.

6.Chemical Laser: It is the laser, in which population inversion is achieved by the chemical reaction directly like Deuterium fluoride laser.

## Gas lasers:

Gas lasers are the most common in industry, some of which have low power (0.5-50) mW like He-Ne Laser. Some of which have high power (1mW-60kW), like carbon dioxide laser. Wavelength of these lasers ranges between ultraviolet, visible light and infrared ray. External energy is pumped into the active medium is electric pumping, whereby free electrons between the two electric poles are accelerated during thier movement and collide with gases, thus excited into higher energy level. Generally, gas laser systems have three components, see figure (41):

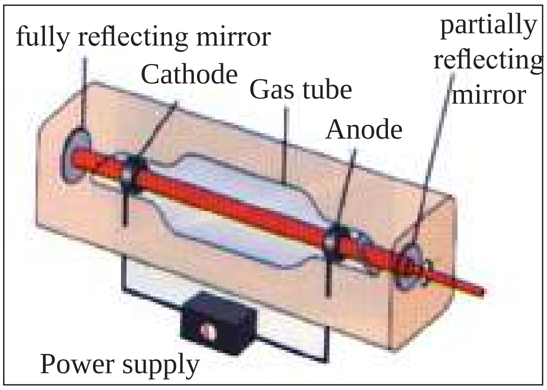



Figure (41) Gas laser components

1. Discharge tube: contains the active gas medium.
2. Power supply: helps achieve excitement of active medium through electric poles.
3. Optical resonator: helps to increase population inversion in the active medium by means of feedback.

Lasers can be classified into three classes according to the state of active medium:

1. Atomic lasers: like He-Ne laser and He-Cd laser.
2. Ionic Lasers like argon ion laser ($Ar^+$) and Krypton ion laser ($Kr^+$).
3. Molecular lasers like carbon dioxide laser.

## He-Ne Laser

Figure (42)

Helium –Neon laser was discovered at the end of the year (1960) by Javan. It is an atomic laser. See figure (42), the active medium of this laser is consists of gases mixture (Helium and Neon) in a glass tube with a specific ratio and (8-12) Torr pressure. Neon atoms are responsible for generating laser, while Helium atoms have assisting role in exciting Neon atoms. The gas active medium is usually pumped by means of electric discharge, imposing (2-4) kV high voltage on the sides of glass tube. See figure (43).

When electric discharge happens inside the tube. Helium atoms absorb the resulting energy from collision of accelerated electrons and helium atoms move from stability state to excite metastable states, this can be represented as follows:

represented as follows:

Since:

$e_1 + He \rightarrow He^* + e_2$

$e_1$: accelerated electron before collision.

$e_2$: electron after collision.

$He^*$: excited helium atom.

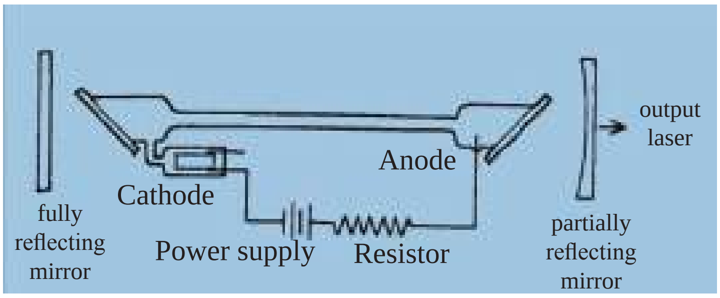



Figure (43)

Excited –Metastable states of helium atoms are similar to excited state of neon atoms, which lead to collision between them. This excites Neon atoms and moves them into excited state; this can be represented as follows:

$$He^* + Ne \rightarrow Ne^* + He$$

Hence, population inversion of Neon atoms happens which leads to stimulated emission, and the atom moves to metastable state. Thus, four laser lines are obtained (632.8) nm, (339, 543, 1153) nm, see figure (44)

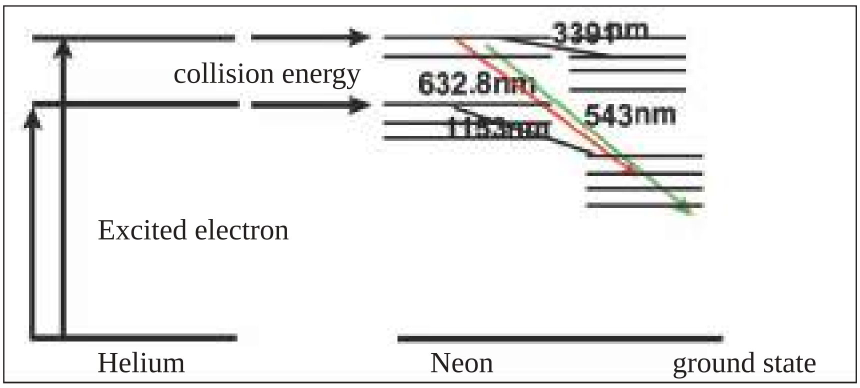



Figure (44) [For refrence only (not required)]

## Carbon Dioxide Laser:

This laser was discovered in 1964; it is the most efficient gas laser as it efficiency reaches about (30%) and has greater output power. It is a molecular laser. The active medium of this laser is a mixture two of carbon dioxide, nitrogen gas and helium gas with a specific ratio. This laser is pumped by electric discharge technique, it emits two laser lines with wavelengths (9.6) µm and (10.6) µm .

## Solid Lasers:

### Ruby Laser:

Ruby laser was the first laser made in 1960. Its consist of a solid cylindrical crystal of ruby, see figure (45). It contains Aluminum Oxide ($Al_2O_3$) doped with Chrome Ions $Cr^3$ (5%) of the total weight with active ions around ($10^{22}$/ $m^3$). It works under three-level system. Pumping is done by flash lamp, see figure (46).

Figure (45)

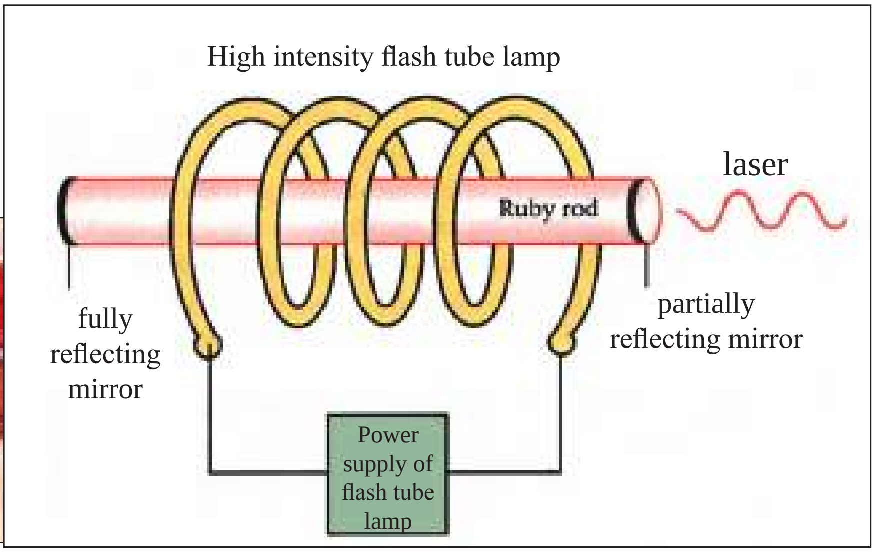



Figure (46)

### Neodymium Yag laser:

The active medium of this laser consists of yttrium aluminum oxide ($Y_3AI_5O_{12}$) with neodymium ions impurities ($Nd^{+3}$) not exceed (1.5%).It works under four-level system inside the crystal. Three different laser lines are obtained ( 914.2nm, 1060nm, 1359nm).

## Semiconductor Lasers:

The active medium of these lasers is made of donor and acceptor semiconductor materials. Conduction band represents higher laser level while valence band represents lower –laser level. Pumping is through electric current. It moves electrons and holes between these bands, see figure (47).

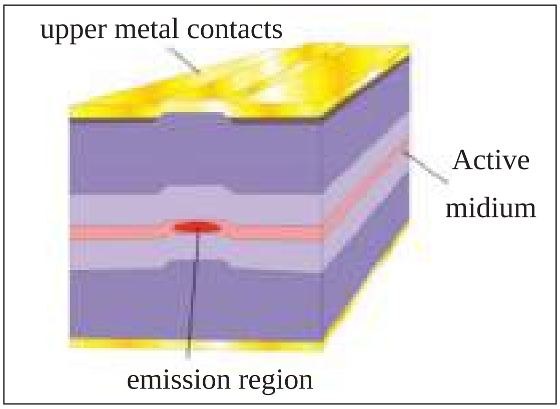



Figure (47)

When a proper voltage is placed with forward bias on the active material of the semiconductor (P-N) used to generate laser, the flowing current increases gradually starting from zero. A spontaneous emission happens at the beginning with wide spectrum, then width of the spectrum decreases when the flowing current increases due to laser action (when it passes threshold current). The spectrum line become very thin at a value larger than the threshold current, see figure (48). It is worth noting that in such lasers, population inversion happens when the holes in valence bands increase and electrons increase in conduction band.

Gallium Arsenide (GaAs) is a semiconductor used as a base to manufacture semiconductors. This laser emits in the infrared region, around (850) µm wavelength.

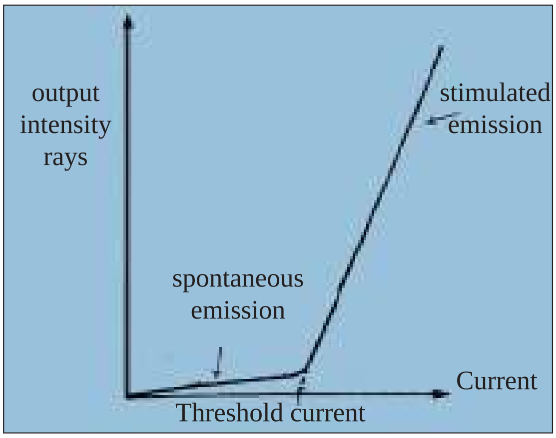



Figure (48)

## 8-15 Some application of laser

1. Industrial Applications: laser is an effective tool in manufacture and a refine of many electronic parts like resistors, capacitors, transistors, and integrated circuits masks, punching and welding of metals. Laser is important in microelectronics because it encloses heat in a tiny spot without touching other components and neighboring parts. Laser is also used in welding solid materials, active and elements, which have high fusibility not to mention precision in making. It sends a condensed and concentrated band.
   It can drill a (5) µm diameter hole in (200) µs the hardest elements (diamond, ruby and titanium) without affecting nature of matter. See figure (49).

Figure (49)

2. Directionality of laser beam and distant travel in straight lines can be utilized in many areas like surveying and construction of buildings, building, massive mechanical and structural designs and huge industries. It is also used to discover deviations on dams and bridges. It is used successfully in extending pipes, digging canals and tunnels, see figure (50).

Figure (50)

3. Many lasers are used in measuring environment pollution: like using ruby laser to detect and mesure carbon dioxide, water vapor and phosphorus dioxide.
4. Laser is used in holography: this imaging system is the best technique to obtain stereoscopic images closer to the truth with high resolution and three-dimensional (length, width and hight), is recorded as the amplitude of lightwave reflected from the object and its phase appears in three dimensions on the eye retina, while normal imaging is recorded the intensity of ray only. See figure (51).

Figure (51)

5. Full control of wavelength and frequency of laser makes it a promising tool in nuclear sciences in separating radioactive isotopes and fusion nuclear reactions.

6. Laser recognizes codes: whether in writing, commercial codes or hidden logos, laser recognizes them. Its fine ray moves around the symbols and detect reflecting beams by means of special devices. If connected on the computer, these devices can automatically be programmed to detect or copy this information. See figure (52).

Figure (52)

7. Laser engraving machine can carve and engrave the three-dimensional laser engraving machine is used in engraving, sculpting, and making souvenirs such as carving on glass and crystal, awards, medals, souvenir gifts (birthday gifts, graduation gifts, and travel photos), crystal pendants, necklaces, wedding photos, footprints and hands for newborns … etc.

8. Commercial applications: laser is used in billboard signs, laser printers and compact disc players. See figure (53).

Figure (53) Some commercial applications for the laser beam.

9. Laser Communications: laser is used directly in the air for close and limited distance communications. For example, it is used to televise images for a distance up to (20) Km because the phenomena of absorption and dispersion of laser beam when passes through dirt and other particles in the atmosphere, therefore, outer space is the best place to send laser beams.

Laser is also used in transfer of information on a distance by means of fiber optics. Communications by fiber optics is very suitable by means of implication and detection, see figure (54).

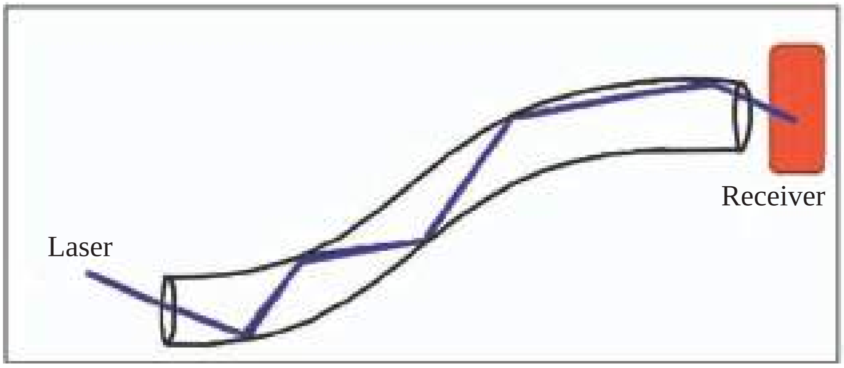



Figure (54) Fiber optics.

10. Laser is used in applied research laboratories, see figure (55)

Figure (55) Applied Research Laboratories for the laser beam.

11. Military uses: it is used in guidance, tracking and measuring distances by means of distance tracker, the wavelength (YACs) or Carbon dioxide laser, because they can penetrate in the atmosphere, see figure (56).

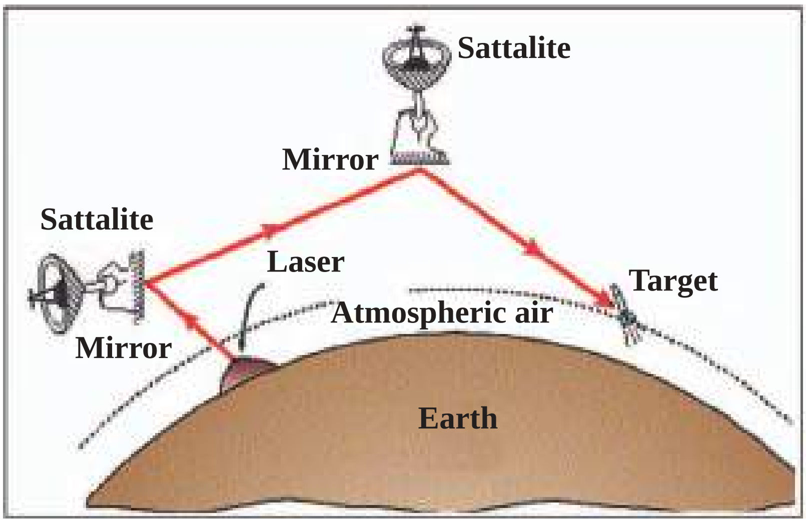



Figure (56) Some military applications for the laser beam.

# Questions of chapter 8

**Q1** Choose the correct statement for each of the following:

1. Bohr's model of atom shows that:
   a. Gaseous elements have identical atomic spectra.
   b. Glowing solid elements have identical atomic spectra.
   c. Glowing liquid elements have identical atomic spectra.
   d. Each element has its own atomic spectrum.

2. When an atom is excited by a continuous radioacting energy then the atom:
   a. Absorbs all radioacting energy. b. Absorbs the suitable energy to excite its atoms.
   c. Absorbs energy continuously. d. None of the above.

3. We get Lyman series in hydrogen spectrum when:
   a. The electron of hydrogen atom transmitted from ($E_5$, $E_4$, $E_3$, $E_2$) energy levels to first energy level.
   b. The electron of hydrogen atom transmitted from ($E_5$, $E_4$, $E_3$, $E_2$) energy levels to second energy level.
   c. The electron of hydrogen atom transmitted from high energy levels to third energy level.

4. In natural state of matter and according to Boltzmann distribution:
   a. Most atoms are in high energy levels.
   b. Most atoms are in low energy levels.
   c. Number of atoms in ground state is less than that in high energy level.
   d. Number of excited atoms is greater than those in the ground state.

5. A hydrogen atom spectrum is:
   a. Continuous. b. Line absorption.
   c. Line. d. Band.

6. Increase in wavelength of scattered X-ray photons by free electrons depend on:
   a. The wavelngth of incident photon.
   b.Speed of light.
   c. Electron mass.
   d. Scattering angle.
   e. Type of metal.

7. Pumping power is high when laser system works under:

a. Three-level system. b. Two-level system.

c. Four-level system. d. Any number of the levels

8. Electric pumping is used when the state of active medium is:

a. Solid. b. Gas. c. Liquid. d. Any active medium.

9. Laser action happen when there is an emission of:

a. Spontaneous and stimulated b. Stimulated and spontaneous.

c. Spontaneous only . d. Stimulated only .

10. Measuring range using laser depends on one of its properties which:

a. Coherency. b. Polarization

c. Monochromatic wavelength. d. Directionality.

**Q2** Give the reason of the following:

1. Wavelengths in absorption spectrum of an element is exist in emission spectrum also.
2. Laser is preferably used in cutting, welding and drilling.
3. Compton Effect is one of the evidence of particle behavior of electromagnetic ray.
4. In producing X-ray , target material is made of high-melting point material.

**Q3** What are basics of laser action?

**Q4** How can we obtain population inversion?

**Q5** What are properties of laser beam?

**Q6** What are the typies of gaseous lasers?

**Q7** What is holography and what is the features that differ from normal photography?

## Problems of chapter 8

**P.1.** Calculate the electron angular momentum of hydrogen atom when it is in the first orbit and when it is in the second orbit again?

**P.2.** What is the amount of energy in (eV) unit for a photon whose wavelength is $(4.5 \times 10^{-7} \text{m})$?

**P.3.** Calculate number of atoms in the higher energy level at room temperature if the number of atoms at ground state is (500)?

**P.4.** What is frequency of emitting photon when the electron of a hydrogen atom trasmit from ($E_4$= -0.85eV) energy level to ($E_2$= -3.4eV) energy level?

**P.5.** What is maximum kinetic energy of an electron and its velocity in X-ray tube at (30kV) potential difference.

**P.6.** What is the amount of maximum frequency of generated X-ray photon if potential difference (40kV) is placed on sides of the tube.

**P.7.** What is the increase in scattered photon wavelength (in Compton Effect) if scattered at ($90^0$) angle if:

Planck constant = $6.63 \times 10^{-34}$ J.s

Electron mass = $9.11 \times 10^{-31}$ kg

Speed of light in vacuum = $3 \times 10^{8}$ m/s

**P.8.** What is the difference between ground state of energy and the next level (higher level) in (eV) units for an atomic system in thermal equilibrium. If room temperature is ($16^0$C). if Boltzmann's constant ($k = 1.38 \times 10^{-23}$ J/k)

**P.9.** If the difference between stable level (ground state) and the next (higher level) is (0.025eV) of an atomic system in thermal equilibrium at room temperature. Find temperature of that room in Celsiu. if Boltzmann's constant ($k = 1.38 \times 10^{-23}$ J/k)

CHAPTER 9

# Relativity Theory

Contents


9-1 Introduction.

9-2 Einstein’s two hypothesis in the special theory of relativity .

9-3 Galilean transformations and Lorentz factor.

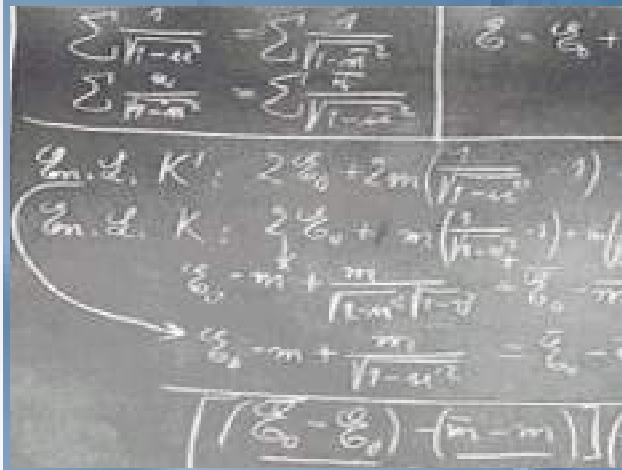
9-4 The most important consequences of the special theory of relativity.

- 9-4-1 Time dilation.
- 9-4-2 Length contraction.
- 9-4-3 Relativistic mass.

9-5 Mass energy equivalence.

9-6 Relativistic mechanic.

- 9-6-1 Relativistic linear momentum.
- 9-6-2 Relativistic kinetic energy.
- 9-6-3 Total relativistic energy.
- 9-6-4 Equivalence of energy and momentum.

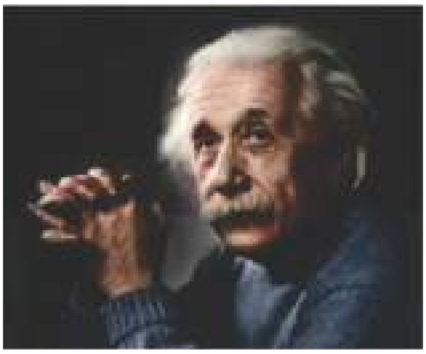
## Behavioural targets

**After studying this chapter, the student should be able to:**

- Illustrate the relation between classical physics and relativistic physics.
- Define the concept of the inertial frames of reference.
- Compare between Galilean transformations and Lorentz transformations.
- Show the effect of particle velocity in measuring the physical dimensions of objects.
- Illustrate the Lorentz factor ($\gamma$) is in terms of the velocity of moving objects.
- Mention some important applications of relativity theory:
  - Time dilation.
  - Length contraction.
  - Relativistic mass.
- Mention a mathematical relation for equivalent mass, momentum, and energy.

| Scientific Terms | |
|---|---|
| Relativity | النسبية |
| Inertial frames of Reference | أطر الإسناد القصورية |
| Observe | المراقب |
| Galilean Transformations | تحويلات غاليلو |
| Lorentz Factor | عامل لورنتز |
| Lorentz Transformations | تحويلات لورنتز |
| Time Dilation | نسبية الزمن |
| Length Contraction | نسبية الطول (انكماش الطول) |
| Relativistic Mass | الكتلة النسبية |
| Mass Energy Equivalence | تكافؤ الكتلة والطاقة |

## 9-1 Introduction



Classical physics is concerned with the objects that move at velocities much less than the speed of light in vacuum, which obeys by Newton laws, as for the objects that move with very high velocity, almost close to speed of light, they follow laws of relativity theory.

The special relativity theory, proposed by Einstein 1905, is considered one of the most dramatic theories ever; it caused so many changes on the concepts of classical physics, nature of nuclear particles and some cosmic phenomena.

The relativity theory depends on the concept of frames of reference. Reference frame is simply the position at which someone observes an event at a given time. This person is called (observer), who observes events and does the measurements.

According to relativity theory, observing a given event in space accurately is done by identifying its position and time using four coordinates (x, y, z, t). (x, y, z) are position coordinates, and (t) it is time coordinate, at which the measurement is done.

For example, when a physical event is described, we use a frame of reference called (S), when these objects move at a constant velocity relative to each other, these moving frames are called inertial frames of reference. Figure (1) shows frames of reference (S) and (S'). They are matched at the moment the measurement starts, move the frame of reference (S') at a constant velocity ($\nu$) compared to the frame of references (S) toward the x-axis.

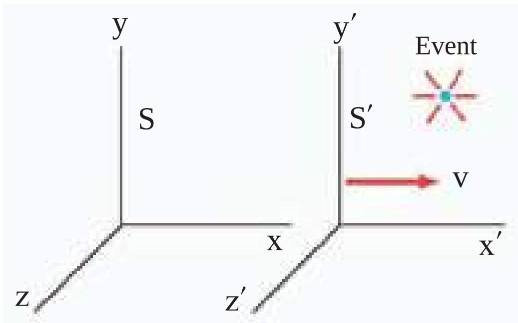


Figure (1)

One might ask: How classic theory and relativity theory conceive the relative movement?

To answer this question: assume an observer at a given reference frame is observing an event in another frame of reference moving in a constant velocity relative to its frame of reference, see figure (2). The classical mechanics assumes that time measured for the event itself is in both inertial frames of references, and measuring time goes along the same rate regardless of movement velocity of reference frames,

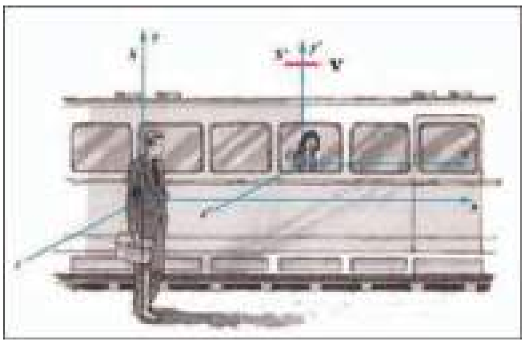


Figure (2) The person in constant frame (s) observer another person in movement frames (s').

i.e. the time interval between two consecutive events must be one for both observers. Although this assumption seems obvious according to classical theory, it seems incorrect when the velocity of the object is close or comparable to the speed of light, in this case, hypotheses of relativity theory must be adopted.

## 9-2 Einstein's two hypothesis in special theory of relativity

The special theory of relativity relies on two principles:

1. Laws of physics must be the same in all inertial frames of reference. This means: measurements in a frame of reference in a state of rest must give same result if it takes place within another frame of reference with a constant velocity relative to the first.
2. Speed of light in vacuum is constant ($c = 3 \times 10^8$ m/s) in all inertial frames of references regardless of observer's velocity or speed of light source.

This hypothesis is an important conclusion to the famous experiment conducted by Michelson-Morley in 1887, which proved that speed of light is constant when moves in all directions, since there is no ether (ether is an invisible hypothetical medium thought to exist in space. It is thought of as the medium in which light travels).

**DO you know?**

Albert Einstein puplished his special theory of relativity in 1905, when he was twenty-six years old, in 1915 he published his general theory of relativity, which dealt with the topic of cosmic gravitation and introduced the term space-time, which expresses the interconnectedness of time and space. He won the Nobel Prize in physics in 1921 for his interpretation of the photoelectric phenomenon.

## 9-3 Galilean transformations and Lorentz factor

When an event moves in space at a constant velocity (for example towards X- axis), to measure this event, classical physics used Galilean transformations which based on three basic conditions according to relation between frames of reference (S, S') which are:

| 1 | 2 | 3 |
|---|---|---|
| parallel axies<br>$x \parallel x'$<br>$y \parallel y'$<br>$z \parallel z'$ | Velocity of referance frame S' is constant<br>$\nu$ = constant | Time is constant in all inertial referance frames<br>$t \parallel t'$ |

Then, Einstein adopted other transformations, which are Lorentz transformations, Lorentz proved, by studying movement of physical particles in electromagnetic field, that velocity of particles has a significant effect in measuring physical dimensions of the object. He also proved that there is a correction factor must be adopted relation to coordinates of frames of reference (S, S').

The correction factor is called Lorentz factor (γ) and expressed by:

$$\gamma = \frac{1}{\sqrt{1 - \frac{\nu^2}{c^2}}}$$

$\nu$ : Velocity of particle, c: Speed of light in vacuum.

Table (1): Represents (γ) value in term of various velocity, also, figure (4) shows a diagram of (γ) values in term of various velocities.

Table (1): represents (γ) value in term of $\nu$/c.

| $\nu$/c | γ |
|---|---|
| 0.0010 | 1. 000 000 5 |
| 0.010 | 1.000 05 |
| 0.10 | 1.005 |
| 0.20 | 1.021 |
| 0.30 | 1.048 |
| 0.40 | 1.091 |
| 0.50 | 1.155 |
| 0.60 | 1.250 |
| 0.70 | 1.400 |
| 0.80 | 1.667 |
| 0.90 | 2.294 |
| 0.92 | 2.552 |
| 0.94 | 2.931 |
| 0.96 | 3.571 |
| 0.98 | 5.025 |
| 0.99 | 7.089 |
| 0.995 | 10.01 |
| 0.999 | 22.37 |

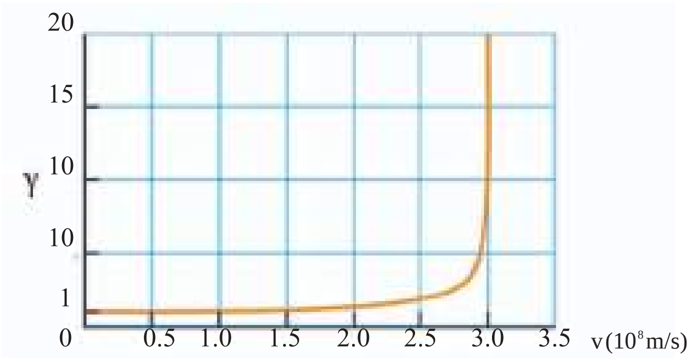



Figure (4) shows a diagram of (γ) values for various velocities. When the velocity closed to speed of light we see the values of (γ) approach to infinity.

**DO you know?**

The figure below shows a truck driver observing a ball thrown in air vertically, as for the outside observer, it is completely different, the movement of the ball looks as in the curve shown on the right side.

## 9-4 The most important consequences of the spacial theory of relativity

In classical physics, measurement of physical quantities like length, time and mass does not depend on the movement or rest of the observer who performs of measurement. As for physics of relativity theory, objects moving at speed closed to speed of light will change in these amounts for the (non-moving) rest observer.

Relativity laws below can be applied to velocities of moving objects even if they are almost the speed of light. Some applications of relativity theory will be addressed: Time dilation, length contraction, and relative mass and equivalence of mass, moment and energy, whose values change according to the velocity of object.

### 9-4-1 Time dilation

In classical mechanics, time of the physical event does not depend on the movement of the observer. As for the physics of special relativity theory, time of the event varies according to position of the observer. Time recorded by a moving observer differs from time recorded by a rest observer. The relation between time recorded by a moving observer with the same velocity of that of the event (t) is:

$$t = \frac{t_\circ}{\sqrt{1 - \frac{\nu^2}{c^2}}}$$

$t_\circ$: time of event recorded by a moving observer at same velocity of event.

t: time recorded by a rest observer.

Figure (5) shows that time recorded by a moving observer at same velocity of event is less than time recorded by a rest observer (the event is moving for the observer).

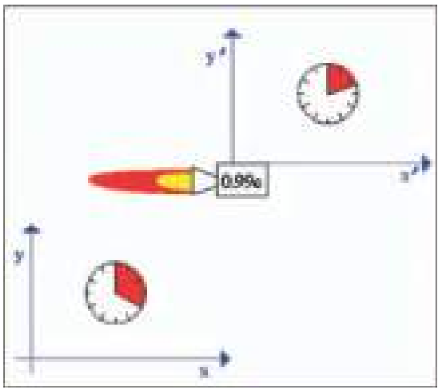


Figure (5) Time of event recorded by a rest observer.

**Example (1)**

An astronaut travelled at constant velocity (0.99c) (very close to speed of light) then back to earth after spending (5 years according to his own calendar in his spaceship). Calculate his age by earth terms:

**The solution:**

Applying relative time equation:

$$t = \frac{t_\circ}{\sqrt{1 - \frac{\nu^2}{c^2}}} \Rightarrow t = \frac{5}{\sqrt{1 - \frac{(0.99c)^2}{c^2}}} = 35.4 \text{ year}$$

i.e: 5 years spent on travel equals (35.4) years spent with his peers on earth.

**Example (2)**

The closest star to the solar system is Centauri, which is (4.3 light years) from earth.

Find:

1. Velocity of a spaceship to reach this star in (7.448 year), as measured by spacemen themselves.

2. Time interval measured by earth people.

Considering that speed of light in vacuum is ($3 \times 10^8$m/s), $\gamma = \frac{1}{\sqrt{1 - \frac{\nu^2}{c^2}}} = 1.155$

(LY): means light years.

**The solution:**

**(1)**

$$\gamma = \frac{1}{\sqrt{1 - \frac{\nu^2}{c^2}}} = 1.155$$

$$\frac{1}{1 - \frac{\nu^2}{c^2}} = 1.334$$

$$\frac{1}{1 - \frac{\nu^2}{c^2}} = \frac{4}{3}$$

$$3 = 4 - 4(\frac{\nu^2}{c^2})$$

$$4(\frac{\nu^2}{c^2}) = 1$$

$$\frac{\nu^2}{c^2} = \frac{1}{4}$$

$$\frac{\nu}{c} = \frac{1}{2}$$

$$\nu = 0.5c = 0.5 \times 3 \times 10^8$$

$\nu = 1.5 \times 10^8$m/s the velocity of sapceship.

**(2)**

$$t = \frac{t_\circ}{\sqrt{1 - \frac{\nu^2}{c^2}}}$$

$$t = t_\circ \gamma$$

$$= 7.448 \times 1.155$$

$t = 8.6$ year Time interval measured by earth people

Another way to solve the question:

$$t = \frac{x}{\nu} = \frac{4.3LY}{1.5 \times 10^8}$$

$$t = \frac{4.3 \times 3 \times 10^8 \times 365 \times 24 \times 3600}{1.5 \times 10^8}$$

$$t = \frac{40.68 \times 10^{15} m}{1.5 \times 10^8}$$

$$t = 2.712 \times 10^8 s$$

$$t = \frac{2.712 \times 10^8}{365 \times 24 \times 3600}$$

$$t = 8.6 \text{ year}$$

### 9-4-2 Length contraction

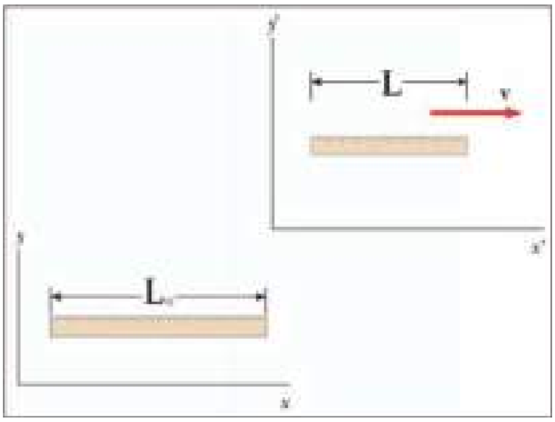


Figure (6) Length contraction

Now we know that time interval are not constant intervals, but measurements vary according to the varies of moving reference frames at which measurement is done, this also applies to lengths too.

Measuring a particular length in a constant reference frame different from the measurements if reference frame is moving. Moving objects for a rest observer will contract (shrink in length) toward the direction of movement, see figure (6).

This means that maximum length can be measured when the object at rest. Length of a moving object (L) compared to rest length ($L_o$) is expressed as follows:

$$L = L_o \sqrt{1 - \frac{\nu^2}{c^2}}$$

Because the values in the root is always less than one, then the relative length (L) is always less than the real length ($L_o$).

**Example (3)**

A spaceship length is (50m) on earth, what length it will be when its moving with velocity of (0.9c)?

**The solution:**

Applying relative length law:

$$L = L_o \sqrt{1 - \frac{\nu^2}{c^2}}$$

$$L = 50\sqrt{1 - \frac{(0.9c)^2}{c^2}} = 21.8 \text{ m}$$

**Example (4)**

An object length is (4m) at rest, calculate its length that measured by a rest observer when the object is moving at a velocity equals to (0.7) of speed of light i.e (0.7c)?

**The solution:**

Applying relative length law:

$$L = L_\circ \sqrt{1 - \frac{\nu^2}{c^2}}$$

$$L = 4\sqrt{1 - \frac{(0.7c)^2}{c^2}} = 4 \times 0.71 = 2.85\text{m}$$

**Question:**

Suppose this object is moving at a velocity of (600km/h). What length it will be when measured by rest observer?

### 9-4-3 Relativistic mass

Another important results of the special theory of relativit is: consider mass as a function of velocity, meaning that mass is not invariat quantity, it is a variable amount according to it's velocity. Change of mass can be calculated according to the following relation:

$$m = \frac{m_\circ}{\sqrt{1 - \frac{\nu^2}{c^2}}}$$

$m_\circ$: mass of object at rest (rest mass).

m: mass of moving object at velocity ($\nu$) (relativistic mass).

**Remember:**

The rest mass of photon equals to zero.

We conclude from the aforementioned relation that relativistic mass is greater than the rest mass, i.e mass of moving object increases with it's velocity.

When velocity of object is low compred to speed of light ($\nu << c$), then:

($m \approx m_\circ$) that is, the change in mass can not be observed, as in the example:

**Example (5)**

An object of mass is (1kg), calculate its mass in the following three cases:

a. If it's velocity is (1000m/s).

b. If it's velocity is (0.9c).

c. If it's velocity is (0.99c).

**The solution:**

Applying relativistic mass law in three cases:

$$m = \frac{m_\circ}{\sqrt{1 - \frac{\nu^2}{c^2}}}$$

We find that the mass of the object becomes :

$$a)\ m = \frac{1kg}{\sqrt{1 - (\frac{10^3}{3 \times 10^8})^2}} = 1.000000000005\ kg$$

$$b)\ m = \frac{1kg}{\sqrt{1 - 0.9^2}} = 2.2942\ kg$$

$$c)\ m = \frac{1kg}{\sqrt{1 - 0.99^2}} = 7.0888\ kg$$

We conclude from the aforementioned results that in small velocity compared to speed of light, no change or no increase in mass can be obesrved, as for velocities close to the speed of light, it is different and this has been proven in nuclear physics.

It is worth noting that nuclear physics has participated in validating these laws, one of the most important concrete experiments is the nuclear radiation field, which are the particles released from some radioactive materials such as Uranium and Radium, which are infinitesimal material particles which move at velocity close to speed of light, increasing their mass in accordance with the aforementioned equation.

## 9-5 Mass energy equivalence

Einstien managed to introduce his well-known equation: $E = mc^2$

This equation stipulates that a very tiny amount of mass gives enormous of energy. Energy resulting from a certain mass equals product of this mass multiplied by square of the speed of light,which produces a very large energy.

This equation explained the energy and long life of stars, these stars lose a very small amount of their matter and give energy that can extend to the universe.

Humans utilised this concept and equation to build and operate nuclear reactors, and nuclear weapons.They both rely on the concept of nuclear fission. The fissile nucleaus can release (200MeV) of energy, equivalent to ($3.2 \times 10^{-11}$J), this released energy is the result from the consumption ($3.56 \times 10^{-28}$kg) of the matter only.

**Example (6)**

What is the amount of energy obtained when one gram is completely transformed into energy? How many months is this energy efficient? If the average consumption is (1000kwh) per month, how many months is this energy efficient?

**The solution:**

Using the law $E = mc^2$

$$E = 1 \times 10^{-3} \times (3 \times 10^{8})^{2} = 9 \times 10^{13}\,J$$

This amount is a very large and can be compared by amount of consumed electric energy by Iraqi household. If consumption rate is (1000kwh) per month, this equals ($3.6 \times 10^{9}$J). Dividing the produced energy by consumed energy, we get the number of equivalent months, i.e.

$$\frac{9 \times 10^{13}}{3.6 \times 10^{9}} = 2.5 \times 10^{4} \text{ months}$$

This means that energy resulting from transformation of one gram of matter into energy, this will sustain the household for more than two thousand years as an electrical operation.

**DO you know?**

The ratio of what the sun loses in one second of its mass is ($2.191 \times 10^{-21}$) only and this equates to more than four billion kilograms ($4.2 \times 10^{9}$ kg). This produced energy is sufficient for the electricity consumption of all countries of the world for a period of one million years.

## 9-6 Relativistic mechanics

We might wonder how other physical concepts are effected by the relativity theory? Like total energy, kinetic energy, and moments.

The theory of relativity emphasizes the necessity to change formulas and laws of most classical physics concepts for objects moving at very high velocity amount relative to formulas and laws:

### 9-6-1 Relativistic linear momentum

Relativistic linear momentum ($P_{rel}$) of a particle with a relativistic mass (m) is moving with a velocity ($\nu$) is given the follwing relation:

$$P_{rel} = m\nu = \frac{m_\circ \nu}{\sqrt{1 - \frac{\nu^2}{c^2}}} \quad \text{Relativistic Linear Momentum}$$

(m) is the relativistic mass of the object.

($\nu$) is the velocity at which the object is moving and ($m_\circ$) is rest mass of the object.

### 9-6-2 Relativistic kinetic energy

The amount of relativistic Kinetic energy $(KE)_{rel}$ as Einstein demonstrated equals the difference between total relativitic energy of the particle moving at velocity ($\nu$) and rest energy of the particale at ($m_\circ c^2$) i.e. kinetic energy is not equal to ($\frac{1}{2}$ $mv^2$) as is the case in classical mechanics rather, it is equal to relativistic energy after subtracting the rest energy .i.e:

$$(KE)_{rel} = mc^2 - m_\circ c^2$$

$$(KE)_{rel} = \left(\frac{1}{\sqrt{1 - \frac{\nu^2}{c^2}}} - 1\right) m_\circ c^2 \quad \text{Relativistic kinetic energy}$$

Since:

$(KE)_{rel}$: represents the relativistic kinetic energy of the particle.

$mc^2$: represents the total relativistic energy of particle moving at ($\nu$).

$m_\circ c^2$: represents the rest energy of the particle.

### 9-6-3 Total relativistic energy

Total relativistic energy ($E_{rel}$) for a particle moving at a velocity ($\nu$) is equal to the sum of relativistic kinetic energy $(KE)_{rel}$ and rest energy ($m_\circ c^2$) of that particle.

$$E_{rel} = (KE)_{rel} + m_\circ c^2$$

Substituting the amount of relativistic kinetic energy mentioned earlier, we get:

$$(E)_{rel} = \frac{m_\circ c^2}{\sqrt{1 - \frac{\nu^2}{c^2}}} \qquad \text{Total relativistic energy}$$

We notice that in the case of a rest particle (its velocity equal zero) at any frame of reference, the total relativistic energy of the particle equals ($E_{rel} = m_\circ c^2$). We conclude from Einstein's relation that total relativistic energy of the rest particle equals its rest energy.

### 9-6-4 Equivalence of energy and momentum

Applying the relativistic relations of total energy and linear momentum:

$$P_{rel} = \frac{m_\circ \nu}{\sqrt{1 - \frac{\nu^2}{c^2}}} \quad , \quad (E)_{rel} = \frac{m_\circ c^2}{\sqrt{1 - \frac{\nu^2}{c^2}}}$$

The following relation can be found:

$$(E_{rel})^2 = (P_{rel})^2 c^2 + m^2_\circ c^4$$

This equation is specifically used in studying nuclei and atoms. Electron units are often used Electron-Volt units (eV) or their multiples (MeV $=10^6$ eV). As for momentum is expressed ($\frac{eV}{c}$) or ($\frac{MeV}{c}$) units. Other units are also used ($\frac{eV}{c^2}$) or ($\frac{MeV}{c^2}$) to express mass.

# Questions of chapter 9

**Q1** Choose the correct answer in the following :

1. Which of the following quantities is constant according to relativity theory:

   a. Speed of light. b. Time. c. Mass. d. Length.

2. A spaceship with a velocity (0.9c) (0.9 of speed of light) sends a light beam, the relative velocity of this beam, which is observed by the crew of another spaceship parallel traveling to the first spaceship and in the same direction.

   a. 0.9c. b. 1.8c. c 1.6c. d. c.

3. According to Einstein's theory of special relativity:

   a. Time and place are correlated.

   b. Energy and mass are correlated.

   c. Time and energy are correlated.

   d. Energy and mass are uncorrelated.

4. According to Einstein's theory of special relativity, all laws of physics are one in the frames of measurement whose velocity:

   a. Uniform acceleration. b. Uniform and constant.

   c. Non- uniform and oscillating. d. Rotational.

5. Relativistic kinetic energy is equal to:

   a. $\frac{1}{2}m\nu^2$ b- $\frac{1}{2}mc^2$. c. $(m-m_o)c^2$. d. $(\nu^2-c^2)m_o$.

6. Total relativistic energy is equal to:

   a. $m^2-m_oc^2$.

   b. $Pc-m_oc^2$.

   c. $(P_{rel})^2c^2+m_o^2c^4$.

   d. $m_oc^2+(KE)_{rel}$

7. According to Einstein's well-known equation of mass energy equivalence:

a. $E = m^2 c$.
b. $E = c^2 m^2$.
c. $E = mc^2$.
d. $E = mc$

8. A clock is ticking once each second, if the clock length is (10cm) when in rest state, if this clock moved with velocity (0.8c) compared to its length to a rest observer, the observer measures the ticking of the clock and length of clock as :

a. Greater than (1s) and longer than (10cm).
b. Less than (1s) and longer than (10cm).
3. Greater than (1s) and shorter than (10cm).
4. Less than (1s) and shorter than (10cm).

9. A rod was placed parallel to the X- axis, then the rod moved parallel to this axis too with velocity (0.8c). The apparent length of the rod is (1m) then its length in a rest reference frame will be:

a. 0.5m.
b. 1.666m.
c. 0.7m.
d. 0.8m.

10. If you were in a rocket moving with velocity of (0.7c) towards a star, what is the velocity will get you to the light of that star:

a. Less than c.
b. Greater than c.
c. At speed of light in vacuum.

**Q2** A particle moving at uniform constant velocity ($\nu = 0.6c$), what is the ratio between relativistic momentum ($P_{rel}$) and classical momentum ($P_{cla}$)?

**Q3** What is the main difference between Galilean transformations and relativity transformations?

**Q4** Some would say matter can neither be created nor destroyed, do you think this is true?

## Problems of chapter 9

**P.1.** One gram of Hydrogen combine with eight grams of oxygen, they formed about nine grams of water giving ($2.86 \times 10^5$J) energy. Calculate the amount of transformed mass as a result of this reaction.

**P.2.** If the amount of energy produced from the sun per one second is ($3.77 \times 10^{26}$ W), find the amount of the lost mass from the sun in one second.

**P.3.** A astronauts sending a massage to the observation station on earth informing them that they will sleep for an hour, then they will continue communicating with them directly. If the velocity of spaceship is (0.7c) relative to the earth, find the time taken by the astronaut sleeping measured by the observers in the observation station on earth.

**P.4.** A ruler length (1m) is move with half speed of the light in the direction of its length. What is the length of the ruler relative to an observer settled on the surface of the earth?

**P.5.** If the lenght of the spaceship is (25m) on the surface of the earth at rest and the lenght of the spaceship become (15m) according to rest observer, when it reaches a velocity of ($\nu$). Find the velocity of this spaceship.

**P.6.** What is the increase in the mass of proton. ($m_o = 1.67 \times 10^{-27}$kg) if its velocity is (0.9c).

**P.7.** What is velocity required in order to increase the mass of an object by (10%) of its rest mass?

**P.8.** Prove that the percentage increase in the mass of an object as (15.47%), if the object moves at a half speed of light.

**P.9.** An object length of (2m) moves at a certain velocity of ($\nu$). If an observer is at rest relative to the object which measured its length and found it equal to (0.8m). Find the velocity of the moving object.

**P.10.** What is the velocity of a particle with a relative kinetic energy equals eight times of its rest mass energy.

**P.11.** What is the velocity of an electron if the relative kinetic energy equals (1.0MeV), knowing that the mass of the electron is ($9.11 \times 10^{-31}$kg). (1MeV = $1.6 \times 10^{-13}$ J).

**P.12.** A spaceship with velocity of (0.999c), left the earth to the centauri star back and forth which is at a distance of ($4.3 \times 10^{16}$m) from the earth. Calculate the interval time of (going to the star and coming back to earth) which in measured by a fixed clock in the spaceship. Compare this time with the interval time measured by a clock on the earth.

# CHAPTER 10

# Nuclear physics

Contents

10-1 Introduction.

10-2 Structure and properties of the nucleus

10-3 Nuclear binding energy.

10-4 Radioactive decay.

10-4-1 Alpha decay.

10-4-2 Beta decay.

10-4-3 Gamma decay.

10-5 Nuclear reactions.

10-6 Nuclear fission.

10-7 Nuclear fusion.

10-8 Hazards and beneficials of nuclear radiation.

## Behavioural targets

**After studying this chapter, the student should be able to:**

- Mention the main properties of the nucleus.
- Mention some characteristics of nuclear force.
- Define the concept of nuclear binding energy.
- Explain the spontaneous decay of some nuclei by alpha decay.
- Know the types of spontaneous decay for some nuclei by beta decay.
- Explain the spontaneous decay of some nuclei by gamma decay.
- Know about the nuclear reaction energy.
- Realize the importance of neutrons' reaction with the nucleus.
- Explain the concept of nuclear fission.
- Explain the concept of nuclear fusion.
- Mention the benefits of nuclear radiation.
- Name the hazards of nuclear radiation.
- Solve various mathematical problems.

| Scientific Terms | |
|---|---|
| Atomic number | العدد الذري |
| Antineutrino | مضاد النيوترينو |
| Antielectron | مضاد الالكترون |
| Daughter nucleus | النواة الوليدة ( البنت) |
| Chain reaction | التفاعل المتسلسل |
| Radius of nucleus | نصف قطر النواة |
| Endoergic reaction | التفاعل الماص للطاقة |
| Exoergic reaction | التفاعل المحرر للطاقة |
| Size of nucleus | حجم النواة |
| Mass of nucleus | كتلة النواة |
| Neutron number | عدد النيوترونات |
| Average binding energy per nucleon | معدل طاقة الربط النووية لكل نيوكليون |
| Nuclear force | القوة النووية |
| Mass defect | النقص ( الفرق) الكتلي |
| (proton-proton) cycle | دورة ( بروتون - بروتون) |
| Parent nucleus | النواة الأم |
| Nuclear reaction energy | طاقة التفاعل النووي |
| Nneutrino | النيوترينو |
| Mass number | العدد الكتلي |
| Positron | البوزترون |
| Natural background radiation | الاشعاع النووي الخلفي الطبيعي |

## 10-1 Introduction

One might ask, why we study nuclear physics? Is this branch of knowledge important for humans? One might ask too about the energy in that small part of the atom called nucleus. See figure (1), which late turned out to be stored mass energy. This nuclear energy is used for

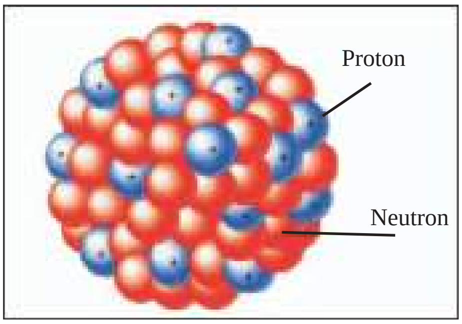


Figure (1) Nucleus atom

peaceful purposes, (as in transforming nuclear energy to electric energy), see figure (2), or for non- peaceful purposes (as in nuclear weapons production). note figure (3). Talking about nuclear energy might raise other questions, to answer these questions, we need to know how nuclear physics arose.


Figure (2) A nuclear reactor to produce electrical energy

(1896) is considered birth date of nuclear physics, French Scientist Henry Becquerel discovered natural radioactivity in Uranium compounds. In (1911) Rutherford proposed the nuclear model of the atom. He assumed that positive charges concentrate in a tiny space at the center of the atoms called nucleus, see figure (4).


Figure (3)

Then discoveries continued later, which opened new horizons not only for nuclear physics but also many disciplines like medicine, industry and agriculture. In this chapter, we will study some features of nucleus and some of its applications.

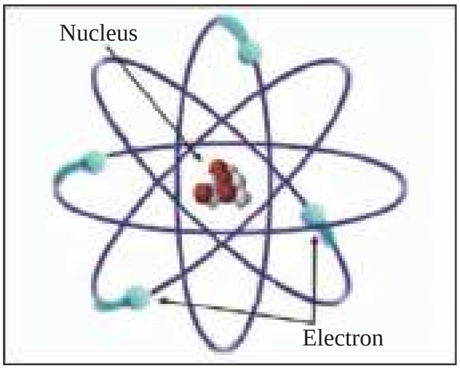


Figure (4) Atom

## 10-2 Structure and properties of the nucleus

Many scientists tried to discover components of the nucleus. It consists of positively charged particles called protons, and neutral charge particles called neutrons (zero charge), the proton and neutron is called nucleon. This means the nucleus consists of nucleons. The proton is symbolized by ( $^{1}_{1}H$ ) or (p), in some cases ( $^{1}_{1}p$ ), the neutron is symbolized ( $^{1}_{0}n$ ) or (n).The number of protons in the nucleus is called the atomic number (Z) , the number of neutrons in nucleus is called neutron number (N). As for total of protons and neutrons in nucleus, it is called mass number (A).It is expressed as:

$$A = Z + N$$

The mass number (A) is written on the upper left of nucleus symbol (X), as follow:

$$^{A}_{Z}X$$

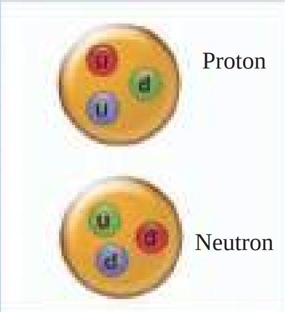
For example, aluminum nucleus, the atomic number is (Z=13), mass number (A=27), so it symbolized by ( $^{27}_{13}Al$ ), see figure (5).

(Al) refers to symbol of aluminum nucleus. Applying the relation (A = Z+N), the number of neutrons in aluminum nucleus (N) is (14) neutrons.

Also, you have learned what is meant by isotopes, they are nuclei which are equal in atomic number and different in neutron number (or mass number) for example: ( $^{6}_{3}Li, ^{7}_{3}Li, ^{8}_{3}Li$ ) are three isotopes of Lithium see figure (6). So, what about nucleus mass? It represents (99.9%) of atom mass. Is How atom nucleus mass

**DO you know?**

Leptons and quarks are elementary particles of matter, the electron is a leptons, while protons and neutrons are made of quarks. From the properties of quarks is that they carry a part of the charge (e), quarks differ from one anther in their mass. For example, a proton contains two up quarks (u) or (up) and one down quark (d) or (down). While a neutron contains two down quark and one up quark. See figure. For your information that the charge of up quark (u) is ( $+\frac{2}{3}e$ ), and the charge down quark (d) is ( $-\frac{1}{3}e$ ).



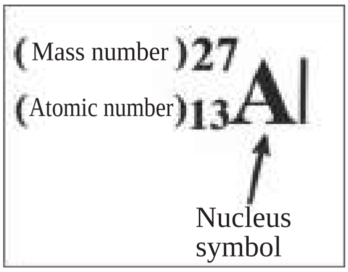



Figure (5)

measured? They are measured by accurate devices like mass spectrometer. Masses of atom nucleus are measured by atomic mass unit (amu) or symboliced by (u) instead of kilogram, which is not appropriate to measure atomic and tiny nuclear masses that equal:

$$1amu = 1u = 1.66 \times 10^{-27}\ kg$$

Since the nucleus contains the (A) nucleons , and Nucleon mass is close to mass of (1u), then approximate mass of nucleus is (m') which equals (A×u).

The nucleus is often described as heavy, medium or light according to mass number (or mass) whether big, medium or small respectively. In this chapter, when we discuss masses of balanced atoms, nuclei and particles (like proton, neutron and alpha particle….etc), we mean rest masses.

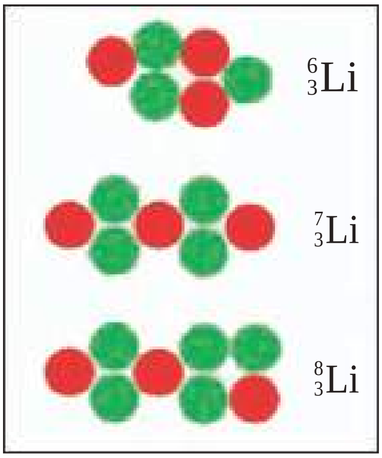


Figure (6)

**Think?**

Can you distinguish the color that represents proton and the color that represents neutron in the figure (6)?

Nuclear physics scientists often express mass with equivalent energy. Equivalent energy of mass can be found by using Einstein’s relation of equivalent mass (m) with energy (E) as the relation:

$$E= mc^2$$

c: Speed of light in vacuum which equals ($3\times10^{8}$ m/s). i.e. the relation between mass and energy is equivalent. Mass can be converted into energy and inverse is true.

So, the equivalent energy of mass (1u) is found equal to (931MeV). According to relation of energy- mass equivalence, the following relation can be expressed as:

$$c^2 = 931\left(\frac{MeV}{u}\right)$$

Now after discussing mass of nucleus, how can we find the nucleus charge? Since neutron charge is zero, the nucleus charge equals total of proton charges. So, the nucleus of any atom is positive and its amount of charge (q) equals (+Ze) whereby (Z) is atomic number of the nucleus and (+e) is the proton charge = ($1.6 \times 10^{-19}$ C).i.e:

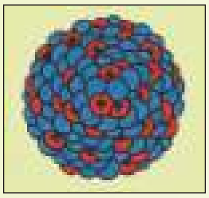
$$q = Ze$$

**Remember:**

$1MeV= 10^{6}\ eV = 1.6 \times 10^{-13}\ J$

**Example (1)**

Find the amount of charge for gold nucleus ( $^{198}_{79}Au$ ), if you know that proton charge is ($1.6 \times 10^{-19}$ C).



**The solution:**

We have the relation: q=Ze

and for the nucleus ( $^{198}_{79}Au$ ); so (Z=79)

Substituting in previous relation, we have:

$$\therefore q = 79 \times 1.6 \times 10^{-19}$$

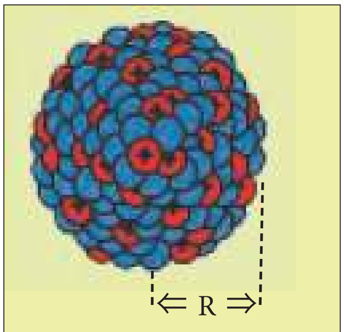
$$\therefore q = 126.4 \times 10^{-19} C \quad \text{the gold nucleus charge.}$$

**DO you know?**

Although the neutron has a neutral charge (its charge is zero), it has a magnetic moment.

Now that we learned briefly what is meant by mass and charge of nucleus. What about nucleus volume? How can radius and volume of nuclear be known? The answer is: first attempt to estimate volume of nucleus and radius was done by Rutherford by alpha particle scattering of gold atom nuclei and similar experiments, that most nuclei atomes are spherical (in this chapter, we will assume that the shape is spherical). He discovered that nucleus radius (R) is directly proportional to cubic root of mass number (A). See figure (7). i.e: give by the following relation ship: ( $R \propto A^{\frac{1}{3}}$ ) and expressed as follows:

$$R = r_0 A^{\frac{1}{3}}$$




Nucleus radius

Figure (7)

($r_0$ ) is a constant amount called radius constant and equals ($1.2 \times 10^{-15}$ m).

Nuclear dimensions range around ($10^{-15}$m), which has very tiny dimensions. Thus, it is important to use a length unit called Femtometers or Fermi (F) ,thus:

1Fermi = 1F = $10^{-15}$ m

This relation can be expressed in meter unit (m) and (F) Fermi unit, as follows:

$$R = \begin{cases} 1.2 \times 10^{-15} A^{\frac{1}{3}} & (m) \\ 1.2 A^{\frac{1}{3}} & (F) \end{cases}$$

**Example (2)**

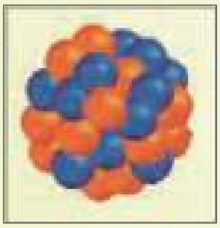
Find radius of copper nucleus ( $^{64}_{29}Cu$ ) in: a. meter (m), b. Fermi (F).

**The solution:**

a. To find radius by meter (m) the following rule applies:

$$R = 1.2 \times 10^{-15} A^{\frac{1}{3}}$$

As for copper nucleus ( $^{64}_{29}Cu$ ), then (A= 64), and by substituting in previous relation we have :



$$R = 1.2 \times 10^{-15} (64)^{\frac{1}{3}} = 1.2 \times 10^{-15} \sqrt[3]{64}$$

$\therefore R = 1.2 \times 10^{-15} \times 4 = 4.8 \times 10^{-15} m$ it is the nucleus radius by meter

b. To find radius by Fermi (F), we have:

$$F = 10^{-15} m$$

$\therefore R = 4.8(F)$ it is the nucleus radius by Fermi

[Also we can find nucleus radius by Fermi (F), by using the relation ( $R = 1.2A^{\frac{1}{3}}$ ), check it yourself and compart the result of your calculation with the result of the step (b) for this example].

Volume of the nucleus (V) can be found by applying the following relation (assuming that shape of nucleus is spherical shape with a radius (R)):

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi r_0^3 A$$

To find approximate density of nucleus ( $\rho$ ), this relation is applied ( $\rho = \frac{m'}{V}$ ), (m′) : represents approximate mass of nucleus (A×u). Approximate density of nucleus ( $2.3 \times 10^{17} \frac{kg}{m^3}$ ) is and compared to water density ( $10^3 \frac{kg}{m^3}$ ), the nucleus density is around ( $2.3 \times 10^{14}$ ) times the density of water, and it is a very huge amount.

## 10-3 Nuclear binding energy

We know that similar charges repulse and since the nucleus contains neutral charge neutrons and positively charged protons (except for normal hydrogen nucleus and its isotopes which contain one proton only). Why these protons do not repulse despite similar charges? If so, will the nucleus disassemble? If this is not the case, how the nucleus maintains stability and bondage? What binds the nucleons together? The answer is: there must be a nuclear attraction force that binds the nucleons of the nucleus. This strong nuclear force is one of the four basic forces in nature; the nuclear force is the strongest in nature. From the properties of nuclear force is short-range and does not depend on charge.

### Nuclear binding energy ($E_b$):

It is the released energy when an appropriate number of protons and neutrons gather to form a nucleus (or energy required to disassemble the nucleus into protons and neutrons). Mass of nucleus does not equal its component protons and neutrons when separated its always less than the sum of the individual masses of protons and neutrons, see figure (8). This difference in mass ($\Delta m$) is called mass defect, and it is equivalent to nuclear binding energy ($E_b$) according to Einstein's (mass-energy) equivalence relation:

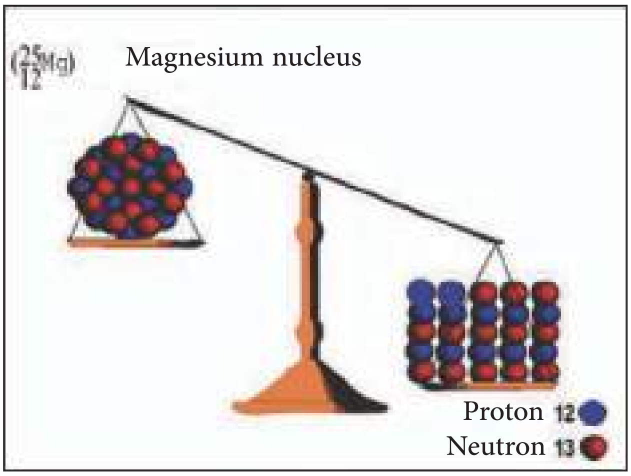


Figure (8)

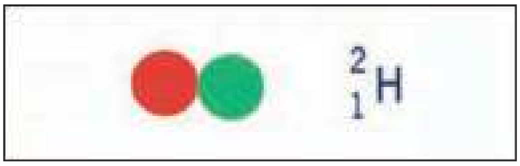


Figure (9)

$$E_b = \Delta mc^2$$

For example, by measuring mass of Deuteron nucleus ($^{2}_{1}H$), which consists of one proton and one neutron, see figure (9). It is found to equal (2.013553u) which is less than the total mass of the proton (1.007276u) and Neutron mass (1.008665u), which equals (2.015941u) when separated. Thus the difference in mass or defect mass ($\Delta m$) is equals (0.002388u) We can find the nuclear binding energy ($E_b$) in (Mev) units as follows:

$E_b = \Delta mc^2$

Substituting in previous relation, ( $c^2 = 931 \frac{MeV}{u}$ ), we get:

$E_b = 0.002388 \times 931 = 2.223$ (MeV).

Practically, it is better to use atom masses instead of nuclei masses, the mass defect ($\Delta m$) is expressed as:

$$\Delta m = ZM_H + Nm_n - M$$

$M_H$: mass of Hydrogen atom.

M: mass of specific atom.

Z: Atomic number.

N: Neutron number

$m_n$:Neutron mass.

Thus, the nuclear binding energy of the nucleus will be:

$$E_b = (ZM_H + Nm_n - M)\, c^2$$

Since atomic masses are measured by (u) unit, the nuclear binding energy unit ($E_b$) is measured by (MeV), thus ( $c^2 = 931 \frac{MeV}{u}$ ).

Quotient of nuclear binding energy ($E_b$) by mass number (A) is called average nuclear binding energy per nucleon ( $E_b'$ ), and expressed as follows:

$$E_b' = \frac{E_b}{A}$$

How ( $E_b'$ ) value change when the mass number of nuclei changes (A)?

Figure (10) shows change in ( $E_b'$ ) with (A), the figure shows that the curve is generally constant except for light nuclei like Deuteron ( ${}^{2}_{1}H$ ) and heavy nuclei like lead nuclei ( ${}^{208}_{82}Pb$ ). It also shows that medium nuclei

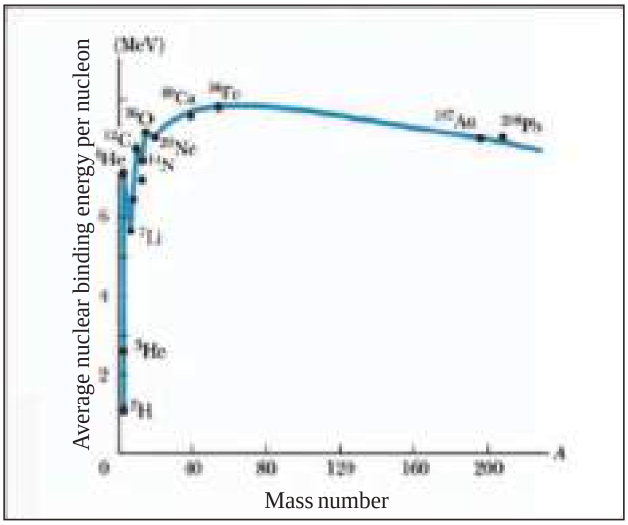


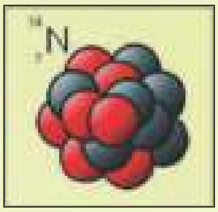

Figure (10)

have the larger values of ( $E_b'$ ) like Iron nucleus ( $^{56}_{26}Fe$ ), thus, medium nuclei are usually the most stable. Light and heavy nuclei can be more stable if a nuclear reaction can change them into medium nuclei. In other words, under convenient circumstances, heavy nuclei become more stable if fission to medium nuclei and vice versa, if light nuclei fused to form heavier nuclei, they become more stable too. In both cases, energy will be released. You will know later in detail about nuclear reactions of fission and fusion in sections (10-6) and (10-7).

**Example (3)**

Find nuclear binding energy for Nitrogen Nucleus ( $^{14}_{7}N$ ) in (MeV) unit, if the mass of the atom ( $^{14}_{7}N$ )is (14.003074u) and mass of hydrogen is (1.007825u) and neutron mass is (1.008665u).Find the average nuclear binding energy per nucleon too.

**The solution:**




We have the relation: $E_b = (ZM_H + Nm_n - M)c^2$

Since the masses are expressed in (u) unit, then:

$$\left(c^2 = 931\frac{MeV}{u}\right)$$

$$\therefore E_b = (ZM_H + Nm_n - M) \times 931(MeV)$$

As for ( $^{14}{}_{7}N$) nucleus: $Z = 7, A = 14, N = A - Z = 14 - 7 = 7$

Substituting these values in previous relation, we get:

$$E_b = [7 \times 1.007825 + 7 \times 1.008665 - 14.003074] \times 931$$

$$\therefore E_b = 0.112356 \times 931 = 104.603(MeV)$$

This is the nuclear binding energy.

[note that defect mass ($\Delta m$) in this example is (0.112356u)]

$$\therefore E_b' = \frac{E_b}{A} = \frac{104.603}{14} = 7.472\left(\frac{MeV}{nucleon}\right)$$

In addition, we can write: $E_b' = 7.472(MeV)$

which is average nuclear binding energy per nucleon.

## 10-4 Radioactive decay

Some nuclei are unstable (radioactive), then they seek to be stable through decay. There are three major types of decay:

### 10-4-1 Alpha decay:

If we ask this question: When does unstable nuclei undergo spontaneous alpha decay? See figure (11-a). The answer is: when the mass and volume of a nucleus are relatively big. Thus, emission of alpha particle from these nuclei helps to achieve larger stability by reducing volume and mass. As you previously studied, alpha particle is helium nucleus, which contains two protons and neutrons ( ${}^{4}_{2}He$ ) or ( $\alpha$ ). See figure (11-b), it has a positive charge (+2e).

In Alpha decay, (as is the case in other radioactive decay) the original nucleus before decay is usually called parent nucleus, the produced nucleus after decay is called daughter nucleus.

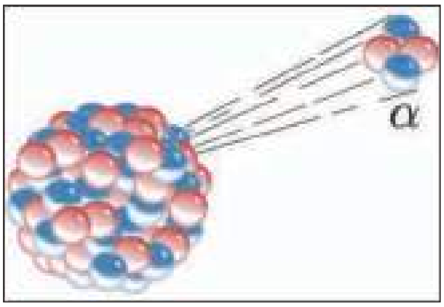


Figure (11-a)

The following equation shows a nuclear equation for a nucleus in alpha decay:

| ${}^{240}_{94}Pu$ | $\rightarrow$ | ${}^{236}_{92}U$ | + | ${}^{4}_{2}He$ |
|---|---|---|---|---|
| (parent nucleus) | | (daughter nucleus) | | (alpha particle) |
| (plutonium nucleus) | | (uranium nucleus) | | |

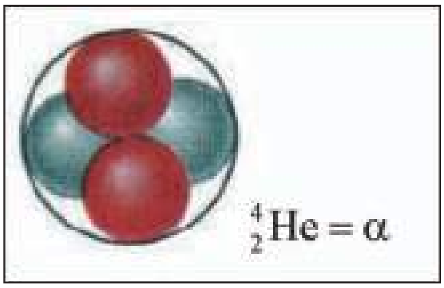


Figure (11-b)

Note figure (12).

What does alpha decay do to mass number and atomic number of parent nucleus? The mass number decreases by four, and the atomic number decreases by two (see previous nuclear equation).

Also, note that when the atomic number changes, nucleus of the element also changes to a nucleus of another element. This is true of other types of decay and nuclear reaction. except Gamma decay, how can we find decay energy for a nucleus in alpha decay?

Assuming that the mass of parent nucleus is ($M_p$) (initially at rest), mass of the daughter nucleus ($M_d$) and alpha particle ($M_\alpha$), then, alpha decay energy ($Q_\alpha$) is expressed as:

$$Q_\alpha = [M_P - M_d - M_\alpha]c^2$$

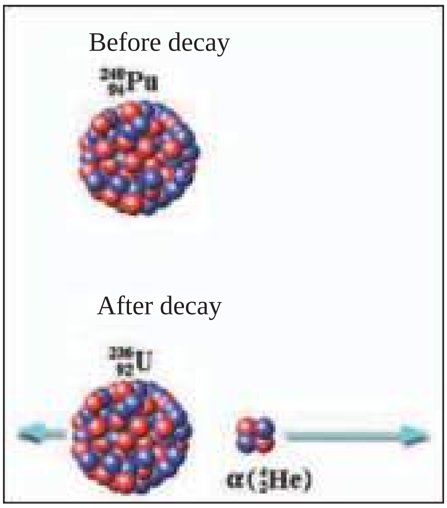


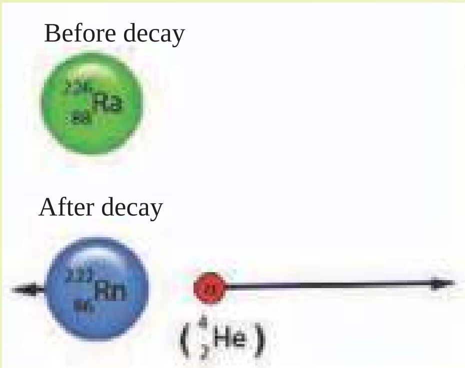
Figure (12)

When atomic mass measured by (u) unit, scince ($c^2 = 931 \frac{MeV}{u}$) then the unit of ($Q_\alpha$), in this case is (MeV). The necessary condition for a nucleus spontaneously decay by (alpha decay) is that the value of energy decay of ($Q_\alpha$) must be positive i.e. ($Q_\alpha$>0). It is worth noting that alpha particle ( with less mass compared to daughter nucleus) will have speed and kinetic energy larger than that of the daughter nucleus according to law of (mass-energy) conservation, and law of linear momentum conservation.

**Example (4)**

Prove that Radium nucleus( $^{226}_{88}Ra$ ) achieves spontaneous decay condition to Radon nucleus ( $^{222}_{86}Rn$ ) by means of alpha decay. Write the nuclear equation of decay, if the atomic masses of each:

$$^{226}_{88}Ra = 226.025406\ (u),$$
$$^{222}_{86}Rn = 222.017574\ (u),$$
$$^{4}_{2}He = 4.002603(u).$$




**The solution:**

The nuclear equation of decay is:

$$^{226}_{88}Ra \rightarrow\ ^{222}_{86}Rn + \ ^{4}_{2}He$$

Parent nucleus  Daughter nucleus  α- particle

Spontaneous decay condition is that value of decay energy ($Q_\alpha$) is positive

We have the relation: $Q_\alpha = [M_p - M_d - M_\alpha]c^2$

Since masses here are in (u) units, then $c^2 = 931 \frac{MeV}{u}$

$$\therefore Q_\alpha = [M_p - M_d - M_\alpha] \times 931\ (MeV)$$

Substituting in previous relation, we have:

$$Q_\alpha = [226.025406 - 222.017574 - 4.002603] \times 931$$

$$\therefore Q_\alpha = 5.229 \times 10^{-3} \times 931 = 4.868\ (MeV)$$

Since ($Q_\alpha$) value is positive, i.e. ($Q_\alpha > 0$)

∴ Spontaneous decay condition is achieved.

## 10-4-2 Beta decay:

It is the second spontaneous radioactive decay through which some nuclei can reach stability. There are three ways where some nuclei can be spontaneously by beta decayed:

1. Emission of negative beta particle ( or electron) (β-) or ( $^{0}_{-1}e$ ), it is a negative charge (-e), this process is called negative beta decay. See figure (13).
2. Emission of positive beta particle (or positron) (β+) or ( $^{0}_{+1}e$ ), it is a positive charge (+e) . This process is called positive beta decay, see figure (14). A positron is a particle which has all properties of electron, but, it has positive charge, (it is called anti-electron).
3. A nucleus captures one of internal orbital electrons of the atom; this process is called electron capture.

Positive Beta decay is accompanied by emission of a particle called Neutrino (its charge and rest mass is zero) ( $^{0}_{0}\nu$ ), or ( $\nu$ ). The atomic number and mass number are zero. While negative beta decay is accompanied by emission of a particle called antineutrino particle ( $^{0}_{0}\bar{\nu}$ ), or ( $\bar{\nu}$ ).The atomic number and mass number of this particle is zero too, (see nuclear decay equations).

One might ask: the nucleus has no electrons or positrons in the first place, how can it emit electron or positron? Where did they come from? The answer is when the nucleus emits the electron, it results from decay of a neutrons in the nucleus into proton, electron and anti-neutrino, see figure (15). This decay is expressed by the following nuclear equation:

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + \beta^{-} + {}^{0}_{0}\bar{\nu}, (\beta^{-} = {}^{0}_{-1}e)$$

This decay happens because the ratio of neutrons to protons in the nuclear is larger than required to achieve stability.

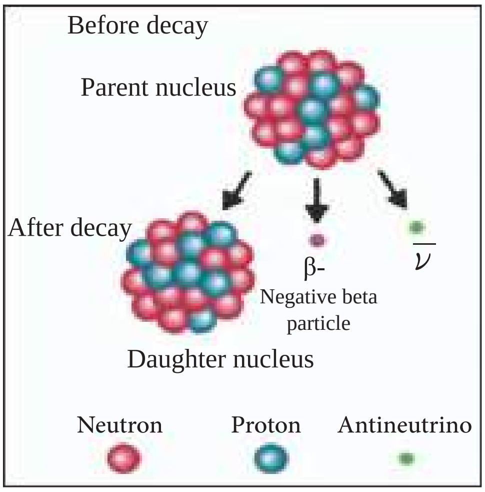



Figure (13)

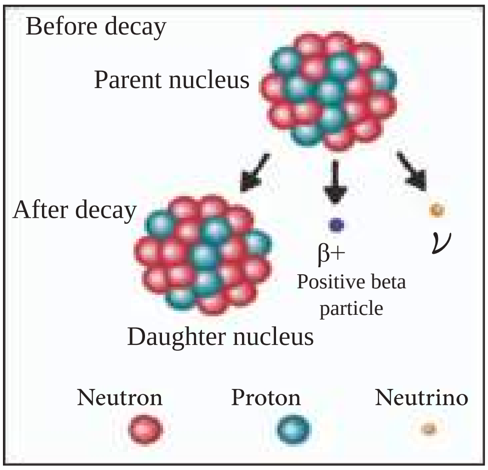
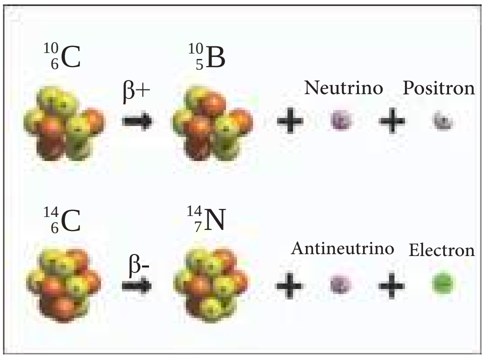



Figure (14)



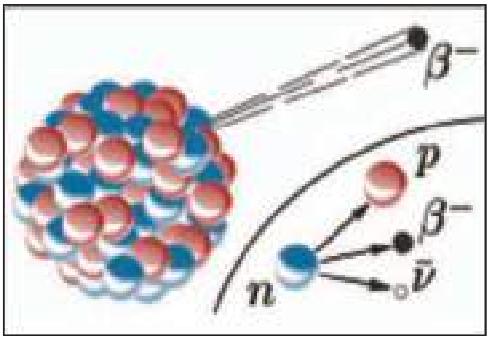




Figure (15)

But when the nucleus emits the positron, it results from decay of a proton in the nucleus in to neutron, positron and neutrino, this decay is expressed by the following nuclear equation:

$^{1}_{1}p \rightarrow {}^{1}_{0}n + \beta^{+} + {}^{0}_{0}\nu, (\beta^{+} = {}^{0}_{+1}e)$

This decay happens because the ratio of neutrons to protons in the nucleus is smaller than required to achieve stability. Below, some examples of three nuclear equations of spontaneously decayed nuclei by beta decay:

$^{64}_{29}Cu \rightarrow {}^{64}_{30}Zn + \beta^{-} + \overline{\nu}$ (Negative beta decay)

$^{13}_{7}N \rightarrow {}^{13}_{6}C + \beta^{+} + \nu$ (Positive beta decay)

$^{41}_{20}Ca + {}^{0}_{-1}e \rightarrow {}^{41}_{19}K + \nu$ (Electron capture)

**Think?**

From observing the adjacent examples of three nuclear equations, the nuclei that have been spontaneous radioactive decay by beta decay, can you know what the decay of the negative beta, the positive beta and the electronic capture do to the values of the mass number and atomic number for the parent nucleus?

## 10-4-3 Gamma decay:

Some nuclei are often in an excited state, i.e. they have extra energy after undergoing alpha or beta decay, how can such nuclei reach stability spontaneously? The answer is: such nuclei can reach stability by Gamma decay (the third spontaneous radioactive decay) and reach more stability by emitting gamma ray, see figure (16-a). If the nucleus moved from a high-energy level to a low-energy level, gamma ray (Photon) will emit. The photon energy equals the difference between levels. Gamma ray, is electromagnetic ray (photons) with high energy and frequency, its rest mass and charge is zero, they are denoted by the symbol ($\gamma$) or ( ${}^{0}_{0}\gamma$ ), because the atomic number and mass number is zero.

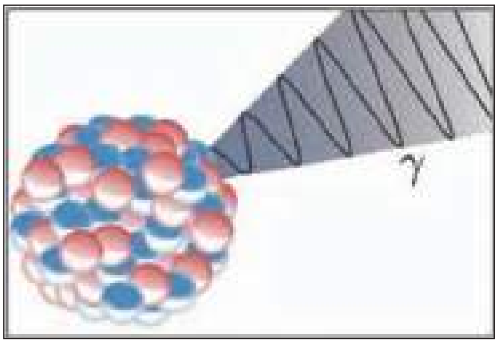


Figure (16-a)

The following equation shows a nuclear equation of a nucleus in gamma decay:

| $^{240}_{94}Pu^{*}$ | $\rightarrow$ | $^{240}_{94}Pu$ | + | $^{0}_{0}\gamma$ |
|---|---|---|---|---|
| (parent nucleus) | | (daughter nucleus) | | (Gamma ray) |
| (plutonium excited nucleus) | | (plutonium nucleus) | | |

(*) sign means that the nucleus is in an excited state, see figure (16-b).

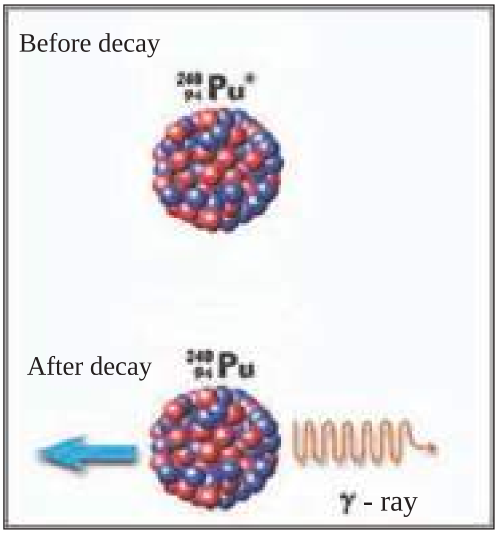


Figure (16-b)

As it is shown previously in nuclear decay equation for Plutonium excited nucleus ( $^{240}_{94}Pu^{*}$ ), the mass number and atomic number remain constant in gamma decay. The relation of gamma energy or photon energy (E) in frequency (f) is as follows:

$$E = hf$$

h: Planck's constant equals: $(6.63 \times 10^{-34} J.s)$

$f = \frac{c}{\lambda}$, Whereby ($\lambda$) is photon wavelength, and (c) is speed of light in vacuum.

## 10-5 Nuclear reactions

We have noticed earlier that structure of nucleus changes when the nucleus undergoes spontaneous radioactive decay by alpha decay or beta decay according to earlier nuclear equations. You might ask, can the structure of the nucleus be changed when thrown by nuclear particles with particular energy? The answer is, yes. Rutherford was the first to prove that an induced nuclear reaction is possible, see figure (17) And as the nuclear reaction below:

$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

(Alpha particle) (Nitrogen nucleus) (Oxygen nucleus ) (Proton )

In case of nuclear equations, sum of atomic numbers and mass numbers must be equal at both sides of the nuclear equation, i.e. that is nuclear equation must be balanced, as shown, for example in the previous nuclear reaction equation. Thus, we note that the nuclear reaction is the one, which makes changes in properties and structure of target nucleus. For example, when Nitrogen nucleus ( $^{14}_{7}N$ ) is thrown by a neutron particle ( $^{1}_{0}n$ ), we can obtain Carbon nucleus ( $^{14}_{6}C$ ) and proton particle ( $^{1}_{1}H$ ), see figure (18).

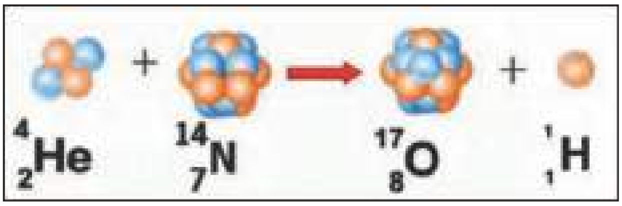


Figure (17)

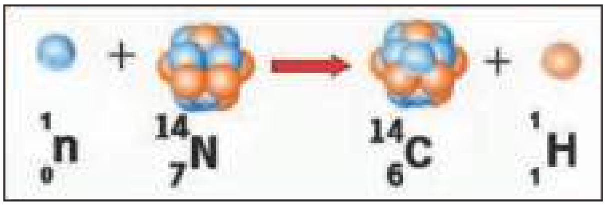


Figure (18)

It is worth noting that nuclear reactions must obey the laws of conservation:

a. (Energy – mass) conservation law.

b. Linear momentum conservation law.

c. Angular momentum conservation law.

d. Electric charge conservation law (or atomic number conservation law).

e. Nucleons number conservation law (or mass number conservation law).

## Nuclear reaction energy

Value of energy of nuclear reaction (Q) can be found as follows: assume a nuclear reaction whereby the target nucleus (X) (usually static at the beginning) whose mass ($M_x$), is thrown by the projectile (a) whose mass is ($M_a$) to produce a nucleus (Y) whose mass is ($M_Y$) and the particle (b) whose mass is ($M_b$), hence, this reaction can be expressed by the following equation:

$$a + X \rightarrow Y + b$$

The value of nuclear reaction energy (Q) can be found from the relation:

$$Q = [(M_a + M_x) - (M_Y + M_b)]c^2$$

Or

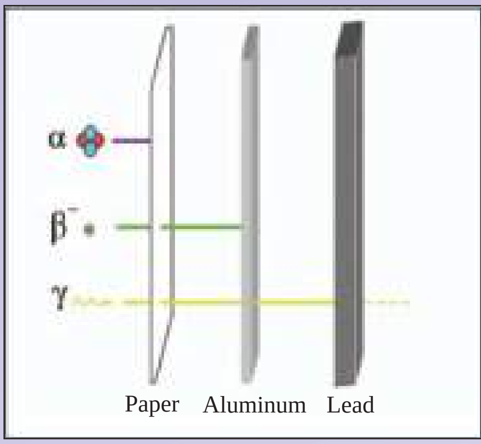
$$Q = [M_a + M_x - M_Y - M_b]c^2$$

When the atomic masses are measured by (u) unit, then ($C^2 = 931 \frac{MeV}{u}$), the unit of (Q) is (MeV). For example if (Q) value is positive (Q>0), then the nuclear reaction is called exoergic reaction.

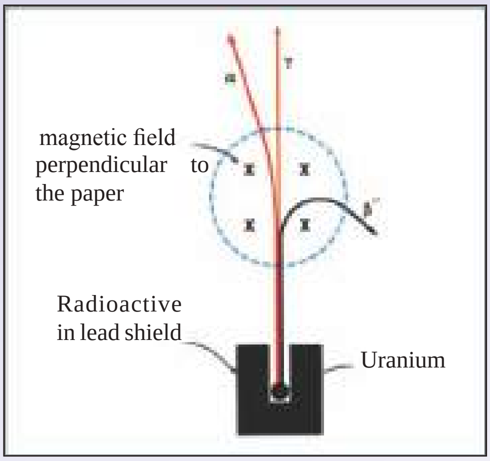
If (Q) value is negative, (Q<0) then the nuclear reaction is called endoergic reaction.

**Remember:**

Alpha particles have the greatest ability to ionize materials, followed by negative beta particles, and the least powerful ones is gamma rays. While for material penetration, Gamma rays have the greatest ability to penetrate materials, followed by negative beta particles, and the least of them are alpha particles (that usually do not penetrate clothing and human skin).




Alpha particles are deflected by the effect of an electric field or a magnetic field in a direction indicating that alpha particles have a positive charge. Negative beta particles are deflected in a direction indicating that they have negative charge, while gamma rays are not deflected by an electric feild or a magnetic field.



It is worth noting that neutrons are important projectiles in nuclear reactions, see figure (19), because neutron charge is zero, therefore it can penetrate into the nucleus easily (easier than alpha particles or protons) because there is no repulsive electrical coulomb between the neutron and the nucleus.

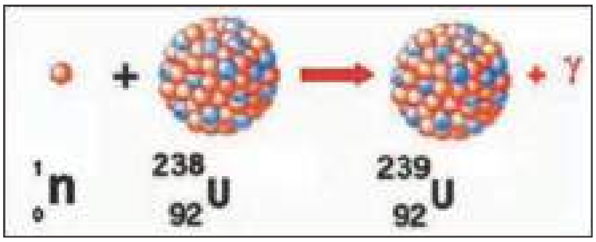



Figure (19)

**Example (5)**

In the following nuclear reaction:

$${}^{4}_{2}He + {}^{14}_{7}N \rightarrow {}^{17}_{8}O + {}^{1}_{1}H$$

Find nuclear reaction energy by (MeV) then show the type of reaction, considering that the atomic masses are:

$${}^{14}_{7}N = 14.003074(u) \quad , \quad {}^{4}_{2}He = 4.002603(u)$$

$${}^{17}_{8}O = 16.999132(u) \quad , \quad {}^{1}_{1}H = 1.007825(u)$$

**The solution:**

From the nuclear reaction:

| ${}^{4}_{2}He$ | + | ${}^{14}_{7}N$ | $\rightarrow$ | ${}^{17}_{8}O$ | + | ${}^{1}_{1}H$ |
|---|---|---|---|---|---|---|
| Projectile (a) Alpha partical | | target nucleus (X) Nitrogen nucleus | | resulting nucleus (Y) Oxygen nucleus | | resulting particle (b) Proton |

Nuclear reaction energy (Q) can be found from the relation:

$$Q = [M_a + M_X - M_Y - M_b]c^2$$

Since masses here are given in (u) unit, then ( $c^2 = 931 \frac{MeV}{u}$ )

$$\therefore Q = [M_a + M_X - M_Y - M_b] \times 931(MeV)$$

Considering the nuclear reaction equation and substituting in previous equation, we have:

$$Q = (4.002603 + 14.003074 - 16.999132 - 1.007825) \times 931(MeV)$$

$$\therefore Q = (-0.001280) \times 931 = -1.192(MeV)$$

Since (Q) value is negative (Q<0), $\therefore$ The reaction is endoergic.

## 10-6 Nuclear fission

We often hear about massive energy released by nuclear fission in its peaceful and non- peaceful uses. What is meant by nuclear fission? It is a nuclear reaction in which a heavy nucleus (like Uranium nucleus ( $^{235}_{92}U$ ) is divided into two nucleus of light masses, by throwing (projecting) this heavy nucleus with slow neutron (thermal neutron) of small energy (0.025eV), see figure (20).

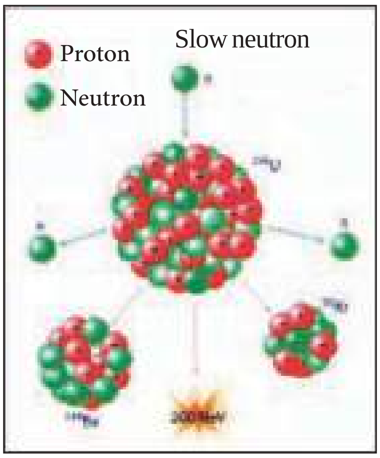


Figure (20)

The result of nuclear fission is new radioactive nuclei and a number of neutrons (typically two or three) as well as massive energy. You might ask where did this massive energy come from? The answer is, this massive energy comes from the fact that sum of resulting masses is less than sum of reacting masses. Thus, the missing (lost) mass turns to massive energy according to Einstein relation of equivalence of (mass- energy). For example: (200MeV) energy releases when one Uranium nucleus fission ( $^{235}_{92}U$ ).

Thus, the released energy from nuclear fission is much larger than that of released from the chemical reactions. For example: Uranium nucleus fission ( $^{235}_{92}U$ ) by a slow Neutron, in the following reaction, see figure (21).

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U^{*} \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

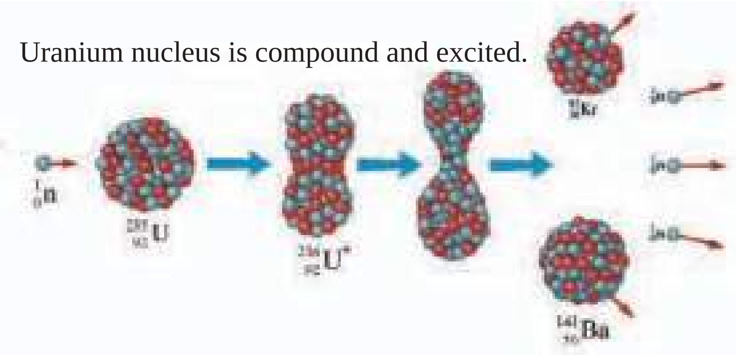


Figure (21) [For reference only (not required)]

The symbol ( $^{236}_{92}U^{*}$ ) means that the uranium nucleus is compound and excited.

### Chain Nuclear reaction:

The reaction at which uranium ( $^{235}_{92}U$ ) nuclei is fission is called chain nuclear reaction, see figure (22).

If the chained nuclear reaction is not controlled, it will cause massive explosion and huge amount

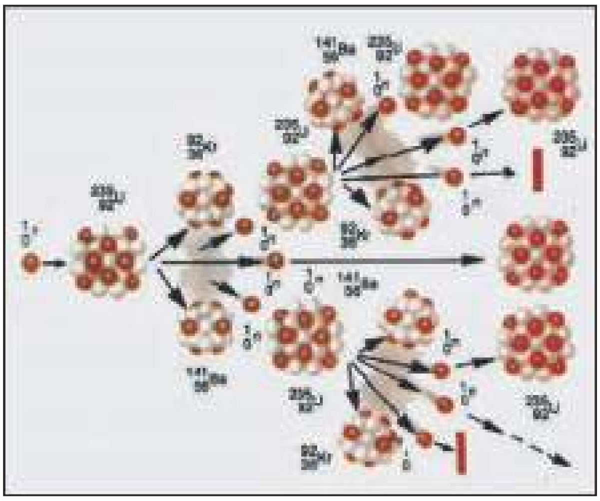


Figure (22) [For reference only (not required)]

of energy. Nuclear bomb (commonly atomic bomb also called fission bomb see figure (23) was made according to this case. Man managed to control chain nuclear reaction. The first controlled chain nuclear reaction was done by the scientist Fermi and his associates in the first nuclear reactor in Chicago in USA (1942), figure (24), shows the core diagram of the first reactor. The nuclear reactor is a series of systems which control chain fission nuclear reaction of the nuclear fuel (like Uranium $^{235}_{92}U$ of Plutonium $^{239}_{94}Pu$) and the resulting energy. Nuclear reactors are now largely used for peaceful purposes and electrical energy, see figure (25-a,b)


Figure (23)

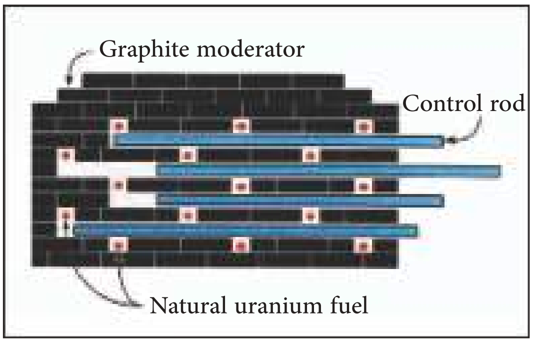


Figure (24)


Figure (25-a)

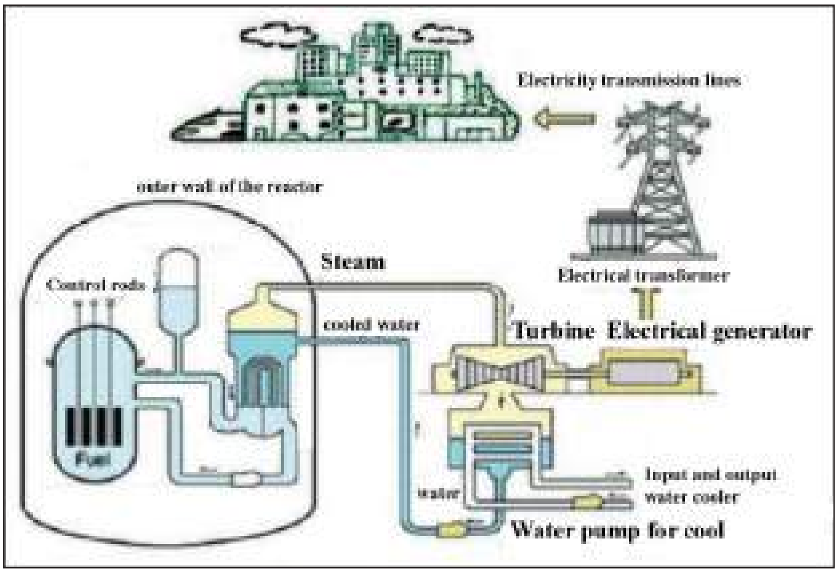


Figure (25-b) components of a nuclear reactor to generate electricity [For reference only (not required)]

| 10-7 | Nuclear fusion |
|---|---|

Have you ever wondered how the sun can have all this massive energy, which reaches the earth? The truth is that this massive energy result from a nuclear reaction called nuclear fusion, which will be discussed now:

## Nuclear Fusion:

It is nuclear reaction whereby, two small nuclei (light mass), are fused to form a heavier nucleus. See figure (26). The mass of the heavier nucleus is less than sum of masses of both original light nuclei. Difference in mass converts to released energy according Einstein relation of (mass-energy) equivalence. According to this, the sun is considered a huge thermal fusion reactor to produce energy. What are the processes and nuclear reactions to produce such huge energy in the sun? Chain reactions of normal Hydrogen nuclei fusion (protons) to produce helium ($^{4}_{2}He$), are the main processes in the core of the sun (where the temperature is $1.5 \times 10^{7} K$), within a series called (proton-proton) cycle. Nuclear fusion releases larger energy than that of nuclear fission for equal masses of nuclear fuels. This concept is applied in militarily to produce the Hydrogen bomb, see figure (27). It is more fatal and lethal than the fission bomb. This kind of fusion bombs is uncontrollable reaction. However, what the controlled fusion reaction is called? Controlled Fusion nuclear reaction is called the inexhaustible energy source because the source for this reaction is Hydrogen (it is abundant and available in water on earth). Nuclear fusion is considered a source of clean energy, because helium is non-radiant by-product, unlike radioactive reactants

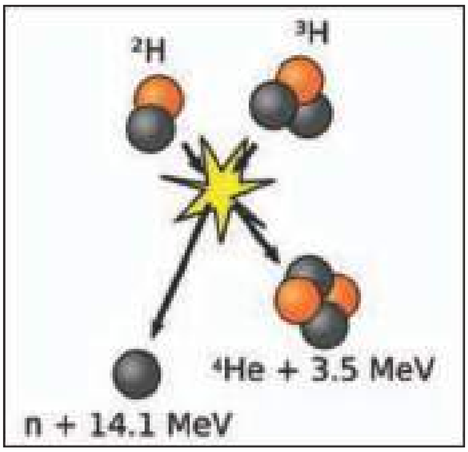
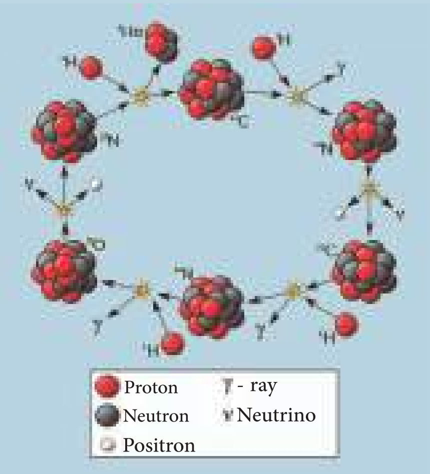



Figure (26)

Figure (27)

**DO you know?**

There is another nuclear fusion reactions called carbon cycle (carbon fusion) and occurs in the stars that its temperature is higher than the temperature of the sun core.



in nuclear fission. There are many difficulties to achieve nuclear fusion, the major difficulty is repulsive electrical coulomb force between protons and reacting nuclei when the distance between them is short. To enable protons overcome repulsive electrical coulomb force, the nuclear reaction temperature must be very high (about $10^8$K), whereby the medium to bear such heat becomes plasma (the fourth state of matter). There is currently no material that can handle such heat. Due to technical difficulties, there is no real advantage from fusion nuclear reaction for peaceful purposes. Scientists now seek to discover new ways to contain reacting plasma needed in nuclear fusion like using the magnetic field to enclose plasma in a container but away from the walls (like tokamak device), see figure (28). If a controlled fusion nuclear reaction is attainable, fusion nuclear reactors will be the future of this energy. Figure (29) shows one of prototypes for a fusion nuclear reactor.

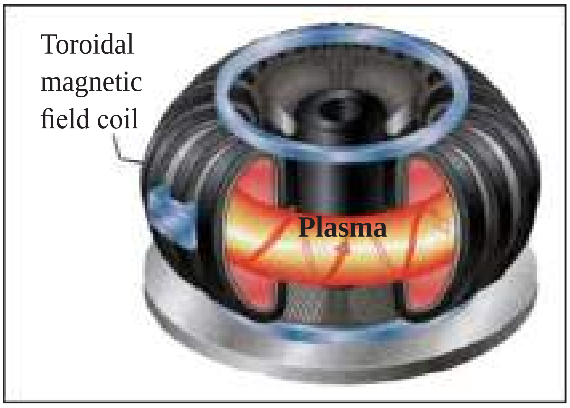



Figure (28) [For reference only (not required)]

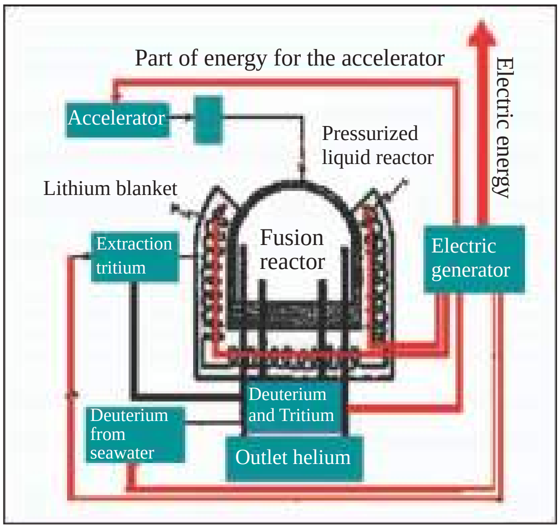



Figure (29) Suggested Design of nuclear fusion reactors [For reference only (not required)]

## 10-8 Hazards and beneficials of nuclear radiation

You might be surprised to know that we all exposed to nuclear radiations all the time. But where these nuclear radiations come from? The logical answer to this equestion is certainly from the environment in which we live. Sources of nuclear reaction are generally divided into two:

1. Sources of natural background nuclear radiation: This includes cosmic ray and nuclear radiation from earth crust, as well as radioactive activity in the human body.

2. Sources of artificial nuclear radiation: including nuclear radioactive sources used in medicine for the purpose of diagnosis and treatment, see figure (30), radioactive nuclear waste, nuclear dust from nuclear weapons test, nuclear radiations produced from reactors, and the use of radioactive nuclear sources used in research and study.

Figure (30)

What are effects and hazards of nuclear radiation on human body?

The degree and type of damage caused by nuclear radiation depends on many factors, like type of radiation (a gamma or alpha particles…etc), the energy of this radiation, and the organ exposed to this radiation (liver, bone or eye..etc.). As the radiation damage in humans body is caused by ionizing body cells .The damage causes early effects like dermatitis or late effects like cancer (physical effects), as for damages in reproductive cells, it might lead to deformed births and this damage might last for generations (hereditary effects). So, what is the precautionary procedure to protect ourselves against external nuclear radiation we might be exposed to?

The answer is: In case exposure to radiation, we must keep this exposure to minimum by :

a. Reduce exposure time of nuclear radiation to minimum.

b. Keep away from nuclear radiation source.

c. Wear protective shields between humans and nuclear radiation source (like lead for example). see figure (31).

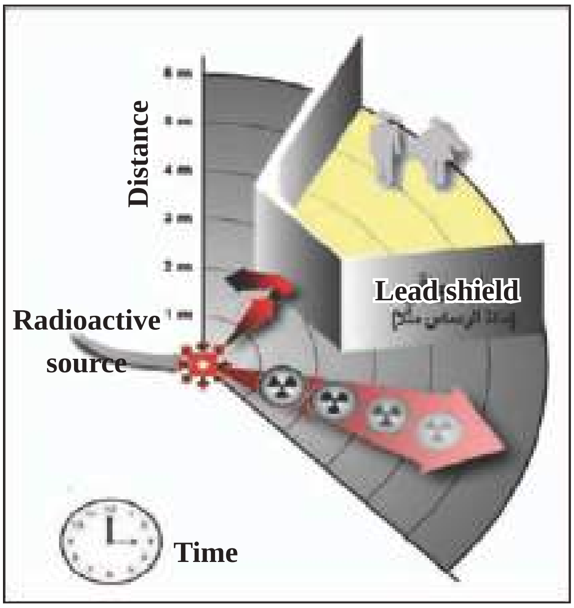



Figure (31)

Are there advantages and useful uses of nuclear radiation and nuclear energy?

Of course, there are many useful and peaceful applications, we will mention some here:

a. The medical field: Nuclear radiation and nuclear energy can be used to fight pathological organisms like viruse, which cause diseases. They are also used to sterile medical equipments.

b. The agricultural field: like studying physiology of plant, plant nutrition, and maintaining of foods. See figure (32).

c. The industrial field: As a fuel to spaceships , see figure (33), and operating ships and submarines. See figure (34). There are many applications of this energy that cannot be summarized here.

Figure (32)

**DO you know?**

The first electric power generation from nuclear energy was in 1951, now there are more than thirty countries investing nuclear energy to generate electric power.

Figure (33)

Figure (34)

# Questions of chapter 10

**Q1** Choose the correct statement for each of the following:

1. The radius of a nucleus (R) is change:

a. Directly proportional with ( $A^{\frac{1}{3}}$ ). b. Inversely proportional with ( $A^{\frac{1}{3}}$ ).

c. Directly proportional with ($A^3$). d. Inversely proportional with ($A^3$)

2. The amount of average nuclear binding energy per nucleon is:

a. Greater for the nucleus of the light elements. b. Greater for the nucleus of the heavy elements

c. Equal to all nucleus of elements. d. Greater for the nucleus of intermediate elements

3. The followings are properties of nuclear forces except one:

a. Binds and holds nucleon of the nucleus. b. Does not depend on the charge.

c. Has very long range. d. The strongest in nature

4. If we assume that binding energy per nucleon for the nucleus of Neon ( $^{20}_{10}Ne$ ) equals (161MeV), then the average binding energy per nucleon for the nucleus of Neon with units MeV equals:

a. 8.05. b. 16.1.

c. 3220. d. 1610

5. The nucleus of the Polonium isotope ( $^{218}_{84}Po$ ) spontaneously decays to the nucleus of isotope Lead ( $^{214}_{82}Pb$ ) via decay of:

a. Gama. b. Negative beta.

c. Positive beta. d. Alpha.

6. When a nucleus suffers spontaneous positive beta decay, the atomic number is:

a. Increased by one. b. Decreased by one.

c. Decreased by four. d. Does not change.

7. In the following nuclear reaction:

$^{4}_{2}He + ^{9}_{4}Be \rightarrow ^{A}_{6}C + ^{1}_{0}n$,

the value of (A) is;

a. 13. b. 12.

c. 5. d. 6.

8. In Nuclear Physics, the two small nuclei (light by its mass) are fuse to form a heavier nucleus is called:

a. Nuclear fission.
b. Electron capture.
c. Positve beta decay.
d. Nuclear fusion.

9. The natural background nuclear radiation sources are:

a. Dust falling from nuclear weapons tests.
b. Cosomic rays.
c. Nuclear radiation produced from nuclear reactors.
d.None of above.

10. Nuclear fission carries out for the nucleus of uranium ( $^{235}_{92}U$ ) by using:

a. Proton with small energy.
b. Alpha particle with small energy.
c. Slow neutron.
d. None of above.

**Q2** What is the meaning of the following?

Positron, nuclear fission, nuclear binding energy, nuclear chain reaction, nuclear fusion, nuclear reactor.

**Q3** What is the particle which:

a. Has a mass number equal one and an atomic number equals zero.
b. Is called anti-electron.
c. Accompanies an electron in spontaneous negative beta decay?
d. Accompanies a positron in spontaneous positive beta decay?

**Q4** What is the condition for spontaneously decay of a nucleus by alpha decay?

**Q5** Causes the followings:

a. Gamma rays emitted spontaneously from some radiated element's nuclei.
b. Neutrons are regarded as important projected of nuclear reaction.

**Q6** What are the types in which some nuclei would be decay spontaneously by beta decay?

**Q7** Since the nucleus basically does not contain electrons, how can the nucleus emit an electron, explain that.

**Q8** What are the conservation laws which must be satisfied in the nuclear reactions?

**Q9** Complete the following nuclear equation:

a. ${}^{2}_{1}H + {}^{9}_{4}Be \rightarrow {}^{7}_{3}Li + ?$

b. ${}^{12}_{6}C^{*} \rightarrow {}^{12}_{6}C + ?$

c. ${}^{56}_{27}Co \rightarrow {}^{56}_{26}Fe + ? + \upsilon$

d. ${}^{1}_{0}n \rightarrow ? + ? + ?$

**Q10** Where is the tremendous energy of nuclear fission come from?

**Q11** What happens if a chain nuclear reaction is not controlled?

**Q12** The uranium nucleus ( ${}^{238}_{92}U$ ) was decay by spontaneous alpha decay to a thorium nucleus (Th). Then thorium nucleus is decay by spontaneous negative beta decay and formed (X) nucleus. Then the (X) nucleus will decay by spontaneous negative beta decay finally formed ( $X'$ ) nucleus .

a. Write the three nuclear equations for this nuclear chain reaction in sequence.

b. Give the name of the nucleus ( $X'$ ).

**Q13** What are the main nuclear processes and reactions to produce the huge energy in Sun?

**Q14** What do we mean when we say the controlled nuclear fusion reaction is of called the source of energy which is inexhaustible. Explain that.

**Q15** What is the main obstacle to obtaining useful energy from nuclear fusion?

**Q16** What is the effect and hazards of nuclear radiation on the human body? Explain this.

**Q17** What precautionary measure is required to be taken in order to protect ourselves from the dangers of external nuclear radiation that we may be exposed to urgently? Explain this.

## Problems of chapter 10

**Hint:**

The mass of Hydrogen atom, ($^{1}_{1}H$) = 1.007825 (u)

The mass of Helium atom, ($^{4}_{2}He$) = 4.002603 (u)

Neutron mass = 1.008665 (u)

$1u = 1.66 \times 10^{-27} (Kg)$ , $h = 6.63 \times 10^{-34} (J.s)$

$c = 3 \times 10^{8} (m/s)$ , $e = 1.6 \times 10^{-19} (C)$

$1eV = 1.6 \times 10^{-19} (J)$

**P.1.** Nuclear fuel is placed inside a nuclear reactor. After the nuclear reaction has taken place, there was less mass which has been converted to nuclear energy (0.25g). Find the amount of nuclear energy produced in (MeV) units.

**P.2.** For the nucleus ($^{56}_{26}Fe$), find:

a. The amount of nucleus charge.

b. The radius of nucleus, measured by (m) firstly then by unit (F) secondly.

c. Nucleus volume, measured by ($m^3$).

If you know: ($\sqrt[3]{7} = 1.913$).

**P.3.** If the radius of Polonium nucleus ($^{216}_{84}Po$) equals twice the radius of an unknown nucleus(X). Find the mass number for the unknown nucleus?

**P.4.** Find the nuclear binding energy of ($^{126}_{52}Te$) nucleus in (MeV) unit firstly, then in (J) unit secondly, if the mass of atom ($^{126}_{52}Te$) is (125.903322 u).

**P.5.** Find the followings for ($^{12}_{6}C$):

a. Defect mass in (u) unit.

b. Nuclear binding energy in (MeV) unit.

c. Average nuclear binding energy per nucleon in (MeV) unit.

If you know (mass of ($^{12}_{6}C$) equal (12u).

**P.6.** Which one of the following two nuclei has nuclear binding energy, greater than the other. Nucleus ($^{3}_{1}H$) or nucleus ($^{3}_{2}He$)? Find the result in (MeV) unit. If the atomic masses of: $^{3}_{1}H$ = 3.016050 (u) , $^{3}_{2}He$ = 3.016030 (u)

**P.7.** Prove that the Plutonium ( $^{236}_{94}Pu$ ) nucleus satisfies spontaneous decay condition to Uranium nucleus ( $^{232}_{92}U$ ) by alpha decay. Also write the nuclear decay equation, given that atomic masses are:

$^{236}_{94}Pu$ =236.046071(u) , ( $^{232}_{92}U$ ) = 232.037168 (u)

**P.8.** Find the change in the mass of a nucleus at rest initially, when nucleus shots gamma radiation with energy (2MeV)? Find the answer in (u) firstly and (kg) secondly. What is the wavelength of these radiation in (m). Neglect the nucleus recoil.

**P.9.** A nuclear reaction happened between a fallen particle and the nucleus of the Beryllium ( $^{9}_{4}Be$ ) at rest. This produces the particle of neutron and Carbon nucleus ( $^{12}_{6}C$ ).

a. Express this reaction as a nuclear reaction equation and hence determine the name of the fallen particle.

b. Find the nuclear reaction energy measured in (MeV) unit.

c. What is the type of this nuclear reaction.

given that atomic mass of ( $^{9}_{4}Be$ ) = 9.012186 (u) , ( $^{12}_{6}C$ ) = 12 (u).

**P.10.** A nuclear reaction has taken place between fallen proton and Samarium nucleus ( $^{150}_{62}Sm$ ) at rest. This reaction produced an alpha particle and Promethium nucleus ( $^{147}_{61}Pm$ ). The nuclear energy equals (6.88 MeV) and the mass of Samarium atom equals (149.917276 u). Express this reaction by nuclear reaction equation. Find the mass of Promethium atom in (u) unit.

**P.11.** Assume that energy of (200 MeV) released by fission of one nucleus from Uranium ( $^{235}_{92}U$ ). Find the number of Uranium nuclei needed to released ( $3.2 \times 10^{12}$ J ) energy.

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